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AUTHOR(S):
Tanaka, Daisuke; Nagashima, Kazuaki; Sasaki, Mayumi; Yamada, Chizumi; Funakoshi, Shogo; Akitomo, Kimiyō; Takenaka, Katsunobu; Harada, Kouji; Koizumi, Akio; Inagaki, Nobuya

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GCKR mutations in Japanese families with clustered type 2 diabetes

Daisuke Tanaka\textsuperscript{a}, Kazuaki Nagashima\textsuperscript{a}, Mayumi Sasaki\textsuperscript{a}, Chizumi Yamada\textsuperscript{a}, Shogo Funakoshi\textsuperscript{a}, Kimiyo Akitomo\textsuperscript{a}, Katsunobu Takenaka\textsuperscript{b}, Kouji Harada\textsuperscript{c}, Akio Koizumi\textsuperscript{c}, and Nobuya Inagaki\textsuperscript{a}

\textsuperscript{a}Department of Diabetes and Clinical Nutrition, Graduate School of Medicine, Kyoto University, Kyoto, Japan

\textsuperscript{b}Takayama Red Cross Hospital, Gifu, Japan

\textsuperscript{c}Department of Health and Environmental Sciences, Graduate School of Medicine, Kyoto University, Kyoto, Japan

Corresponding Author:

Nobuya Inagaki

Department of Diabetes and Clinical Nutrition,
Graduate School of Medicine, Kyoto University

54 Shogoin-Kawahara-cho, Sakyo-ku, Kyoto, 606-8507, Japan

Telephone: +81-75-751-3562

Fax: +81-75-771-6601

E-mail: inagaki@metab.kuhp.kyoto-u.ac.jp

Running Title: GCKR mutations in Japanese families
Abstract:

Objective

The aim was to investigate the genetic background of familial clustering of type 2 diabetes.

Subjects and Methods

We recruited Japanese families with a 3-generation history of diabetes. Genome-wide linkage analysis was performed assuming an autosomal dominant model. Genes in the linkage region were computationally prioritized using Endeavour. We sequenced the candidate genes, and the frequencies of detected nucleotide changes were then examined in normoglycemic controls.

Results

To exclude known genetic factors, we sequenced 6 maturity onset diabetes of the young (MODY) genes in 10 familial cases. Because we detected a MODY3 mutation HNF1A R583G in one case, we excluded this case from further investigation. Linkage analysis revealed a significant linkage region on 2p25-22 (LOD score = 3.47) for 4 families. The 23.6-Mb linkage region contained 106 genes. Those genes were scored by computational prioritization. Eleven genes, i.e., top 10% of 106 genes, were selected and considered them as primary candidates. Considering their functions, we eliminated 3 well characterized genes and finally sequenced 8 genes. GCKR ranked highly in the computational prioritization. Mutations (minor allele frequency less than 1%) in exons and the promoter of GCKR were found in index cases of the families (3 of 18 alleles) more frequently than in controls (0 of 36 alleles, P=0.033). In one pedigree with 9 affected members, the mutation GCKR g.6859C>G was concordant with affection status. No mutation in other 7 genes that ranked highly in the prioritization was concordant with affection status in families.

Conclusions
We propose that $GCKR$ is a susceptibility gene in Japanese families with clustered diabetes. The family based approach seems to be complementary with a large population study.

**Keywords:** Genetic susceptibility, Linkage analysis, MODY, $HNF1A$, $GCKR$

**Abbreviations:**

- GAD: Glutamic acid decarboxylase
- GCKR: Glucokinase regulator
- HLOD: Heterogeneity logarithm of the odds
- HNF4α: Hepatocyte Nuclear Factor 4α
- LOD: Logarithm of the odds
- MAF: Minor allele frequency
- MODY: Maturity onset diabetes of the young
- RFLP: Restriction fragment length polymorphism
- SNP: Single nucleotide polymorphism
1. Introduction

The national survey in 2007 reported that 8.9 million people suffer from diabetes in Japan [1]. Most of these have type 2 diabetes, and the number of such patients has increased continuously. Both genetic and environmental factors play important roles in the pathogenesis of type 2 diabetes [2].

To elucidate the genetic factors underlying the pathogenesis of type 2 diabetes in the Japanese population, several genome-wide linkage analyses in Japanese sib-pairs have been performed [3-5]. Linkage to 11p13–p12 is consistently implicated in these studies [5]. Recent successes with genome-wide association analyses in the Japanese population have revealed a susceptibility variant in KCNQ1 located at 11p15.5 [6, 7], a locus not far from the region suggested in linkage analyses. The association of susceptibility loci including TCF7L2, CDKAL1, CDKN2A/B, IGF2BP2, SLC30A8, and HHEX with diabetes has been established in Caucasian populations and replicated in the Japanese population [8]. However, the loci identified in association studies have uniformly small effect sizes, and can explain only a small portion of the genetic background of diabetes in the Japanese population. Approaches other than sib-pair linkage analyses and association analyses may therefore be required to elucidate a greater aspect of the genetic background of type 2 diabetes.

