CLINICAL STUDY

Intrauterine and postnatal growth failure with normal GH/IGF1 axis and insulin-resistant diabetes in a consanguineous kinship

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Abstract

Objective: To describe the clinical and biochemical features, and perform molecular analysis for candidate abnormalities in a novel familial syndrome of intrauterine growth retardation (IUGR), failure of an adolescent growth spurt with proportional adult short stature, minimal subluxation of the 5th metacarpal–phalangeal joint, and adult-onset insulin-resistant diabetes unrelated to obesity or other manifestations of metabolic syndrome (MS).

Design: Detailed clinical history, auxological, biochemical, radiological, and molecular studies, including DNA analysis and in vitro study of the GH/IGF1 pathway.

Materials and methods: Ten affected adults from two generations of five related families were studied in detail, and information obtained about nine other likely affected individuals.

Results: Height Z-scores ranged from −7.3 to −3.8. Unaffected parents of the older generation and frequency of confirmed and suspected instances of the syndrome in the two generations studied is consistent with autosomal recessive inheritance. Insulin resistance was uniformly present in seven subjects tested who were not taking insulin. Diabetes severity did not correlate with overweight. Subjects did not have other typical manifestations of MS such as substantial hyperlipidemia, osteoporosis, or hypertension. No biochemical abnormality in the GH/IGF1 axis or molecular defect was found.

Conclusions: While the association of IUGR and adult MS, including diabetes, has been well documented, these subjects did not have typical manifestations of MS. Abnormalities in common components that could result in a combination of IUGR, severe postnatal growth, and insulin resistance have been ruled out. A mutation in an unidentified gene may affect intrauterine and postnatal growth, with insulin resistance directly affected or as a result of this growth phenomenon.

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Introduction

Intrauterine growth retardation (IUGR) is followed by catch-up growth postnatally in ~90% of cases (1) and has been associated with increased frequency of obesity and risk for adult metabolic disease, including type 2 diabetes, related to insulin resistance (2). In the absence of syndromic causes of IUGR such as Silver–Russell syndrome (3), which typically involves postnatal growth failure as well, ~50% of instances are due to maternal factors including alcohol consumption, undernutrition, illness, and placental insufficiency, with the remainder being largely unexplained and sporadic (4). Rare hormonal causes include mutations affecting insulin secretion or action, or insulin-like growth factor 1 (IGF1) and its receptor (5).

We have studied ten members in two generations of a consanguineous family having IUGR without dysmorphism, proportional postnatal growth failure with reported failure of an adolescent growth spurt, and adult insulin resistance. In addition, we have obtained data about a deceased affected relative and stature information about eight individuals likely to be affected on the basis of measured or estimated stature corresponding to that of the affected individuals, but unavailable for detailed examination. This appears to be a new syndrome that is unexplained by current knowledge.

Materials and methods

Ten subjects were studied at the Institute for Endocrinology, Metabolism, and Reproduction (IEMYR) in Quito, Ecuador. One affected individual was deceased and eight other possibly affected subjects and 32
unaffected relatives had heights and weights measured in their community. Heights were taken at the IEMYR as the average of three measurements using a wall-mounted calibrated stadiometer. Lower segment was measured as the distance from the top of the symphysis pubis to the floor, and arm span from middle finger tips of outstretched arms. Hand length was taken from distal wrist crease to middle fingertip across the palmar surface and foot length from heel to tip of longest toe along the plantar surface. Height Z-score was calculated from US National Center for Health Statistics data for 20-year-old individuals (6). Other auxological measurements were compared with published reference data (7, 8, 9). Percentage body fat and bone mineral density were determined by dual energy X-ray absorptiometry (DXA; Lunar, Madison, WI, USA). Body fat percentage by DXA was used to define overweight and obesity as a more reliable method than body mass index (BMI) (10). Radiographic studies were done of the long bones, hips, thorax, hands, and feet to rule out skeletal abnormalities.

Detailed medical history was obtained, especially regarding birth length and weight and presence or absence of diabetes. For the deceased subject, stature was estimated from photographs and medical history confirmed by four close relatives. Similarly, detailed familial relationships were explored for a total of six generations.

