Mutations in the Liver Glycogen Synthase Gene in Children with Hypoglycemia due to Glycogen Storage Disease Type 0

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Abstract

Glycogen storage disease type 0 (GSD-0) is a rare form of fasting hypoglycemia presenting in infancy or early childhood and accompanied by high blood ketones and low alanine and lactate concentrations. Although feeding relieves symptoms, it often results in postprandial hyperglycemia and hyperlactatemia. The glycogen synthase (GS) activity has been low or immeasurable in liver biopsies, whereas the liver glycogen content has been only moderately decreased. To investigate whether mutations in the liver GS gene (GYS2) on chromosome 12p12.2 were involved in GSD-0, we determined the exon-intron structure of the GYS2 gene and examined nine affected children from five families for linkage of GSD-0 to the GYS2 gene. Mutation screening of the 16 GYS2 exons was done by single-strand conformational polymorphism (SSCP) and direct sequencing. Liver GS deficiency was diagnosed from liver biopsies (GS activity and glycogen content). GS activity in the liver of the affected children was extremely low or nil, resulting in subnormal glycogen content. After suggestive linkage to the GYS2 gene had been established (LOD score = 2.9; P < 0.01), mutation screening revealed several different mutations in these families, including a premature stop codon in exon 5 (Arg246X), a 5′-donor splice site mutation in intron 6 (G+1T→CT), and missense mutations Asn39Ser, Ala339Pro, His446Asp, Pro479Gln, Ser483Pro, and Met491Arg. Seven of the affected children carried mutations on both alleles. The mutations could not be found in 200 healthy persons. Expression of the mutated enzymes in COS7 cells indicated severely impaired GS activity. In conclusion, the results demonstrate that GSD-0 is caused by different mutations in the GYS2 gene. (J. Clin. Invest. 1998. 102:507–515.) Key words: glycogen synthase deficiency • childhood hypoglycemia • ketotic hypoglycemia • postprandial hyperglycemia • glycogen storage

Methods

Patients

Patient 1 (family Y). Male child D.Y. was born in 1988 to unrelated Turkish parents living in Austria. He had three seemingly healthy brothers. He was referred at age 4 because of short stature. Height

Introduction

Hypoglycemia in children associated with hepatic glycogen synthase (GS) deficiency is a seemingly rare disorder also referred to as glycogen storage disease type 0 (GSD-0) (1–4). Patients present in infancy or early childhood with fasting hypoglycemia accompanied by high levels of blood ketones and low levels of alanine and lactate (1–3). Feeding relieves symptoms and reverses the abnormal biochemical profile often resulting in postprandial hyperglycemia and hyperlactatemia. The GS activity has been low or immeasurable in liver biopsies, whereas the liver glycogen content has been decreased only moderately, suggesting some residual glycogen synthesis (1–3).

Although the disease seems to be inherited in an autosomal recessive fashion (1–3), the underlying molecular defects have not been known. GS deficiency could be the consequence of defective expression or activation of the GS or synthesis of a defective protein. Mice lacking the transcription factor CCAAT/enhancer-binding protein α (C/EBPα) gene (5–7) do not store liver glycogen normally and they die from hypoglycemia (8). Using polymorphic microsatellite markers flanking the C/EBPα gene on human chromosome 19, we could exclude linkage between this chromosomal region and GSD-0. Furthermore, mixing the liver homogenates from affected and unaffected individuals did not activate the GS (2). Therefore, available data point at an inherited defect in the GS enzyme.

To examine whether mutations in the liver GS gene (GYS2) were involved in GSD-0, we determined the exon-intron structure of the GYS2 gene and studied nine affected children from five families for linkage using intragenic and flanking polymorphic markers. After linkage to the chromosomal region 12p12.2 (9) had been established, we screened the coding regions, the exon-intron boundary regions, and part of the putative promoter of the GYS2 gene for mutations. Mutations were found in all affected children, indicating that GSD-0 is caused by molecular defects in the GYS2 gene.

Acknowledgments

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1. Abbreviations used in this paper: G-6-P, glucose-6-phosphate; GS, glycogen synthase; GSD-0, glycogen storage disease type 0; GYS2, liver GS gene; SSCP, single-strand conformational polymorphism; UDPG, UDP glucose.