In the present study, we used a family-based approach, because high degrees of familial clustering can raise the relative risk and provide better insight to novel loci of larger effect size [9]. Familial clustering of diabetes is well known, the typical example being MODY [10]. On the other hand, in most families in Japan, familial clustering cannot be attributed to mutations of the 6 known MODY genes [10], and genetic predisposition in such families has not been ascertained.
We recruited families having a 3-generation history of diabetes and performed genome-wide linkage analysis. We selected candidate genes in the linked chromosomal region and searched for rare and common nucleotide changes the genes in familial cases and unaffected controls.
2. Material and Methods

2.1. Families and Additional Index Cases

We recruited patients from collaborating hospitals in Japan who had diabetes with a 3-generation family history, which is suggestive of autosomal dominant mode of inheritance [11]. If ≥2 family members with diabetes were alive and donated DNA, the families were regarded as suitable subjects for the present study. Families including members with positive GAD (Glutamic Acid Decarboxylase) antibody were excluded from the study. Four families met these criteria and were included in the linkage analysis (Figure 1). Affected status of the participants was determined in two ways. First, if participants had been diagnosed with diabetes and treated with oral hypoglycemic agents or insulin injection, they were regarded as affected. Second, if participants had not been treated with oral hypoglycemic agents or insulin injection, they underwent HbA1c (Hemoglobin A1c) measurement for screening of impaired glucose tolerance. The value for HbA1c is estimated as an NGSP (US National Glycohemoglobin Standardization Program) equivalent value (%) calculated by the formula

\[
\text{HbA1c} (\%) = \text{HbA1c (JDS, Japanese Diabetes Society)} (\%) + 0.4\% \text{, considering the relational expression of HbA1c (JDS)(\%) measured by the previous Japanese standard substance and measurement methods and HbA1c (NGSP)} [12]. \text{If their HbA1c levels were} \geq 6.0\%, \text{they were also regarded as affected. HbA1c} \geq 6.0\% \text{is the level defined as possible diabetes mellitus in the 2007 survey of the Ministry of Labor, Health and Welfare of Japan} [1].

In addition to these subjects, 6 index cases from other families with a 3-generation history of diabetes were included in the study (Supplementary Figure 1). In these families, although we confirmed the affected status of some of the family members, DNA samples were available.
only for the index cases but not for other family members. Together with the 4 index cases
from the families included in the linkage analysis, a total of 10 unrelated cases with a
3-generation history of diabetes were available for DNA sequencing. The clinical features of
family members and additional index cases are shown in Table 1.

2.2. Normoglycemic controls

An annual medical check-up program was performed in Nyukawa district of Takayama
City, Japan. Nine-hundred ninety local residents (430 men, 560 women) were recruited in the
program and consented to donate their DNA. From 2002 to 2007, participants underwent
physical examination and blood tests including fasting plasma glucose and HbA1c every year.
We selected normoglycemic controls from the participants in the cohort. Subjects defined as
normoglycemic controls had the following characteristics: HbA1c <6.0% and fasting plasma
glucose <5.5mmol/l during 5-year follow-up span, and age ≥55. The number of subjects that
satisfied the definition was 206 (81 men, 125 women).

2.3. Genotyping Family Members

Genomic DNA was extracted from blood samples with a QIAamp DNA Blood Mini Kit
(Qiagen Inc). PCR amplification from genomic DNA was performed with
fluorescence-labeled (6-FAM, HEX, NED) and tailed primers. PCR primers to analyze
microsatellite markers comprised an approximately 10cM human index map (ABI Prism
Linkage Mapping Set Version 2.5: 382 markers for 22 autosomes), and other microsatellite
fine markers were designed according to information from the UniSTS map. PCR reactions
were carried out in 7.5 μl with 50 ng genomic DNA, using AmpliTaq Gold DNA Polymerase (Applied Biosystems) in a 2-step amplification program. DNA fragments were analyzed on an Applied Biosystems 3130 Genetic Analyzer. Genotyping errors and inconsistent relationships were checked with the use of GENEHUNTER (version 2.1) software [13]. If the results of genotyping were missed or ambiguous, we treated them as an unknown genotype in the linkage analysis. The rate of genotyping failure was 0.057% (7/11842).

2.4. Linkage and Haplotype Analyses

Both affected and unaffected family members were included in the linkage analysis. Participants with HbA1c level <6.0% were considered as unaffected if the age was ≥55 and as unknown if the age was <55, considering the assumed age-dependent penetrance of diabetes. The purpose of including members assigned as unknown was to increase the accuracy of haplotype estimation in affected members, although inclusion did not increase the statistical power. Multipoint parametric analyses for autosomes were run using GENEHUNTER assuming an autosomal dominant model [13]. Because locus heterogeneity could be associated with diabetes, LOD (log of the odds) score and HLOD (heterogeneity LOD) score were calculated. The disease allele frequency was set at 0.00001 and a phenocopy frequency of 0.00001 was assumed. Population allele frequencies for each microsatellite marker were assigned equal portions for individual alleles. We used a 2-stage design: first, all chromosomal regions were screened by genotyping at an approximately 10cM density (screening), and the regions where LOD scores were highest were considered potentially interesting. Second, these regions were further finely mapped at approximately 1- to 2-cM densities (fine mapping). Regions where LOD scores were above 3.3, a level
corresponding to genome-wide significance [9], were considered as linkage regions. Haplotypes were constructed with the GENEHUNTER program.

2.5. Prioritization of Candidate Genes

The 23.6-Mb linkage region on chromosome 2p25-22 contained 106 genes annotated in Ensemble genome browser (www.ensembl.org). The genes were computationally prioritized using Endeavour (www.esat.kuleuven.be/endeavour/) [14]. We selected 6 MODY genes (HNF4A, GCK, HNF1A, PDX1, HNF1B, and NEUROD1) as training genes because a dominant mode of inheritance was assumed in the highly clustered families in linkage analysis. We adopted all databases available in Endeavour, which prioritized glucokinase regulator (GCKR) at the first rank.