Five subjects underwent clonidine and insulin-induced hypoglycemia stimulation for GH release, and three subjects had 7-day GH stimulation of IGF1, IGF binding protein 3 (IGFBP3), and acid labile subunit (ALS). Measurements of GH, GH binding protein (GHBP), IGF1, and IGFBP3 were performed by the commercial laboratory, Esoterix (Calabasas Hills, CA, USA). Seven subjects who had not been treated with insulin had the quantitative insulin sensitivity check index (QUICKI) calculated according to the formula: 1/(log (fasting insulin in μU/ml) + log (fasting glucose in mg/dl)). Impaired insulin sensitivity was considered when QUICKI was < 0.357 (11).

Cell culture

Primary fibroblast cultures were established from skin biopsies taken from five affected individuals (12). The fibroblasts were maintained in α-MEM (Cellgrow, Mediatech, Herndon, VA, USA) supplemented with 15% fetal bovine serum (Invitrogen Life Technologies, Inc.) at 37°C in 5% CO2. Cells were serum starved overnight before treatment with or without IGF1 (10 ng/ml) or insulin (50 ng/ml) for 15 min, and cell lysates were collected for immunoblot analysis.

Genomic DNA and cDNA

Genomic DNA from either whole blood or primary fibroblast cultures was obtained for five subjects (13). Primers and conditions for PCR amplification and

<table>
<thead>
<tr>
<th>cDNA</th>
<th>Name</th>
<th>Human phenotype associated with defect (OMIM)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ligand</td>
<td>IGF1</td>
<td>IUGR, severe short stature, intellectual compromise (*147440)</td>
</tr>
<tr>
<td>Receptors</td>
<td>GHR</td>
<td>Severe postnatal short stature, GH insensitivity, IGFD</td>
</tr>
<tr>
<td></td>
<td>IGF1R</td>
<td>Rabson–Mendenhall syndrome, NIDDM (*147670)</td>
</tr>
<tr>
<td></td>
<td>INSR</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Ptk3–AKT pathway</td>
<td></td>
</tr>
<tr>
<td></td>
<td>IRS1</td>
<td>SNPs associated with NIDDM (+ 147545)</td>
</tr>
<tr>
<td></td>
<td>PIK3CA P3K</td>
<td>Tumors, cancers (*171834)</td>
</tr>
<tr>
<td></td>
<td>PIK3R1 P3K</td>
<td>Unknown</td>
</tr>
<tr>
<td></td>
<td>PDK1</td>
<td>Insufficient associated with schizophrenia (*164730)</td>
</tr>
<tr>
<td></td>
<td>AKT1</td>
<td>Diabetes mellitus type 2, lipodystrophy, hepatic steatosis (*164731)</td>
</tr>
<tr>
<td></td>
<td>AKT2</td>
<td>Hypoglycemia</td>
</tr>
<tr>
<td>PRKACA</td>
<td></td>
<td></td>
</tr>
<tr>
<td>mTOR–S6K pathway</td>
<td>RPS6KB1</td>
<td>Protein kinase, cAMP-dependent, catalytic, α</td>
</tr>
<tr>
<td></td>
<td>RPS6KB2</td>
<td>Ribosomal protein S6 kinase, 70 kDa, polypeptide 1 (also known as S6K1)</td>
</tr>
</tbody>
</table>

IUGR, intrauterine growth retardation; IGFD, IGF deficiency; NIDDM, noninsulin-dependent diabetes mellitus. * denotes OMIM (Online Mendelian Inheritance in man)

aActivating mutations.

bMouse Pipk1a−/−: reduced islet cells, hyperglycemia (32).

cLoss of function mutations.

dActivating mutation (33).

eMouse Pipkaa−/−: runted, reduced IGF (34).

fMouse Rps6kb1−/−: IUGR, but catch-up growth (35, 36).

gMouse Rps6kb2−/−: slightly larger than wild-type (37).
sequencing of genomic GH receptor (GHR), IGF1 receptor (IGF1R), and IGF1 genes have been described in an earlier study (14). Total RNA was extracted from primary fibroblast cells and cDNA was synthesized (13). The primers for PCR amplification and sequencing are shown in Table 1.