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was 86.5 cm (−3 SD) and weight was 11.4 kg (−3 SD). Serum growth hormone concentration was subnormal (5.1 ng/ml). After an overnight fast, the blood glucose was 1.7 mmol/liter, whereas free fatty acids and β-hydroxybutyrate concentrations were high. In relation to hypoglycemia, the plasma insulin levels were appropriately reduced and cortisol, lactate, pyruvate, and alanine concentrations were normal. An oral glucose tolerance test (1.75 g/kg body wt) provoked an excessive rise of blood glucose (10.1 mmol/liter) and lactate (7.0 mmol/liter), whereas free fatty acids and β-hydroxybutyrate were normal. A similar metabolic profile was seen 1 h after a meal. At age 7, a liver biopsy showed low GS activity with glycogen content in the low normal range (Table I). He tolerated fasting periods of 5 h, refused uncooked cornstarch (3), but was given a midnight meal instead. His mental development was normal.

**Patient 2 (family M).** Female child L.M. was born in 1987 in Oregon. At age 5 she presented with fasting hypoglycemia and postprandial hyperglycemia. Her blood glucose levels rose from 2.7 to 22 mmol/liter after feeding. The glycogen content in a liver biopsy was low (Table I), whereas the activities of glucose-6-phosphatase, debranching enzyme, total and active phosphorylase, fructose-1,6-bisphosphatase, and fructose aldolase as well as the glucose-1-phosphate/glucose ratio were all normal. GS activity was not measured, but the clinical picture together with the biochemical findings suggested GSD-0. Symptoms of hypoglycemia were prevented by ingestion of cornstarch. Her mental development has been slow. Her mother also develops hypoglycemia during prolonged fasting.

**Patient 3 (family M).** Male child S.M., born in 1989, was the younger brother of patient 2. At age 3, he developed symptoms of fasting hypoglycemia and postprandial hyperglycemia. No liver biopsy was performed but he was suspected to have the same disorder as his sister. Cornstarch feeding prevented hypoglycemia. His mental development was normal.

**Patient 4 (family M).** Female child M.M., born in 1989, was the younger sister of patient 2. At age 5 she presented with fasting hypoglycemia and postprandial hyperglycemia. Her mental development was normal.

**Patient 5 (family F).** Female child I.F., born in 1987 to unrelated German parents. At age 3.5 she was drowsy in the mornings, occasionally vomited, and her pediatrician discovered hypoglycemia. At age 4 she was suspected of having liver disease. Metabolic profiles were indicative of GSD-0. Glycogen content in the liver was low and GS activity was virtually absent (Table I) (3).

**Patient 6 (family J).** Male child D.J. was born in 1991 to unrelated German parents. At age 2 he appeared tired in the mornings and uninterested in his breakfast. He recovered after eating. At age 3.5 his pediatrician diagnosed hypoglycemia and ketonuria. Metabolic profiles were indicative of GSD-0. The diagnosis of hepatic GS deficiency was confirmed by a liver biopsy, which demonstrated low glycogen content and GS deficiency (Table I) (3).

**Patient 7 (family J).** M.J., born in 1989, was the older brother of patient 6. Metabolic profiles indicative of GSD-0 were observed but no liver biopsy was performed (3).

**Patient 8 (family S).** Female child K.S. was born in 1966 to unrelated British parents. With the establishment of daytime feeding, early morning behavioral changes, drowsiness, and lack of attention was noted. Symptoms were reversed by food intake. At 7 yr of age she had occasional morning convulsions. Fasting hypoglycemia and ketonuria were discovered and GS deficiency was diagnosed by a liver biopsy (Table I) (2, 10). At age 29 she gave birth to a healthy child (11).

**Patient 9 (family S).** D.S., born in 1964, was the older brother of patient 8. When he was old enough to go through the night without feeding, he became drowsy and unresponsive in the morning until the first meal. Symptoms ceased after 3 yr of age. At age 13 he was examined together with his sibling and the metabolic profiles resembled those of his sister with diagnosed GSD-0 (12). A liver biopsy was not performed.

### Liver biopsies and biochemical analyses

In five children, open or percutaneous liver biopsies were performed during infusion of 10% glucose after the children had fasted for at least 4 h. Liver biopsies taken from cadaveric kidney donors with parenteral nutrition served as controls (3). The specimens were frozen immediately and kept at −20°C until analyzed for glycogen (13), glycogen–iodine complex (14), and GS (EC 2.4.1.11) activity (3).  