2.6. Sequencing

We directly sequenced the coding exons of 6 MODY genes (HNF4A, GCK, HNF1A, PDX1, HNF1B, and NEUROD1) in the 10 index cases. We sequenced GCKR including all exons found in the National Center for Biotechnology Information (NCBI) Evidence Viewer (www.ncbi.nlm.nih.gov) and the 2-kb promoter region in the index cases from families and in control subjects. We also selected other 7 genes that are highly prioritized within the 11th rank (10.3%) in the linkage region using Endeavour excluding 3 genes with known metabolic functions unrelated to glucose metabolism (Supplementary Table 1). We sequenced the entire coding exons of the 7 genes in the index cases from families included in the linkage analysis. Forward and reverse PCR primers for each exon were selected in an intronic sequence 50 bp
away from the intron/exon boundaries and primers to amplify the GCKR promoter region
were also selected. Sequencing primer data for GCKR is shown in Supplementary Table 2.
PCR products were run on 2% agarose gel, and the appropriate bands were excised and then
purified with the use of the QIAquick Gel Extraction Kit (Qiagen). Sequencing results were
analyzed on an ABI Prism 3130 Avant DNA sequencer (Applied Biosystems). Any nucleotide
changes identified in sequencing were searched for SNPs (single nucleotide polymorphisms)
in the dbSNP database (www.ncbi.nlm.nih.gov/SNP/).

2.7. Genotyping SNPs

If minor allele frequencies (MAF) of nucleotide changes identified in sequencing were
unregistered in the HapMap JPT database on dbSNP as of April 2010 and the minor allele
appeared in <2 of all subjects, MAF was determined in the expanded population. We defined
mutation as MAF<1% [15]. To determine whether each nucleotide change was a mutation or
not, we genotyped 105 normoglycemic controls randomly selected from the cohort
(Supplementary Table 3), because genotyping of 210 normal chromosomes is necessary to
achieve 80% power to detect a polymorphism present in 1% of the population [16]. The
PCR-RFLP (restriction fragment length polymorphism) method for HNF1A R583G, GCKR
g.-689G>A, GCKR g.-299G>A, GCKR E252K and FOSL2 R198H and Taqman method for
GCKR g.6859C>G were used.

2.8. Statistical analysis

Frequencies of mutations (MAF<1%) and common nucleotide changes (MAF≥1%)
identified in *GCKR* sequencing in the index cases and in normoglycemic controls were compared by the Fisher exact test with SAS software (version 8.2).

2.9. *Ethics*

The methods used in this study were approved by the Ethics Committee of the Kyoto University Institutional Review Board, and approved written informed consent was obtained from each participant.
3. Results

3.1. Characteristics of Family Members

Four families with a 3-generation history of diabetes were enrolled in this study (Figure 1, Table 1). Every family included no less than 1 member that had been diagnosed with diabetes before the age of 50. Sixteen members (6 men, 10 women) had previously been diagnosed with diabetes. Thirteen out of the 16 members with diabetes were lean (BMI<25). Six members were treated with insulin and another 10 members were treated with oral hypoglycemic agents. Twelve family members who had not been diagnosed with diabetes underwent HbA1c measurement and 3 of them had HbA1c level ≥ 6.0%. These 3 members had already been diagnosed with impaired glucose tolerance before this study and were included as affected members in the study.

3.2. Exclusion of MODY gene mutations in the index cases

For the 10 index cases, we performed direct sequencing in entire coding exons of the MODY genes. The detected missense SNPs were $HNF1A$ I27L (rs1169288), $HNF1A$ S487N (rs2464196), $HNF1A$ R583G, and $HNF4A$ T117I (rs1800961) (Supplementary Table 4). $HNF1A$ R583G is a mutation that is reported to cause MODY [17], thus we excluded the carrier of the mutation (additional index case #6, Table 1) from further investigation. $HNF1A$ I27L and $HNF1A$ S487N are common in the general population (MAF=0.386 and 0.341, respectively in HapMap-JPT). $HNF4A$ T117I was associated with late-onset type 2 diabetes but it was not the cause of MODY in a previous report [18].
3.3. Linkage Analysis

A total of 30 members (19 affected members) from 4 families were included in the linkage analysis, assuming an autosomal dominant model. The genome-wide linkage results in the screening are shown in Figure 2. Regions of potential interest by multipoint LOD and HLOD scores were observed on chromosomes 2p24 and 7q34. After fine mapping, 2p25-22 was revealed to be a significant linkage region (Figure 3, LOD and HLOD=3.47) while the region on 7q34 was discarded. The size of the region with positive HLOD score was 23.6Mb (D2S2199-D2S2230). In the region, a haplotype segregated in affected and unaffected members in the pedigrees 1, 2, and 3, but not in the pedigree 4.