**Western immunoblot analysis**

Preparation of cell lysates and subsequent western immunoblot analyses were performed (13, 14). The antibodies employed in this study were from Cell Signaling Technologies (Beverly, MA, USA), unless otherwise specified: anti-phospho–Tyr-100, anti-phospho–Thr308-Akt rabbit monoclonal IgG, anti-phospho–Ser473-Akt rabbit polyclonal IgG, anti-PI3K p85, and anti-PI3K p110α were rabbit polyclonal antibodies. Anti-insulin receptor substrate 1 (IRS1) was from Santa Cruz, Biotechnologies Inc., Santa Cruz, CA, USA. Secondary antibodies (anti-rabbit IgG) were obtained from Amersham-Pharmacia Biotech. Immunoprecipitation was performed as previously described (14). All immunoblot data shown are representative of at least two independent experiments.

The studies were carried out after obtaining informed consent in compliance with the institutional review boards of the IEMYR and Oregon Health and Science University.

**Results**

**Genealogy**

The 11 confirmed and eight suspected subjects, from five families, are first, second, or third degree relatives. As is the custom in Spanish culture, offspring carry two last names, from each of the parents’ paternal line. All subjects carry a single common name as one of their last names. The members of the older generation do not have affected parents (Fig. 1). Their sibships comprise 42 individuals; therefore, 36% are confirmed or suspected to be affected. Among the offspring of affected individuals in this generation, four of 15 (27%) are confirmed or suspected to be affected (Fig. 1). Unaffected parents of the older generation and frequency of confirmed and suspected instances of the syndrome in the two generations studied is consistent with autosomal recessive inheritance.

**Birth and infancy history**

All confirmed affected subjects were born of uneventful pregnancies at term, with birth lengths varying from 25 to 40 cm (−14 to − 5.6 SDS), and all were said to have very low birth weights. Similar information was obtained for the deceased individual, #11 (Fig. 1, Table 2). Subject #8 was so small, at 25–30 cm and <1000 g, that the parents were told she would not live, but she survived with intense maternal care and breastfeeding for her first 18 months. Subject #2 had knee contractures and required surgical intervention at 7 and 8 years of age before she was able to walk. None of the normal statured relatives had IUGR.

**Clinical phenotype**

Considering all 19 confirmed or suspected affected individuals, there were 11 females and eight males, ranging in age from 20 to 69 years. Demographic and auxological data are presented in Table 2. Height Z-scores varied from −7.3 to −3.8. The 20 unaffected relatives <70 years of age had height Z-scores of −2.3 to +0.4. Upper to lower segment ratio (U/l) Z-scores, with the exception of the woman with leg deformities, ranged from −0.3 to +3.0, and were within 2 S.D.s of normal in 7/10 subjects. This contrasts with the observations made in 35 Ecuadorian adults with short stature due to GHR deficiency (GHRD), 75% of whom had U/l Z-scores > +2.5 (15). Subject #2 had a markedly abnormal U/l Z-score of +6 as the result of her lower extremity deformities; if her lower segment were proportional to her upper segment, her height would be 141 cm. −3.8 Z-score, and therefore still abnormal. Her arm span of 135 cm and hand and foot length, the shortest among the subjects, were further consistent with the syndrome. All subjects reported an absence of an adolescent growth spurt, but they underwent normal sexual maturation. Arm span was normal for height in all subjects. Head
circumferences were more normal than stature, varying from −3.5 to −1.4  Z-score. Hand length Z-scores ranged from −1.4 to −3.5, less abnormal than stature. Foot length Z-scores corresponded to the range in stature Z-scores (−6.0 to −3.6). Radiographs showed minimal subluxation of the 5th metacarpal–phalangeal joints bilaterally in all ten subjects (Fig. 2). Deformity was not noted on physical examination.

**Diabetes, body composition, and insulin sensitivity**

Diabetes developed between 26 and 37 years of age in six of the ten subjects studied at the IEMYR and by report in three of the other nine at about age 30 (Table 2B). As part of the present study, one subject (#7, Table 2A) was diagnosed at 57 years of age and another (#4) at age 47 was found to have impaired fasting glucose (IFG) and impaired glucose tolerance (IGT) based on American Diabetes Association criteria (16).