### Isolation and partial sequence of the human GYS2 gene

A human placental genomic library in phage (catalog No. 946205; Stratagene, La Jolla, CA) was screened with [α–32P]dCTP-labeled (Pharmacia Biotech, Uppsala, Sweden) 2.1-kb long GYS2 cDNA probe (15) containing the whole coding sequence and with a PCR probe containing only the first 441 bp of the cDNA. The probes were labeled to a specific activity of >10⁶ cpm/μg DNA using the Ready-to-go DNA labeling kit (Pharmacia Biotech). Labeled probes were purified in Sephadex-G50 nick-columns (Pharmacia Biotech). Several genomic clones containing parts of the GYS2 gene were isolated and five of them (GYS2-AE1-3, GYS2-A6, GYS2-A14, GYS2-A16, and GYS2-A21) were chosen for further analysis. The genomic clone GYS2-AE1-3 was extracted when the genomic library was screened with the 441-bp PCR probe, whereas the other clones were extracted with the 2.1-kb cDNA probe. These clones were digested with several restriction enzymes, run on an agarose gel, and blotted on a nylon filter. The blots were then probed with a 2.1-kb GYS2 cDNA probe to identify the fragments containing exons. DNA fragments carrying exons and the 5′-flanking region were subcloned into a pGEM4Z vector (Promega, Madison, WI) or amplified by PCR either from genomic or genomic clone DNA. All the exons, exon-intron boundaries, and the 5′-flanking region were sequenced bidirectionally by the diodeoxy chain termination method using either a Sequenase 2.0 sequencing kit (U.S. Biochemicals, Cleveland, OH) or an ABI PRISM dye termina- 

### Table I. Biochemical Analysis of the Liver Biopsy Specimens

<table>
<thead>
<tr>
<th>Patient number</th>
<th>1</th>
<th>2</th>
<th>5</th>
<th>6</th>
<th>8</th>
<th>Controls</th>
</tr>
</thead>
<tbody>
<tr>
<td>Glycogen (g/100 g of liver)</td>
<td>2.5</td>
<td>0.8</td>
<td>0.7;1.7</td>
<td>1.2</td>
<td>0.65</td>
<td>2.4–6.4</td>
</tr>
<tr>
<td>Absorption maximum of the glycogen–iodine complex (nm)</td>
<td>471</td>
<td>ND</td>
<td>ND</td>
<td>471</td>
<td>468</td>
<td>454–478</td>
</tr>
<tr>
<td>GS activity (μmol/g × min)</td>
<td>0.12</td>
<td>ND</td>
<td>0.00;0.04</td>
<td>0.0</td>
<td>0.04</td>
<td>1.1–5.5</td>
</tr>
<tr>
<td>with G-6-P</td>
<td>0.02</td>
<td>ND</td>
<td>0.00;0.02</td>
<td>0.0</td>
<td>&lt; 0.01</td>
<td>0.03–0.6</td>
</tr>
</tbody>
</table>

ND, Not done.
CA) and automated sequencer analysis (ABI model 373; Perkin Elmer). The intron sizes were determined by Southern blotting, restriction mapping, and/or sequencing of the PCR products. Each clone containing part of the GYS2 gene was also screened for microsatellite markers by hybridization of the Southern blots containing restriction enzyme–digested GYS2 genomic clone DNA with a degenerated [α-32P]dCTP-labeled CA/GT– probe. Positive fragments were subcloned into a PGEM4Z vector and sequenced.

**Linkage analysis**

Linkage to the GYS2 gene was tested using an intragenic microsatellite marker GYS2-CA, which we identified in the gene and flanking markers GATAgH01 (16), D12S1606 (17), and D12S1688 (17). The affected individuals and their family members were haplotyped using radioactive PCR followed by fragment separation on a 5% denaturing polyacrylamide gel. For GYS2-CA, 30 ng of genomic DNA was amplified using 3 pmol of [γ-32P]dATP end-labeled oligonucleotide primer GYS2-CAF (5’-CTGATAGTGAATCTACAGC) and 3 pmol of unlabeled primer GYS2-CAR (5’-TGATAGTGAATCTACATTAACTACAC) with 0.5 U Taq polymerase (Perkin Elmer) in 1X ammonium sulfate buffer (16 mM ammonium sulfate; 67 mM Tris, pH 8.8; 0.01% Tween), 1.5 mM magnesium chloride, 200 μM of the deoxynucleotide triphosphates, and 2% formamide. PCR reactions were performed in Gene Amp PCR System 9600 (Perkin Elmer) with initial denaturation (5 min at 94°C), followed by 30 cycles of denaturation (30 s at 94°C), annealing (30 s at 60°C), and extension (30 s at 72°C) and by final extension (10 min at 72°C). The earlier described PCR conditions were used for markers GATAgH01, D12S1606, and D12S1688 (16, 17). An autosomal recessive inheritance with 100% penetrance was assumed and the LOD score calculated (all five family members, and in 200 healthy control subjects. The missense mutations Ala339Pro, His446Asp, and Met491Arg were confirmed by PCR with the primer pairs used in the SSCP followed by digestion with restriction enzymes AluI, BseDI, and BstNI, respectively (New England Biolabs, Beverly, MA). For detection of intron 6 (G to A) mutations, Asn39Ser, Pro479Gln, and Ser483Pro mutations, which did not create or destroy a known restriction enzyme recognition site, the PCR from genomic DNA was performed using one of the SSCP primers (Table II) and a new primer where a single nucleotide mismatch was introduced (the mismatch nucleotide is underlined) to create an AluI (E6-GT/CT-F, 5’-GATTTTGTGCAAGGGTATTTCTATAG with primer E6R; for