3.4. Candidate Genes

We searched candidate genes in the implicated linkage region by applying a gene prioritization approach implemented in Endeavour software. We selected 6 MODY genes as training genes. The 2 top-ranked genes were glucokinase regulatory protein (GCKR) and nuclear receptor coactivator 1 (NCOA1). GCKR ranked high in prioritization using gene-gene interaction databases (first rank in 5 out of 7 interaction databases), mainly because the interaction of glucokinase and glucokinase regulatory protein has been demonstrated in previous studies [19, 20]. NCOA1 also ranked high in prioritization using gene-gene interaction databases (second rank in 2 out of 7 interaction databases), because nuclear receptor coactivator 1 has been reported to interact with HNF4α (Hepatocyte Nuclear Factor 4α) as a coactivator [21]. Together with GCKR and NCOA1, genes that are highly prioritized
within the 11th rank (10.3% of annotated genes) were considered as candidate genes except 3 genes with well-characterized metabolic functions unrelated to glucose metabolism (Supplementary Table 1).

3.5. Direct Sequencing in GCKR and other candidate genes

We performed direct sequencing in exons and the 2-kb promoter region of GCKR. Sequencing was performed in 9 index cases from families and in 18 normoglycemic controls in parallel. The 18 control subjects were randomly selected from 206 normoglycemic controls (Supplementary Table 3). Detected sequence changes in the 9 index cases and 18 controls are shown in Table 2. Five nucleotide changes (g.-959 Insertion AATGTTG, E66E, E77G, g.9709G>A, and L446P) were considered to be common variants, because the minor allele was found in not less than 2 subjects out of a total of 27 case and control subjects. To determine whether or not each of the other nucleotide changes (g.-689G>A, g.-299G>A, E252K and g.6859C>G) was a mutation (MAF<1%), genotyping was performed in a total of 105 normoglycemic controls. g.-689G>A, g.-299G>A and g.6859C>G were not detected in the 105 controls, and were regarded as mutations, while E252K was detected in 4 controls out of 105 (MAF=1.9%) and was regarded as a common change. The number of alleles having mutations was thus significantly larger in the index cases from families than in the controls (3/18 alleles vs. 0/36 alleles, P=0.033, Fisher exact test).

We performed direct sequencing in the entire coding exons of other 7 candidate genes in index cases from 4 families. One missense mutation FOSL2 R198H (MAF=0.004 in normoglycemic controls) was detected. No other mutations were detected in other 6 genes (Supplementary Table 5).
3.6. Segregation of the mutations with the Phenotype in Pedigrees

In index cases from the 4 families included in the linkage analysis, 3 sequence changes of \textit{GCKR} were detected (g.-959 Insertion AATGTTG, g.6859C>G and L446P). We tested the segregation of \textit{GCKR} g.6859C>G, a mutation detected in pedigree 3, with the phenotype in the pedigree. Another 2 changes (\textit{GCKR} g.-959 Insertion AATGTG and \textit{GCKR} L446P) were commonly detected in controls (3/36 alleles and 11/36 alleles respectively). In pedigree 3, \textit{GCKR} g.6859C>G was detected in all 9 affected members, but was not detected in the unaffected member (II-7). We performed linkage analysis and haplotype construction in 2p25-22 using the \textit{GCKR} g.6859 genotype together with the microsatellite markers. The parametric multipoint LOD score for pedigree 3 was 2.67 at the \textit{GCKR} g.6859 locus. Haplotype analysis revealed that all affected individuals in pedigree 3 shared a disease haplotype within D2S2199-D2S2230, which includes \textit{GCKR} g.6859G (Figure 4). In pedigree 3, another sequence change, \textit{GCKR} L446P, was detected, but \textit{GCKR} L446P did not co-segregate with the disease. Haplotype analysis revealed that the minor allele of \textit{GCKR} L446P (g.11169C) resided on a different haplotype than \textit{GCKR} g.6859G in affected subjects III-11, 12, 13, 14 (Figure 4).

We tested the segregation of \textit{FOSL2} R198H, a mutation detected in pedigree 4, with the phenotype. \textit{FOSL2} R198H was detected in 2 affected subjects (II-2, II-22) but not detected in one subject (II-1).
4. Discussion and Conclusions

Recent progress in genome-wide association studies has identified tens of type 2 diabetes susceptibility genes. Even so, only a small portion of the genetic background of diabetes has been explained in the Japanese population. The loci identified in association studies have only very small effect sizes. We hypothesized that rare disease variants with larger effect sizes remain to be discovered that may explain a greater part of the genetic background. Family-based linkage study is an important alternative for the identification of rare disease variants. Indeed, studies with large families with highly clustered diabetes have revealed important mutations involved in MODY and other dominantly inherited diabetes, including a KCNJ11 mutation [22]. We therefore recruited families with a 3-generation history of diabetes. The validity of our strategy was strengthened by the fact that one case out of the 10 index cases recruited in our study carried a previously reported rare disease variant HNF1A R583G.

Our family analysis revealed a significant linkage region on chromosome 2p25-22 that has not been reported in previous Japanese sib-pair analyses [3-5]. Because our approach was based on a higher degree of familial clustering than sib-pair analyses, the linkage region suggested in the present study might well go undetected in sib-pair analyses that include an admixture of sib-pairs with both low and high degrees of familial clustering. In the present study, we conducted a computational approach targeting the linkage region on chromosome 2p25-22. One hundred and six known genes were present in this linkage region. Prioritization of the candidate gene was possible by integrating the information available from multiple publicly available databases [14]. GCKR and other 7 gens ranked high in the prioritization, and were selected as candidate genes.
GCKR regulates glucokinase (GCK), the first glycolytic enzyme, in liver. GCKR-null mice exhibit elevated postprandial glucose [19]. Adenoviral-mediated overexpression of GCKR in mouse liver increases GCK activity and lowers fasting blood glucose. It was suggested that GCKR, a competitive inhibitor of GCK activity, also has a paradoxical role in extending GCK half-life by stabilizing the enzyme [20]. If so, diminished expression of GCKR in human might cause decreased GCK activity in liver and lead to impaired liver glucose uptake, which suggests the GCKR mutation as a possible cause of the disease in linked families.