At age 32, subject #1 had an oral glucose tolerance test (OGTT) with a fasting level of 4.8 mmol/l, and a level of 7.5 mmol/l at 2 h with normal HbA1c (Table 3). Subject #2 had acanthosis nigricans of the neck, axilla, linea alba, and inner thighs. Subject #3 had maintained a healthy lifestyle to avoid developing diabetes; her older sister (#5) and brother (#7) were affected. Subject #4 had maintained a healthy lifestyle with regular exercise in a job requiring 5–6 h of walking a day and did not have symptoms of diabetes. His fasting blood glucose level was 6.22 mmol/l (IFG) with a 2-h level of 9.78 mmol/l (IGT). Subject #5 had diabetes for 23 years, since age 26, had maintained a healthy lifestyle to avoid developing diabetes; her older sister (#5) and brother (#7) were affected. Subject #4 had maintained a healthy lifestyle with regular exercise in a job requiring 5–6 h of walking a day and did not have symptoms of diabetes. His fasting blood glucose level was 6.22 mmol/l (IFG) with a 2-h level of 9.78 mmol/l (IGT). Subject #5 had diabetes for 23 years, since age 26,
Metabolic data. Body mass index (BMI) calculated as the ratio of weight to height in meters squared. Percent body fat was determined by dual energy X-ray absorptiometry. Quantitative insulin sensitivity check index (QUICKI) was calculated for those not taking insulin, according to the formula: 1/(log (fasting insulin in mU/ml) + log (fasting glucose in mg/dl)); impaired insulin sensitivity was considered when QUICKI < 0.357 (4) in subjects not requiring insulin (10). No subjects were receiving medication for hyperlipidemia.

<table>
<thead>
<tr>
<th>Subject no.</th>
<th>Weight (kg)</th>
<th>BMI (kg/m²)</th>
<th>Fat (%)</th>
<th>DM therapy</th>
<th>HbA1c (% Hb)</th>
<th>Insulin (pmol/l)</th>
<th>QUICKI</th>
<th>Cholesterol (mmol/l)</th>
<th>HDL (mmol/l)</th>
<th>TG (mmol/l)</th>
<th>LDL (mmol/l)</th>
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</thead>
<tbody>
<tr>
<td>1</td>
<td>43.0</td>
<td>23.3</td>
<td>0.324</td>
<td>0</td>
<td>5.4</td>
<td>9.11</td>
<td></td>
<td>4.7</td>
<td>5.4</td>
<td>4.7</td>
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<tr>
<td>2</td>
<td>43.4</td>
<td>24.5</td>
<td>0.368</td>
<td>Insulin</td>
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<td>7.05</td>
<td></td>
<td>6.7</td>
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<tr>
<td>3</td>
<td>40.0</td>
<td>23.0</td>
<td>0.368</td>
<td>Metformin</td>
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<td>5.56</td>
<td></td>
<td>6.4</td>
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<tr>
<td>4</td>
<td>48.3</td>
<td>24.0</td>
<td>0.0</td>
<td>Diet/exercise</td>
<td>6.2</td>
<td>11.4</td>
<td></td>
<td>5.8</td>
<td>5.8</td>
<td>5.8</td>
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</tr>
<tr>
<td>5</td>
<td>34.2</td>
<td>21.5</td>
<td>0.331</td>
<td>Insulin</td>
<td>7.6</td>
<td>144.2</td>
<td></td>
<td>7.2</td>
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</tr>
<tr>
<td>6</td>
<td>38.7</td>
<td>22.9</td>
<td>0.331</td>
<td>Metformin</td>
<td>8.5</td>
<td>7.18</td>
<td></td>
<td>7.8</td>
<td>7.8</td>
<td>7.8</td>
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</tr>
<tr>
<td>7</td>
<td>33.2</td>
<td>19.7</td>
<td>0.324</td>
<td>Diet/exercise</td>
<td>9.4</td>
<td>5.67</td>
<td></td>
<td>8.7</td>
<td>8.7</td>
<td>8.7</td>
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<tr>
<td>8</td>
<td>43.7</td>
<td>22.1</td>
<td>0.358</td>
<td>Metformin</td>
<td>9.7</td>
<td>5.67</td>
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<td>8.7</td>
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<tr>
<td>9</td>
<td>43.3</td>
<td>22.0</td>
<td>0.324</td>
<td>Glibenclamide</td>
<td>9.4</td>
<td>4.75</td>
<td></td>
<td>8.7</td>
<td>8.7</td>
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</tr>
</tbody>
</table>

Abnormal values and impaired fasting glucose/impaired glucose tolerance are indicated by (*). All of these seven individuals also had elevated triglycerides, all ten subjects had normal high-density lipoprotein cholesterol (HDL-C) and low-density lipoprotein cholesterol (LDL-C) serum levels (Table 3).