**Table II. Oligonucleotide Primer Pairs Used to Amplify the GYS2 Gene**

<table>
<thead>
<tr>
<th>Exon</th>
<th>Upstream primer sequence</th>
<th>Downstream primer sequence</th>
<th>Size of PCR product (bp)</th>
<th>Annealing temperature (°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>GGAGGCAGCTGTAAGAGAAGAATG</td>
<td>CTAATGCTCTGACGACCTAG</td>
<td>194</td>
<td>56</td>
</tr>
<tr>
<td>2</td>
<td>ATGTCTACATCGATGAATAGATAG</td>
<td>AAGTTTACTGAGATAGCTGCAAG</td>
<td>268</td>
<td>58</td>
</tr>
<tr>
<td>3</td>
<td>TCTTGCATAGTGAATATTACTACCTAC</td>
<td>GTGTGCGTCCTCTCGGTG</td>
<td>283</td>
<td>62</td>
</tr>
<tr>
<td>4</td>
<td>ATGCAAGATCTTTCTGGAATG</td>
<td>GCTGACTGCAATCTGGAAGG</td>
<td>278</td>
<td>52</td>
</tr>
<tr>
<td>5</td>
<td>AGGGCCATTGTAGCAAAATGCTG</td>
<td>GTAACATCTGACGACCTGAAAG</td>
<td>239</td>
<td>62</td>
</tr>
<tr>
<td>6</td>
<td>TTCTCATACATGCTCTTCTG</td>
<td>CAAAACATCATATGCTGATAC</td>
<td>234</td>
<td>58</td>
</tr>
<tr>
<td>7</td>
<td>TGTCTACTGTTGCTCTATCCAT</td>
<td>GAGAAGAGTTCCTCCTACAAG</td>
<td>226</td>
<td>56</td>
</tr>
<tr>
<td>8</td>
<td>AATGTCTAAAGTCCTCCTATCTACAT</td>
<td>GCCGACGATGATGCTTACCT</td>
<td>262</td>
<td>62</td>
</tr>
<tr>
<td>9</td>
<td>AAGAATCGATTAATTTTCAAG</td>
<td>TTAAGATGTTGATGCTAAATTG</td>
<td>253</td>
<td>54</td>
</tr>
<tr>
<td>10</td>
<td>ATCTGATAGTGAATGACTCTG</td>
<td>AAGTCTTTTAAAATTCGACTCC</td>
<td>245</td>
<td>60</td>
</tr>
<tr>
<td>11</td>
<td>GAAGTTGCAATGACCTTTGTTG</td>
<td>CTAGAGAAGATGTAATTTATCTACAG</td>
<td>275</td>
<td>62</td>
</tr>
<tr>
<td>12</td>
<td>TACAGAAATACCAAAATGAGGAGG</td>
<td>CAAATTACAAAAATCCACACTC</td>
<td>250</td>
<td>62</td>
</tr>
<tr>
<td>13</td>
<td>TGAGTTGGCTGCTGAGCC</td>
<td>TTCTGGTCTAGGTTGCTTCTG</td>
<td>197</td>
<td>60</td>
</tr>
<tr>
<td>14</td>
<td>GAAGAATTGTTTAAGTTGCTTAC</td>
<td>GAATCAGATATTTATGCTCACCTGG</td>
<td>289</td>
<td>62</td>
</tr>
<tr>
<td>15</td>
<td>TACCTGATTTGAGATGTATCAAGG</td>
<td>GCTCTGCTGATGATGCTTCC</td>
<td>236</td>
<td>62</td>
</tr>
<tr>
<td>16A</td>
<td>GAAACCAGAACAGAGCTTGTTGATG</td>
<td>GAGGACTGAGGGTCAGAG</td>
<td>123</td>
<td>62</td>
</tr>
<tr>
<td>16B</td>
<td>AGTACACGTCTCTCCTACAG</td>
<td>AAATGAAATTGTTGCGATT</td>
<td>251</td>
<td>56</td>
</tr>
<tr>
<td>5’-A</td>
<td>ATTTTCAGTTCTACTGTTTATCC</td>
<td>GAAGCAGCCCAAGGAGATCTACAG</td>
<td>195</td>
<td>56</td>
</tr>
<tr>
<td>5’-B</td>
<td>CCTATTCCAGGAGGATCTCTACC</td>
<td>ACCAGCTTGTTGATGCTTCT</td>
<td>226</td>
<td>62</td>
</tr>
<tr>
<td>5’-C</td>
<td>TGTTATCTACAGGAGGCTTCG</td>
<td>AGAAAAATCCTCTGATGAGGCA</td>
<td>198</td>
<td>58</td>
</tr>
</tbody>
</table>