We sequenced entire exons and the 2-kb promoter region of GCKR in 9 index 3-generation cases and in 18 control subjects. The rare variants were significantly more frequent in index cases from families than in control subjects. In addition, exonic rare variant g.6859C>G in pedigree 3, which was not detected in 105 control subjects, was clearly segregated in all 9 affected members in pedigree 3. Previous reports have shown the association of common GCKR variants with fasting plasma glucose, glucose level after glucose challenge, and diabetes risk in various ethnic groups [23-30]. In Japanese population, a common variant GCKR rs780094 is associated with fasting glucose and diabetes risk [27, 30]. Our family study suggests the effect of rare GCKR variants on diabetes susceptibility that has not been revealed by previous association studies. A recent study has shown the excess of rare GCKR variants in individuals with hypertriglycerideremia [31], which supports our idea that rare GCKR mutations also affect the diabetes susceptibility.

On the other hand, the only one mutation in other 7 highly prioritized genes was FOSL2 R198H and it did not co-segregate with the phenotype in the pedigree. Therefore, we tentatively eliminate the possibility that these genes are involved in familial clustering of diabetes patients in the current pedigrees.

Our study has several limitations. First is the large size (23.6Mb) of the linkage region.
Only 4 families could be included in the linkage analysis because we limited the cohort to
3-generation families with ≥2 affected members who donated DNA. Further efforts to recruit
large families are needed to narrow down the linkage region. Second, because the GCKR
g.6859C>G mutation was in a non-coding exon, confirming the relevance of the mutation as
the cause of the disease is difficult. Investigation of the effect of the mutation in human liver,
where GCKR is predominantly expressed [32], is required, but liver specimens of family
members are currently unavailable. Although we tried to determine the mRNA level in
peripheral blood of family members, GCKR mRNA was only barely detectable with the
RT-PCR method (data not shown), so comparison of the GCKR mRNA level between
affected and unaffected members was not possible. We speculate that the g.6859C>G mutatin
might affect GCKR function in liver through mRNA transcription or splicing processes [33].
GCKR g.-689G>A and g.-299G>A mutations located in the promoter also might affect the
expression of GCKR, but TRANSFAC database [34] expected no binding sites of
transcription factors at the two promoter mutations.

In conclusion, with systematic investigation we propose that GCKR is a susceptibility gene
in Japanese families with clustered diabetes. A family-based approach may be a promising
strategy to elucidate the complex genetic background of common diseases including type 2
diabetes.
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### Table 1. Characteristics of family members and additional index cases.