Insulin sensitivity analyses of the seven subjects who did not have manifest diabetes or require insulin for management of their diabetes are summarized in Table 3. All of them demonstrated impaired insulin sensitivity by QUICKI. While seven of the ten test subjects had elevated serum total cholesterol concentrations, and two of these seven individuals also had elevated triglycerides, all ten subjects had normal high-density lipoprotein cholesterol (HDL-C) and low-density lipoprotein cholesterol (LDL-C) serum levels (Table 3).

Percentage body fat determined by DXA (Table 3) met the gender- and age-specific criteria for obesity in one man and one woman and for overweight in four women (10). This contrasts with the BMI data which identified no individuals as obese (BMI > 30 kg/m²) and only one at the borderline for overweight (BMI 25 kg/m²) (6). Bone mineral density Z-scores adjusted for age and gender ranged from −1.0 to +2.3, with the majority of the subjects having above-average scores (Table 2A). Thus, there was no evidence of osteoporosis as a late complication of IUGR (2). Blood pressures (data not shown) were normal (<130/70 mmHg) in all but one subject who had a pressure of 140/78 mmHg.

Among the 32 unaffected relatives aged 26 to 91 years, only one was known to have diabetes – a 91-year-old male who developed his diabetes at 70 years of age, which was controlled with diet and exercise.

Social adaptation

All subjects did average or better work in school; three of the four males who were studied at the EEMYR were very good students. All ten individuals in Table 2A were married. Eight of the subjects had children. One man and one woman decided not to have children because they did not want to run the risk of passing on the condition.
GH/IGF1 axis

All subjects had normal GHBP, IGF1, IGFBP3, and ALS serum concentrations, and all but one responded normally to GH stimulation (Table 4). IGF1 concentrations increased 2.5-, 3-, and 4.5-fold, in response to GH administration, in the three subjects thus tested, while IGFBP3 concentrations increased 50% or more and ALS levels increased >100, 50, and 10%.

Genetic and cellular evaluations

The severe short stature, with normal serum IGF1 levels that increased with administration of rhGH, was suggestive of resistance to IGF1. Molecular defects of the Igf1r gene are associated with IGF1 resistance (5). Furthermore, in rodents, pancreas-specific ablation of the IGF1R gene led to diabetes (17, 18). Therefore, the IGF1R gene and cDNA of our subjects were sequenced and IGF1R was found to be wild-type as was the insulin receptor (INSR) gene (Table 1). The IGF1 and GHR genes were also normal.

Because the IGF1R and INSR genes were wild-type (Table 1), the possibility of defects downstream of these two highly homologous receptors was considered. For sequencing, we targeted genes encoding for signal molecules known to be activated by both systems and associated with short stature or potential diabetes phenotypes for sequencing. As shown in Table 1, all cDNAs analyzed were wild-type.

Although all components analyzed were normal at the cDNA level, it is possible that one or more of the components was not normally expressed at the protein level or was incapable of being normally activated. IGF1-induced signaling, specifically activation of PI3K/AKT, was evaluated in fibroblasts from one of the subjects and compared with normal, control fibroblasts. PI3K/AKT signaling, exemplified by phosphorylation of IRS1 (tyrosines) and AKT (serine and threonine), appeared to be normally activated by IGF1 treatment (Fig. 3A). Insulin, furthermore, similarly activated AKT (Fig. 3B), indicating that at least the pathway to PI3K/AKT appeared to be normal.

Discussion

We have described a previously unrecognized familial association of IUGR, postnatal growth failure with absence of an adolescent growth spurt despite normal sexual maturation, minimal subluxation of the 5th metacarpal–phalangeal joint, and insulin resistance with frequent development of generally non-insulin-requiring diabetes unrelated to obesity. As is typical of type 2 diabetes, the need for insulin therapy occurred in some individuals, indicating inadequate β cell response to the increasing demand with peripheral resistance. Both the resistance and the β cell failure could theoretically result from defects in combined insulin and IGF1 action.