Primer sequences for amplifying exons 2–15, the downstream primer for exon 1, and the upstream primer for exon 16 (16A) are designed from intronic regions. The upstream primer for exon 1, the downstream primer for exon 16, (16A) and the primers for amplifying exon 16B are designed from the GYS2 cDNA (15). Exons 16A and 16B amplify the coding regions of exon 16 (nucleotides 1919–1991 and 1971–2222, respectively). 5’-A amplifies the first 74 nucleotides of exon 1 and the first 121 nucleotides upstream of the 5’-nontranscribed region. 5’-B and 5’-C amplify fragments from the 5’-region (nucleotides –74 to –300 and –252 to –450, respectively).

**Single-strand conformational polymorphism (SSCP) analysis**

For the SSCP analysis (19), 50 ng of genomic DNA extracted from each affected individual, their family members, and at least two healthy control subjects was amplified with 10 pmol each of the GYS2 gene-specific intronic primer pairs (Table II). The PCR was carried out in 20-μl reactions using 0.5 U of Taq polymerase and including 0.05 μl of [α-32P]dCTP (3,000 Ci/mmol) (Pharmacia Biotech). Reactions were diluted 1:1 with 95% formamide buffer, denatured 5 min at 94°C, cooled, and electrophoresed on a gel with 5% glycerol (8 W for 13 h at room temperature) and on a glycerol-free (35 W for 4 h at 4°C) nondenaturing 5% polyacrylamide gel (49:1 acrylamide/bis-acrylamide). When shifts in the band pattern were observed, the corresponding exon was PCR amplified from genomic DNA, isolated from an agarose gel, and sequenced bidirectionally using the same primers as for SSCP.

**Confirmation of mutations by restriction enzyme digest**

All the identified missense mutations and the intron 6 splicing site mutation were confirmed by PCR of the genomic DNA followed by restriction enzyme digestion and agarose gel electrophoresis in all affected subjects, the studied family members, and in 200 healthy control subjects. The missense mutations Ala339Pro, His446Asp, and Met491Arg were confirmed by PCR with the primer pairs used in the SSCP followed by digestion with restriction enzymes AluI, BseDI, and BstNI, respectively (New England Biolabs, Beverly, MA). For detection of intron 6 (G to A) mutations, Asn39Ser, Pro479Gln, and Ser483Pro mutations, which did not create or destroy a known restriction enzyme recognition site, the PCR from genomic DNA was performed using one of the SSCP primers (Table II) and a new primer where a single nucleotide mismatch was introduced (the mismatch nucleotide is underlined) to create an AluI (E6-GT/CT-F, 5’-GATTTTGTGCAAGGGTATTTCTATAG with primer E6R; for

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Western blot analysis

The expression of the GYS2-WT and the different mutated liver GSs was analyzed using Western blot analysis. A negative control (COS7 cells transfected with the pcDNA3.1 vector), GYS2-WT, GYS2-39Ser, GYS2-246X, GYS2-339Pro, GYS2-446Asp, GYS2-479Gln, and a rat liver control sample were homogenized in 50 mM KF, 10 mM EDTA, pH 7.0. Samples were separated on 7.5% acrylamide resolving, 4.5% acrylamide stacking gels at 200 V for 45 min. The proteins were electrotransferred to nitrocellulose membranes at 100 V for 60 min and incubated with a polyclonal rat liver GS antibody prepared in chicken (IgY). The second antibody was anti–chicken IgG (Sigma) and the detection was done using avidin alkaline phosphatase conjugate (Bio Rad, Hercules, CA), paranitroblue tetrazolium chloride, and 5-bromo-4-chloro-3-indolyl phosphate.

GenBank accession numbers

The nucleotide sequences of the GYS2 gene were submitted to the EMBL with accession numbers AJ003087-AJ003102.

Results

Clinical and biochemical phenotype.

Fasting hypoglycemia associated with increased plasma concentrations of \( \beta \)-hydroxybutyrate and free fatty acids dominated the clinical picture in six of the children with GSD-0. After a glucose challenge or a meal, the plasma concentrations of ketones and free fatty acids were normalized while plasma glucose and lactate concentrations rose markedly. In the five children who had liver biopsies, the liver glycogen content was low, whereas the liver GS activity was low or nil (Table I). Glycogen structure, where analyzed, was normal (Table I).