<table>
<thead>
<tr>
<th>ID</th>
<th>Current Age</th>
<th>Sex</th>
<th>BMI</th>
<th>HbA1c (%)</th>
<th>Age when diagnosed (Diagnosis)</th>
<th>Current therapy</th>
</tr>
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<td>Pedigree 1</td>
<td></td>
<td></td>
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<tr>
<td>II-4</td>
<td>70</td>
<td>F</td>
<td>16.2</td>
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<tr>
<td>II-5</td>
<td>71</td>
<td>F</td>
<td>22.5</td>
<td>10.6</td>
<td>60 (DM)</td>
<td>Insulin 66U/d</td>
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<td>F</td>
<td>21.9</td>
<td>5.4</td>
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<tr>
<td>III-2</td>
<td>37</td>
<td>M</td>
<td>26.0</td>
<td>6.9</td>
<td>20 (DM)</td>
<td>Insulin</td>
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<tr>
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<td>79</td>
<td>M</td>
<td>19.2</td>
<td>7.5</td>
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<td>Insulin 25U/d</td>
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<td>18.6</td>
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<tr>
<td>II-3</td>
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<td>F</td>
<td>19.3</td>
<td>5.2</td>
<td></td>
<td></td>
</tr>
<tr>
<td>III-5</td>
<td>46</td>
<td>F</td>
<td>19.6</td>
<td>4.9</td>
<td></td>
<td></td>
</tr>
<tr>
<td>IV-1</td>
<td>23</td>
<td>M</td>
<td>19.9</td>
<td>5.6</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Pedigree 3</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>II-7</td>
<td>92</td>
<td>F</td>
<td>22.3</td>
<td>5.9</td>
<td></td>
<td></td>
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<tr>
<td>III-2</td>
<td>77</td>
<td>F</td>
<td>23.9</td>
<td>9.3</td>
<td>30 (DM)</td>
<td>Oral drug</td>
</tr>
<tr>
<td>III-5</td>
<td>72</td>
<td>F</td>
<td>22.0</td>
<td>8.1</td>
<td>60 (DM)</td>
<td>Insulin 16U/d</td>
</tr>
<tr>
<td>III-6</td>
<td>69</td>
<td>F</td>
<td>19.8</td>
<td>8.0</td>
<td>65 (DM)</td>
<td>Insulin 16U/d</td>
</tr>
<tr>
<td>III-8</td>
<td>66</td>
<td>F</td>
<td>19.1</td>
<td>6.5</td>
<td>64 (IGT)</td>
<td>Diet</td>
</tr>
<tr>
<td>III-10</td>
<td>59</td>
<td>F</td>
<td>19.3</td>
<td>10.2</td>
<td>57 (DM)</td>
<td>Oral drug</td>
</tr>
<tr>
<td>III-11</td>
<td>67</td>
<td>F</td>
<td>20.4</td>
<td>6.9</td>
<td>62 (DM)</td>
<td>Oral drug</td>
</tr>
<tr>
<td>III-12</td>
<td>66</td>
<td>M</td>
<td>21.1</td>
<td>N/A</td>
<td>57 (DM)</td>
<td>Oral drug</td>
</tr>
<tr>
<td>III-13</td>
<td>64</td>
<td>F</td>
<td>20.0</td>
<td>6.6</td>
<td>25 (DM)</td>
<td>Insulin</td>
</tr>
<tr>
<td>III-14</td>
<td>62</td>
<td>M</td>
<td>20.2</td>
<td>10.3</td>
<td>50 (DM)</td>
<td>Oral drug</td>
</tr>
<tr>
<td>Pedigree 4</td>
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<td></td>
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<td></td>
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<tr>
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<td>F</td>
<td>28.2</td>
<td>6.7</td>
<td>60 (DM)</td>
<td>Oral drug</td>
</tr>
<tr>
<td>II-2</td>
<td>73</td>
<td>F</td>
<td>25.1</td>
<td>6.4</td>
<td>50 (DM)</td>
<td>Oral drug</td>
</tr>
<tr>
<td>II-3</td>
<td>67</td>
<td>F</td>
<td>19.0</td>
<td>5.5</td>
<td></td>
<td></td>
</tr>
<tr>
<td>II-4</td>
<td>64</td>
<td>M</td>
<td>N/A</td>
<td>5.4</td>
<td></td>
<td></td>
</tr>
<tr>
<td>III-1</td>
<td>52</td>
<td>F</td>
<td>20.4</td>
<td>5.3</td>
<td></td>
<td></td>
</tr>
<tr>
<td>III-2</td>
<td>50</td>
<td>M</td>
<td>20.8</td>
<td>6.2</td>
<td>35 (DM)</td>
<td>Oral drug</td>
</tr>
<tr>
<td>Additional Index Cases</td>
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<td></td>
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<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>57</td>
<td>M</td>
<td>25.7</td>
<td>7.1</td>
<td>30 (DM)</td>
<td>Oral drug</td>
</tr>
<tr>
<td>2</td>
<td>47</td>
<td>F</td>
<td>22.9</td>
<td>10.0</td>
<td>36 (DM)</td>
<td>Insulin 20U/d</td>
</tr>
<tr>
<td>3</td>
<td>68</td>
<td>F</td>
<td>19.7</td>
<td>7.1</td>
<td>45 (DM)</td>
<td>Insulin 19U/d</td>
</tr>
<tr>
<td>4</td>
<td>60</td>
<td>F</td>
<td>24.7</td>
<td>10.4</td>
<td>40 (DM)</td>
<td>Insulin 51U/d</td>
</tr>
<tr>
<td>5</td>
<td>60</td>
<td>F</td>
<td>28.0</td>
<td>9.7</td>
<td>50 (DM)</td>
<td>Insulin 8U/d</td>
</tr>
<tr>
<td>6</td>
<td>54</td>
<td>F</td>
<td>34.5</td>
<td>9.1</td>
<td>40 (DM)</td>
<td>Insulin</td>
</tr>
</tbody>
</table>

BMI: Body Mass Index, DM: Diabetes Mellitus, IGT: Impaired Glucose Tolerance
Table 2. Mutations and common nucleotide changes in exons and the promoter of GCKR in 9 index cases in families and in 18 controls.

<table>
<thead>
<tr>
<th>Position</th>
<th>Change</th>
<th>Description</th>
<th>Effect</th>
<th>Index Cases from Families (n=9)</th>
<th>Controls(n=18)</th>
<th>Minor Allele Frequency [MAF]</th>
</tr>
</thead>
</table>
|            |                  |                     | Major      | Minor                         | Major          | Minor                       | p  
| Mutations (MAF<1%) |                  |                     |            |                               |                |                             | Fisher exact test. |
| Promoter   | g. -689G>A       |                     | 17         | 1                             | 36             | 0                           | 0.33  |
| Promoter   | g. -299G>A       |                     | 17         | 1                             | 36             | 0                           | 0.33  |
| Exon 9     | g. 6859C>G       | Noncoding exon      | 17         | 1                             | 36             | 0                           | 0.33  |
|            |                  |                     |            |                               |                |                             |                      |
| Total      |                  |                     | 15         | 3                             | 36             | 0                           | 0.033 |
|            |                  |                     |            |                               |                |                             |                      |
| Common changes |                  |                     |            |                               |                |                             |                      |
| Promoter   | g. -959          |                     | 16         | 2                             | 33             | 3                           | 1.00  |
|            | insAATGTGG       |                     |            |                               |                |                             | N/D               |
| Exon 2     | g. 468G>A        | Synonymous          | 17         | 1                             | 35             | 1                           | 1.00  |
| Exon 3     | g. 671A>G        | Missense            | 17         | 1                             | 33             | 3                           | 1.00  |
| Exon 10    | g. 8817G>A       | Missense            | 18         | 0                             | 35             | 1                           | 1.00  |
| Exon 11    | g. 9709G>A       | Noncoding exon      | 17         | 1                             | 33             | 3                           | 1.00  |
| Exon 14    | g. 11169T>C      | Missense            | 8          | 10                            | 25             | 11                          | 0.087  |

GenBank Accession No. NT_022184.15

* Fisher exact test.  
* Frequency in 105 normoglycemic controls.  
* Frequency in HapMap-JPT.
Figure Captions

Figure 1. Four pedigrees with familial aggregated diabetes mellitus.