The relationship of IUGR and later development of components of the metabolic syndrome (MS), including obesity, diabetes, hypertension, dyslipidemia, and osteoporosis, has been thought to be an effect of programming the fetus for insulin resistance (2, 19). The relationship between IUGR and adult development of glucose intolerance and the MS has been documented in numerous populations and ethnicities (20).

The most prevalent explanation for the association of decreased fetal growth and adult metabolic disease is the thrifty phenotype hypothesis (19). Fetal undernutrition is postulated to lead to selective distribution of nutrients to essential survival functions, such as brain growth, with metabolic changes that increase postnatal survival in a similarly undernourished environment. These adaptations then become detrimental in the presence of adequate or greater nutrition. This scenario has been substantiated in survivors of the Dutch famine at the end of World War II who were in utero at the time (21).

Table 4  Peak serum GH response to clonidine and insulin-induced hypoglycemia, GH binding protein (GHBP) concentrations (normal range 686–2019 pmol/l), baseline insulin-like growth factor 1 (IGF1), IGF binding protein 3 (IGFBP3), and acid labile subunit (ALS, normal range 7.0–16 mg/l) in five subjects and response to 7-day GH stimulation in three subjects. Age- and gender-specific norms for IGF1 and age-specific norms for IGFBP3 are given in parentheses.

<table>
<thead>
<tr>
<th>Subjects</th>
<th>#1</th>
<th>#6</th>
<th>#8</th>
<th>#9</th>
<th>#10</th>
</tr>
</thead>
<tbody>
<tr>
<td>GH/clonidine (µg/l)</td>
<td>5.0</td>
<td>1.6</td>
<td>0.6</td>
<td>2.3</td>
<td>10.1</td>
</tr>
<tr>
<td>GH/hypoglycemia (µg/l)</td>
<td>14.9</td>
<td>10.1</td>
<td>11.8</td>
<td>1.0</td>
<td>13.3</td>
</tr>
<tr>
<td>GHBP (pmol/l)</td>
<td>1385</td>
<td>2218</td>
<td>2087</td>
<td>1519</td>
<td>1421</td>
</tr>
<tr>
<td>Basal IGF1 (µg/l)</td>
<td>146 (87–368)</td>
<td>105 (53–287)</td>
<td>110 (53–287)</td>
<td>131 (60–220)</td>
<td>78 (60–220)</td>
</tr>
<tr>
<td>Peak IGF1 (µg/l)</td>
<td>–</td>
<td>–</td>
<td>500</td>
<td>401</td>
<td>295</td>
</tr>
<tr>
<td>Basal IGFBP3 (mg/l)</td>
<td>3.3 (2.0–4.2)</td>
<td>3.4 (1.9–3.6)</td>
<td>3.2 (1.9–3.6)</td>
<td>2.3 (1.9–3.6)</td>
<td>1.9 (1.9–3.6)</td>
</tr>
<tr>
<td>Peak IGFBP3 (mg/l)</td>
<td>–</td>
<td>–</td>
<td>4.6</td>
<td>3.9</td>
<td>3.5</td>
</tr>
<tr>
<td>Basal ALS (mg/l)</td>
<td>15</td>
<td>18</td>
<td>21</td>
<td>10</td>
<td>10</td>
</tr>
<tr>
<td>Peak ALS (mg/l)</td>
<td>–</td>
<td>–</td>
<td>23</td>
<td>23</td>
<td>15</td>
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</table>
There are noteworthy differences between these well-documented observations and the present population. Firstly, it is not possible to invoke an environmental explanation for selective undernutrition (e.g. famine, maternal illness) of the subjects, who have younger and older siblings who are unaffected. The apparent autosomal recessive pattern of inheritance also would be inconsistent with an environmental or maternal explanation for fetal underdevelopment. The subjects in the present study had postnatal growth failure, did not have hypertension or uniform or severe dyslipidemia, and did not have osteoporosis. While they were not, as a group, obese as defined by percentage body fat on DXA study, four of the six women and one of the four men met the criteria for obesity or overweight. However, there did not appear to be any correlation between degree of obesity by this definition and severity of diabetes; the single man thus defined as obese only had IFG and IGT with a normal HbA1c, controlled by lifestyle, while the three men who did not meet the DXA criteria for overweight had symptomatic diabetes for 10–15 years by the time they were his age. Similarly, the 32-year-old woman obese as per DXA criteria was the only subject with normal glucose metabolism despite insulin resistance. The three insulin-requiring individuals included only one who was overweight by DXA criteria.