Genomic structure of the GYS2 gene.

Cloning and characterization of the five genomic clones isolated with GYS2 cDNA probes revealed that the GYS2 gene is composed of 16 exons and spans \( >30 \) kb (Table III and see Fig. 2). All the sequences at the exon-intron junctions conform to the GT/AG rule (22) (Table III) and the exon-intron boundaries are conserved with the human muscle GS gene (GYS2) (23). The genomic clone GYS2-AE1-3, which was extracted with the 441-bp PCR probe, was shown to contain exon 1 and the 5′-flanking region of the GYS2 gene. The genomic clone GYS2-A21 was found to contain exons 2–4, the GYS2-A14 exons 2–5, the GYS2-A6 exons 6–11, and the GYS2-A16 exons 12–16. None of the extracted genomic clones contained the whole intron 1 or intron 11 sequences, and because we could not amplify these introns from a genomic DNA, they are presumed to be long.

Linkage analysis.

The segregation of chromosome 12p12.2 markers in five families with GSD-0 is shown in Fig. 1. Using a recessive model of inheritance, linkage of GSD-0 to the GYS2 gene was suggested in these families with a combined LOD score of 2.9 (\( P < 0.01 \)).

Mutation screening.

Mutation screening by SSCP and sequencing revealed several DNA variants in the affected children (Fig. 1). In family Y, the proband (patient 1), whose both alleles had similar haplotypes, carried a mutation causing a premature stop codon in exon 5, Arg246X (CGA→TGA), on both alleles (Fig. 1). Also two of the unaffected brothers of patient 1 carried the Arg246X mutation on one allele, whereas the third unaffected brother did not have the mutation. In family M (patients 2–4), a mutation in the 5′-donor splicing site of intron 6 (\( G^+T\rightarrow CT \)) was identified. The mutation was inherited from the mother by all three affected children. The DNA
from the father was not available for the study but a Pro479Gln mutation (CCA→CAA) in exon 12 was identified in all three children. Since this mutation occurred on identical haplotypes and was not seen in the mother, it most likely represents the mutation inherited from the father.

In family F, patient 5 was shown to carry two missense mutations. A Ala339Pro mutation (GCT→CTG) in exon 7 was inherited from the mother and a Met491Arg mutation (ATG→AGG) in exon 12 was inherited from the father. Also, the unaffected sister carried the Ala339Pro mutation, but she did not have the Met491Arg mutation. In family J, patients 6 and 7 carried an Asn39Ser mutation (AAT→AGT) in exon 1 and a Ser483Pro mutation (TCC→CCC) in exon 12. In family S, a His446Asp mutation (CAC→GAC) in exon 11 was inherited from the mother by patients 8 and 9, but no mutation that could have been inherited from the father was found despite SSCP analysis and direct sequencing of all the exons and 450 bp of the 5′-flanking region of the GYS2 gene. None of the identified mutations could be seen in the 400 control chromosomes. All the mutations identified in the GYS2 gene are summarized in Fig. 2.

**Expression of the mutated liver GS enzymes in the COS7 cells.** The expression of the wild-type liver GS in COS7 cells resulted in ~30 times higher total GS activity compared with intracellular GS activity (334±13 vs. 11±4 nmol/min × mg protein) (Table IV). The GS activities of the mutated liver GS enzymes were at highest 3.5 and 1.1% of the wild-type activity (Table IV). Western blot analysis using a polyclonal rat liver GS antibody detected the expected 80-kD band in the GYS2-WT, GYS2-39S, GYS2-446D, GYS2-479Q, GYS2-483P, and GYS2-491R and in the rat liver sample. The antibody did not detect the GYS2-246X and GYS2-339Pro samples (data not shown).

### Discussion

Knowledge of the genomic structure allowed us to screen the GYS2 gene in children with proven or suspected GSD-0. A

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**Table III. Exon-Intron Boundary Sequences of the GYS2 Gene**