Figure 2. Multipoint HLOD and LOD scores in genome-wide linkage analysis for 4 pedigrees.

Figure 3. Multipoint HLOD and LOD scores in fine mapping of D2S168-D2S2259 and D7S640-D7S636.

Figure 4. Haplotype analysis in the D2S168-D2S2259 region and the GCKR g. 6859C>G genotype for pedigree 3.
Figure 2.
Figure 3.

Chromosome 2
(11-43Mb)

Chromosome 7
(133-151Mb)

Fine Mapping

Figure 3.

Chromosome 2
(11-43Mb)

Chromosome 7
(133-151Mb)

Fine Mapping
Figure 4.

Pedigree 3

III-2  III-5  III-6  III-8  III-10  III-11  III-12  III-13  III-14

DSS168  GCKR  DSS2198  g. 3859

Haplotype shared by all affected individuals

Normal haplotype

Marker names beside the vertical bars indicate that obligate recombination occurred between these markers.

* GCKR g. 6859C>G genotype
### Supplementary Table 1. Genes that are highly prioritized in the linkage region using Endeavour.

<table>
<thead>
<tr>
<th>Rank</th>
<th>Symbol</th>
<th>Description</th>
<th>Known metabolic function</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>GCKR</td>
<td>Glucokinase regulatory protein</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>NCOA1</td>
<td>Nuclear receptor coactivator 1</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>FOSL2</td>
<td>Fos-related antigen 2</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>APOB</td>
<td>Apolipoprotein B-100 precursor</td>
<td>Lipid Metabolism&lt;sup&gt;a&lt;/sup&gt;</td>
</tr>
<tr>
<td>5</td>
<td>MYCN</td>
<td>N-myc proto-oncogene protein</td>
<td></td>
</tr>
<tr>
<td>6</td>
<td>RBKS</td>
<td>Ribokinase</td>
<td></td>
</tr>
<tr>
<td>7</td>
<td>XDH</td>
<td>Xanthine dehydrogenase/oxidase</td>
<td>Purine Metabolism&lt;sup&gt;a&lt;/sup&gt;</td>
</tr>
<tr>
<td>8</td>
<td>KHK</td>
<td>Ketohexokinase</td>
<td></td>
</tr>
<tr>
<td>9</td>
<td>NRB1</td>
<td>Nuclear receptor-binding protein</td>
<td></td>
</tr>
<tr>
<td>10</td>
<td>CAD</td>
<td>Glutamine-dependent carbamoyl-phosphate synthase, Aspartate carbamoyltransferase, Dihydroorotase</td>
<td>Pyrimidine Metabolism&lt;sup&gt;a&lt;/sup&gt;</td>
</tr>
<tr>
<td>11</td>
<td>RDH14</td>
<td>Retinol dehydrogenase</td>
<td></td>
</tr>
</tbody>
</table>

<sup>a</sup>Excluded from candidate genes
Supplementary Table 2. Sequencing Primers for \textit{GCKR}

<table>
<thead>
<tr>
<th>GCKR</th>
<th>Forward</th>
<th>Reverse</th>
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</thead>
<tbody>
<tr>
<td>promoter1a</td>
<td>TGACTAGCTGTGGTTGACCCT</td>
<td>promoter1b</td>
</tr>
<tr>
<td>promoter2a</td>
<td>CCCCCATCCCTATCCCTTCT</td>
<td>promoter2b</td>
</tr>
<tr>
<td>promoter3a</td>
<td>GGGTTTTGGTGAGGCTCAAAT</td>
<td>promoter3b</td>
</tr>
<tr>
<td>1a</td>
<td>TAGTGACCAGGAAAGGGTGTT</td>
<td>1b</td>
</tr>
<tr>
<td>1c</td>
<td>TAATATGCCAGAGCACCAAA</td>
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</tr>
<tr>
<td>2a</td>
<td>AGCAAGACATGGGAGTCAAA</td>
<td>2b</td>
</tr>
<tr>
<td>3a</td>
<td>AATGTAGCCCTGCCCTAATACG</td>
<td>3b</td>
</tr>
<tr>
<td>4a</td>
<td>TTCTGATGCACTTGAGCCTT</td>
<td>4b</td>
</tr>
<tr>
<td>5a</td>
<td>ACCTCAATCCCAATGCAGCT</td>
<td>5b</td>
</tr>
<tr>
<td>5c</td>
<td>AGAGCGTTGAAATAGGCCATTG</td>
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</tr>
<tr>
<td>6a</td>
<td>TGGTACTATCAGATGCAATGCC</td>
<td>6b</td>
</tr>
<tr>
<td>7a</td>
<td>TAAGGGAGCTGTGGCCTTCA</td>
<td>7b</td>
</tr>
<tr>
<td>7c</td>
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<td></td>
</tr>
<tr>
<td>8a</td>
<td>AGTGTAGACTCTCCTCACCAGG</td>
<td>8b</td>
</tr>
<tr>
<td>9a</td>
<td>ATTTAAACGCTGGGCTGCT</td>
<td>9b</td>
</tr>
<tr>
<td>10a</td>
<td>ATCCCAAGCCTCCTCACTCAT</td>
<td>10b</td>
</tr>
<tr>
<td>11a</td>
<td>TGAACCTAAGTGATCTGCCCCA</td>
<td>11b</td>
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</table>
Supplementary Table 3. Characteristics of normoglycemic controls.