An alternative explanation for the association of diminished fetal growth and adult insulin-resistant diabetes would be the presence of gene defects causing both low birth weight and insulin resistance with susceptibility to diabetes in adulthood, which has been termed the fetal insulin hypothesis (22). Monogenic diseases that affect glucose sensing (glucokinase deficiency), insulin secretion (transient neonatal diabetes), or insulin sensitivity (Donohue and Rabson–Mendenhall syndromes) can impair fetal growth. While mutations in the gene encoding glucokinase can result in low birth weight and mild diabetes, the diabetes is of young onset, postnatal growth is normal, and the condition is dominantly transmitted (23). Donohue syndrome is characterized by facial dysmorphism with severe postnatal failure to thrive and death in infancy (24). Newborns with Rabson–Mendenhall syndrome have fasting hypoglycemia and develop severe insulin-dependent diabetes in childhood; they have premature dysplastic dentition, course facial features, and pineal hyperplasia (25). A single individual with a syndrome of severe IUGR with modest postnatal growth failure and adult statural deficit (−3 SDS), early puberty, diabetes onset at age 23, and failure of lactation had a paternally derived translocation breakpoint disrupting regulation of the \( IGF2 \) gene; her daughter carrying this balanced translocation was unaffected (26). The subjects in this study had more severe short stature, normal age of onset of puberty, the familial occurrence was quite different, and the females had no problem with nursing their offspring. Although the subjects in this report do not correspond to any of these disorders, a genetic cause of insulin resistance that also influences postnatal growth is a credible explanation for their condition. An example is suggested by the observation in a large cohort that birth size was influenced by common genetic variation in expression of the insulin gene regulated by the variable number of tandem repeats (VNTR) locus, and that this effect was most pronounced in those individuals who did not have postnatal catch-up growth (27).
The uniform presence of insulin resistance in this syndrome with little or no obesity is in marked contrast to our experience with GHRD, in which severe obesity was generally accompanied by remarkable insulin sensitivity. The obese GHRD subjects had normal triglyceride levels as a reflection of insulin sensitivity and absence of diabetes (28, 29).

The components of the GH/IGF1 pathway were found to be intact, with GH, IGF1, and IGF1R expression and functions apparently normal. IUGR as a result of disturbance in this pathway only occurs with defects of IGF1 and IGF1R genes (30). The IGF1 mutations also result in severe mental retardation, deafness, micrognathia, and severe postnatal growth failure. With heterozygosity for IGF1R mutation, there is more modest postnatal growth failure than with IGF1R mutation or in the present syndrome, and no or mild retardation; there is also microcephaly with IGF1R mutation and less severe reduction in head circumference with mutation of IGF1R (5). Bilateral minimal metacarpal–phalangeal subluxation of the fifth finger is an unusual and distinctive feature. We are unaware of any dysmorphic syndrome with this abnormality, which has only been described as the result of trauma or rheumatoid arthritis (31).

The genetic basis of the syndrome in these subjects remains elusive despite an extensive analysis of known components downstream of the IGF1R and insulin receptor signaling systems. Our preliminary analysis of serine (Ser9) phosphorylation of GS3Kβ and threonine (Thr398) phosphorylation of S6K, as consequences of activated AKT and the mTOR pathways, suggests normal signaling (data not shown). Hence, common components that could result in a combination of IUGR, severe postnatal growth, and insulin resistance have been ruled out. It is likely that an as yet unidentified component or mutation is affecting intrauterine and postnatal growth, with the insulin resistance directly affected or as a by-product of this growth phenomenon. One possibility would be a tissue-specific mutation affecting insulin secretion, as has been suggested by studies on mice with specific knockout of β cell IGF1Rs (17, 18).

**Declaration of interest**

R G Rosenfeld has received payments for consulting or lectures from Tercica Inc. This potential conflict of interest has been received and managed by OHSU.

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**References**


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