<table>
<thead>
<tr>
<th>Exon</th>
<th>Exon size</th>
<th>5′ splice donor</th>
<th>3′ splice acceptor</th>
<th>Amino acid interrupted</th>
<th>Intron size</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>149</td>
<td>GAT AAA G</td>
<td>gtttgtaactgctct</td>
<td>TT GGA GGC</td>
<td>Val (41)</td>
</tr>
<tr>
<td>2</td>
<td>182</td>
<td>GGC TGC CAG</td>
<td>gtaaggagaactgaca</td>
<td>G G</td>
<td>—</td>
</tr>
<tr>
<td>3</td>
<td>192</td>
<td>TTT AAA GAG</td>
<td>gttggtttattata</td>
<td>G G</td>
<td>—</td>
</tr>
<tr>
<td>4</td>
<td>183</td>
<td>CCT CAT AAG</td>
<td>gtaaatatctctccc</td>
<td>G G</td>
<td>—</td>
</tr>
<tr>
<td>5</td>
<td>145</td>
<td>AAG CCT G</td>
<td>gttattatatccttg</td>
<td>G G</td>
<td>—</td>
</tr>
<tr>
<td>6</td>
<td>118</td>
<td>TTC TAT GG</td>
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<tr>
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<tr>
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<td></td>
<td></td>
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Exon sequences are in capital letters and intron sequences are in lowercase letters. The amino acids corresponding to the exon sequence are shown under the nucleotide sequence, and the amino acid preceding or interrupted by an intron is indicated. Introns are positioned by applying the GT/AG rule (22). The sizes of introns 1 and 11 were not determined.
suggestive recessive linkage to the \textit{GYS2} gene was established in these five families with nine affected children and mutation screening of the \textit{GYS2} gene revealed unique mutations in each family (Figs. 1 and 2).

In family Y, patient 1 carried an Arg246X nonsense mutation in exon 5 on both alleles (Fig. 1). This premature stop codon presumably leads to loss of 65\% of the COOH-terminal part of the protein, including amino acids 246–400 and 500–600, which may include the catalytic and the allosteric G-6-P binding sites (15). Surprisingly, this patient had practically normal glycogen concentration and the least severe reduction in the GS activity (Table I). His unrelated parents and two brothers, who were heterozygous carriers of the Arg246X mutation, did not show ketotic fasting hypoglycemia nor an exaggerated rise in blood glucose and lactate during the oral glucose tolerance test. However, liver biopsies have not been performed in them. Expression of the \textit{GYS2} cDNA with the Arg246X mutation in COS cells demonstrated that this stop codon leads to a total loss of GS activity (Table IV). Rat liver GS antibody did not bind to the GYS2-246X in the Western blot analysis, which indicates that this truncated GS was either not recognized by the antibody or the expressed protein is unstable.

In patients 2–4 in family M we identified a mutation in the 5'-donor splicing site of intron 6, which was inherited from the mother by all three affected children (Fig. 1). This mutation destroys the conserved donor splice site, which predictably results in skipping of exon 6 (amino acids 275–314) and a frameshift with exons 5 and 7 linked together. This, in turn, will create a premature stop codon in exon 7. If expressed, this transcript would code for a 57\% truncated protein with 29 mis-coded amino acids in the COOH-terminal end. The mother, who carries the mutation only in one chromosome, also devel-
ops hypoglycemia during prolonged fasting, which could indicate that this truncated protein may disturb the structure of the wild-type liver GS, which is believed to be a dimer (24). The DNA from the father was not available but a Pro479Gln mutation in exon 12 was identified in all three children. Since this mutation occurred on identical haplotypes and was not seen in the mother, it most likely represents the mutation inherited from the father. In agreement with this, no GS activity was detected in COS cells expressing the mutated enzyme with glutamine in codon 479 instead of proline (Table IV).

Five different missense mutations in exons 1 (Asn39Ser), 7 (Ala339Pro), 11 (His446Asp), and 12 (Ser483Pro and Met491Arg) were identified in patients S–9 from families F, J, and S (Fig. 1). In families F and J, the patients were compound heterozygotes for two different mutations on different alleles. When the mutated GYS2 cDNAs were expressed in COS cells, the GS activities at high UDPG and G-6-P concentrations were at highest 3.5 and 1.1% of the wild-type activity (Table IV). All the expressed GSs with missense mutations, except the GYS2-339Pro, were detected as 80-kD bands in the Western blot analysis, showing that these mutations affect the GS activity. Whether the GYS2-339Pro was not detected because of structural changes leading to loss of epitopes detected by the used antibody or if this mutation affects the stability of the mutated enzyme is not known. In family S (patients 8 and 9), only one mutation was identified despite SSCP analysis and direct sequencing of all the exons and 450 bp of the 5’-flanking region. The unidentified disease-causing mutation in family S is presumably located outside the coding region and exon-intron junctions and could, for example, silence or impair the expression of the GYS2 gene or produce novel splice sites altering the mRNA processing.