<table>
<thead>
<tr>
<th></th>
<th>Subjects for sequencing (n=18)</th>
<th>Subjects for genotyping SNPs (n=105)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Men</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Number</td>
<td>10</td>
<td>52</td>
</tr>
<tr>
<td>Age (y: mean ± SD)</td>
<td>64.0 ± 4.4</td>
<td>68.3 ± 8.1</td>
</tr>
<tr>
<td>BMI (mean ± SD)</td>
<td>22.6 ± 2.0</td>
<td>22.5 ± 2.6</td>
</tr>
<tr>
<td>Fasting Plasma Glucose (mmol/l: mean± SD)</td>
<td>4.86 ± 0.21</td>
<td>4.74 ± 0.31</td>
</tr>
<tr>
<td>HbA1c (%: mean±SD)</td>
<td>5.64 ± 0.12</td>
<td>5.45± 0.17</td>
</tr>
<tr>
<td>Women</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Number</td>
<td>8</td>
<td>53</td>
</tr>
<tr>
<td>Age (y: mean ± SD)</td>
<td>61.1 ± 6.1</td>
<td>66.5 ± 8.3</td>
</tr>
<tr>
<td>BMI (mean ± SD)</td>
<td>21.4 ± 2.3</td>
<td>21.7 ± 2.8</td>
</tr>
<tr>
<td>Fasting Plasma Glucose (mmol/l: mean± SD)</td>
<td>4.66 ± 0.29</td>
<td>4.68 ± 0.38</td>
</tr>
<tr>
<td>HbA1c (%: mean ± SD)</td>
<td>5.64 ± 0.20</td>
<td>5.48 ± 0.16</td>
</tr>
</tbody>
</table>

SD: Standard deviation.
### Supplementary Table 4. Missense SNPs of MODY genes in 10 index cases.

<table>
<thead>
<tr>
<th>Gene</th>
<th>SNP</th>
<th>Major/Minor</th>
<th>Major</th>
<th>Minor</th>
<th>Minor Allele Frequency [MAF]</th>
</tr>
</thead>
<tbody>
<tr>
<td>HNF1A</td>
<td>I27L</td>
<td>C/A</td>
<td>8</td>
<td>12</td>
<td>0.386&lt;sup&gt;c&lt;/sup&gt;</td>
</tr>
<tr>
<td>HNF1A</td>
<td>S487N</td>
<td>A/G</td>
<td>9</td>
<td>11</td>
<td>0.341&lt;sup&gt;c&lt;/sup&gt;</td>
</tr>
<tr>
<td>HNF1A</td>
<td>R583G</td>
<td>C/G</td>
<td>19</td>
<td>1&lt;sup&gt;a&lt;/sup&gt;</td>
<td>0.000&lt;sup&gt;d&lt;/sup&gt;</td>
</tr>
<tr>
<td>HNF4A</td>
<td>T117I</td>
<td>C/T</td>
<td>19</td>
<td>1&lt;sup&gt;b&lt;/sup&gt;</td>
<td>0.000&lt;sup&gt;c&lt;/sup&gt;</td>
</tr>
</tbody>
</table>

<sup>a</sup> Additional index case #6.

<sup>b</sup> Additional index case #2.

<sup>c</sup> Frequency in HapMap-JPT.

<sup>d</sup> Frequency in 105 normoglycemic controls.
**Supplementary Table 5. Nucleotide changes in coding exons of 7 genes in the linkage region in index cases from 4 families.**

<table>
<thead>
<tr>
<th>Gene</th>
<th>SNP</th>
<th>Major/Minor</th>
<th>Major</th>
<th>Minor</th>
<th>Minor Allele Frequency [MAF]</th>
</tr>
</thead>
<tbody>
<tr>
<td>NCOA1</td>
<td>P504P</td>
<td>A/T</td>
<td>7</td>
<td>1</td>
<td>0.307&lt;sup&gt;a&lt;/sup&gt;</td>
</tr>
<tr>
<td>FOSL2</td>
<td>R198H</td>
<td>G/A</td>
<td>7</td>
<td>1</td>
<td>0.004&lt;sup&gt;b&lt;/sup&gt;</td>
</tr>
<tr>
<td>KHK</td>
<td>V49I</td>
<td>G/A</td>
<td>5</td>
<td>3</td>
<td>0.166&lt;sup&gt;a&lt;/sup&gt;</td>
</tr>
</tbody>
</table>

<sup>a</sup> Frequency in HapMap-JPT.
<sup>b</sup> Frequency in 105 normoglycemic controls.
Supplementary Figure 1. Pedigrees of Additional Index Cases

Index Case 1

Index Case 2

Index Case 3

Index Case 4

Index Case 5

Index Case 6

OHA  Patients treated with Oral Hypoglycemic Agent
Insulin  Patients treated with Insulin injection