We think that the identified mutations are the cause of GSD-0 for the following reasons. First, we expressed the mutated GSs in COS cells and demonstrated that all of these mutations result in either immeasurable or very low GS activity, regardless of whether measured as total activity or at physiological concentrations of UDPG or G-6-P (Table IV). Second, seven of the affected children carried mutations in both alleles. Finally, the mutations were not detected in 400 control chromosomes. We can only speculate about the mechanisms by which the identified mutations could affect the catalytic efficiency of the enzyme. The Asn39Ser mutation is located close to the proposed UDPG binding site (amino acids 40–43) (25, 26). The Ala339Pro mutation in the highly conserved exon 7 could result in distortion of the three-dimensional structure by introducing a helix breaking amino acid proline. The His446Asp mutation in exon 11 represents a change from a reactive basic to an acidic amino acid and could change the angle beyond the conserved region coded by exon 12. This, in turn, could affect transmission of the phosphorylation signal to the catalytic and/or G-6-P binding site. The Pro479Gln, Ser483Pro, and Met491Arg mutations are located in exon 12, which shows 95% conservation between the GYS2 and GYS1 genes (15, 23). These substitutions occur in an area of strong negative charge density and thus likely affect the regulation of the catalytic efficiency and/or transmission of phosphorylation signals to the G-6-P binding site (27).

Some intriguing findings remain to be explained. Although the GS activity was almost lacking in the liver of the patients, the glycogen content was only moderately decreased and the glycogen structure was apparently normal (Table I, reference 3). This points at an alternative, GS-independent pathway for glycogen synthesis in the liver (28). The most likely explanation would be the reversal of the glycogen phosphorylase reaction. Already Lewis et al. (1) suggested that under certain circumstances the function of liver GS could be taken up by glycogen phosphorylase, as the phosphorylase reaction is reversible and phosphorylase activity exceeds synthase activity by 10-fold in the liver (29). Even a modest reversal of phosphorylase activity could thus result in significant glycogen synthesis. However, this would require a marked decrease in cell pH and a very high glucose-1-phosphate concentration (30).

Fasting hypoglycemia is usually the consequence of insufficient liver glucose output, either due to inappropriately high insulin secretion or inherited defects in liver glucose production. The latter represents the sum of two processes, glycogenolysis and gluconeogenesis. In overnight fasted healthy individuals the two processes contribute equally to net liver glucose output, whereas during prolonged fasting the contribu-
tion of gluconeogenesis increases (31, 32). Although some glycogen was shown to be synthesized in the liver of GSD-0 patients, they become hypoglycemic already a few hours after the meal. A recent report by Petersen et al. may have illuminated this problem by showing that during hypoglycagogenous euglycemic hyperinsulinemia, the inhibition of net gluconeogenesis in the liver is exclusively through the activation of GS, whereas glycogen phosphorylase is unaltered, resulting in extensive glycogen cycling (33). GS is not activated in the liver of GSD-0 patients and the glycogen stores are most likely depleted during normoglycemic conditions. How a defect in liver glycogen synthesis without a concomitant defect in gluconeogenesis can lead to hypoglycemia remains unclear. Metabolic profiles (2, 3, 10) suggest that the patients cannot switch to gluconeogenesis rapidly enough to ensure a normal hepatic glucose output (11). It is possible that glucagon is suppressed by the postprandial hyperglycemia characteristic of the patients with GSD-0 and that the glucagon to insulin ratio remains too low to stimulate phosphoenolpyruvate carboxykinase, the rate-limiting enzyme for gluconeogenesis (34). The postprandial hyperglycemia and hyperlactatemia is explained by an inability to trap sufficient glucose as glycogen in the liver (11).

Although GSD-0 has been considered a rare disorder, it may be an underdiagnosed disease (3). In four families, five affected siblings were discovered only after the probands had been diagnosed (3, 12). The disease can obviously have a mild course. The distinction from other forms of ketotic hypoglycemia in childhood is difficult. The availability of a genetic diagnosis of the disease should now allow screening of symptomatic children.

Glucose intolerance and postprandial hyperglycemia were consistent findings in the patients. Therefore, the question arises of whether mutations in the GYS2 gene could contribute to glucose intolerance of type 2 diabetes as well. When screening 165 patients with type 2 diabetes and 165 healthy controls, we did not find any association between the GYS2-CA microsatellite polymorphism and type 2 diabetes. Neither could we observe linkage to this chromosomal region in families with type 2 diabetes (35).

In conclusion, mutations in the GYS2 gene provide a genetic explanation for GSD-0. The disease certainly involves a defect in the liver GS and we propose that the name GSD-0 is replaced by liver GS deficiency. Glycogen biogenesis is still not fully understood (36). The findings of only moderately decreased liver glycogen stores may point at an alternative, GS-independent pathway for glycogen formation in the liver.

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References


