Identification of a novel mutation disrupting the DNA binding activity of GCM2 in autosomal recessive familial isolated hypoparathyroidism

L Baumber, C Tufarelli, S Patel, P King, C A Johnson, E R Maher, R C Trembath

**Key points**

- Hypoparathyroidism is a heterogeneous group of disorders with both acquired and inherited causes, each presenting clinically with hypocalcaemia.
- Familial isolated hypoparathyroidism is characterised by hypocalcaemia and hyperphosphataemia and may be due to an inherited deficiency or the abnormal activity of parathyroid hormone (PTH).
- Mutations in FIH, familial isolated hypoparathyroidism-retardation-dysmorphism, and Kenny-Caffey syndrome. Accidental Fih disease causing mutations, which include two missense amino acid substitutions within the signal peptide from the prepro-PTH, followed by cleavage of the signal peptide from the prepro-PTH, which include two missense amino acid substitutions within the signal region of the prepro-PTH gene, leading to inefficient cleavage by signal peptidases.
- Heterozygous defects in the calcium sensing receptor (CASR) have been detected in autosomal dominant FIH and sporadic cases of hypoparathyroidism. All known CASR mutations in FIH lead to receptor activation. The CASR normally functions to provide a negative feedback loop, whereby binding of extracellular Ca2+ activates the receptor, resulting in decreased PTH secretion by parathyroid cells, and also through inhibition of calcium reabsorption in the renal distal tubule. Constitutive activation of this receptor therefore results in hypocalcaemia and hypercalciuria.

Notwithstanding these reports, the molecular genetic basis of most cases of autosomal recessive FIH remains unknown. Recently, a homozygous deletion within the human GCM2 (glial cells missing, Drosophila homologue B, previously referred to as GCM2) gene has been shown to underlie hypoparathyroidism in one patient, while other compelling evidence indicates a critical role for GCM2 in normal parathyroid gland function. Mutations studies revealed a novel homozygous missense mutation of the DNA binding domain of GCM2, functional analysis of which now provides an important tool for the further delineation of GCM2 bioactivity and molecular mechanisms necessary for parathyroid gland development.

**METHODS**

**Clinical data**

Subject IV:2 (fig 1), the second child of first cousin parents, was diagnosed as a neonate with primary hypoparathyroidism after presenting with convulsions. Her older sister had died in infancy following seizures and retrospectively was assumed to be similarly affected. The proband had no evidence of immunodeficiency, renal abnormalities, autoimmune disease, or dysmorphisms. Physical examination was unremarkable; in particular, she had no evidence of neuromuscular irritability. Renal, liver, and thyroid functions were unremarkable.

**Abbreviations:** CASR, calcium sensing receptor; EMSA, electrophoretic mobility shift assay; FIH, familial isolated hypoparathyroidism; PTH, parathyroid hormone
were all normal. Biochemical investigations confirmed hypocalcaemia with a calcium level of 1.98 mmol/l (normal range 2.13–2.58), phosphate 2.02 mmol/l (normal range, 1.30–2.20), and a low PTH level of 5 ng/l (normal range, 12–72), findings compatible with primary hypoparathyroidism. She was treated with alphacalcidol and subsequent growth and development were reported to be normal.

The unaffected sister of subject IV:2 married a first cousin and subsequently had two children (V:1 and V:2), both diagnosed clinically with primary hypoparathyroidism. Individual V:1 was a full term normal delivery, weighing 3.2 kg. She presented at 6 weeks of age with focal seizures involving the left arm and leg associated with left sided facial twitching. Laboratory investigation revealed hypocalcaemia at 1.35 mmol/l and hyperphosphataemia at 3.23 mmol/l. Alkaline phosphatase was markedly elevated at 1805 U/l (normal range, 76–196). Serum calcium levels were maintained by calcium and vitamin D supplementation. At presentation, magnesium was 0.69 mmol/l (normal range, 0.70–1.00), PTH level was less than 10 ng/l, and 25-hydroxy vitamin D level measured 11 nmol/l (normal range, 15.0–100.0). Chromosome analysis showed a normal female karyotype and FISH studies for the DiGeorge/velo-cardio-facial syndrome region on chromosome 22 showed no deletion.

Her younger sister (subject V:2) was a full term normal delivery weighing 2.75 kg. Because of the family history, she was screened for hypocalcaemia shortly after birth and initial serum calcium was 1.97 mmol/l. PTH level was at the lower end of the normal range (10 ng/l). She was also treated with vitamin D and calcium supplementation.

Informed consent was obtained from all subjects or their parents and the study was approved by the relevant local research ethics committees.

Molecular genetic analysis
Genomic DNA was extracted from 10 ml of peripheral blood by standard techniques. Autozygosity mapping was performed using fluorescently labelled microsatellite markers with an average heterozygosity of 75%. Markers for each locus are listed in table 1. PCR amplifications were achieved using MJ Research (Waltham, MA) DNA Engines (10 μl reactions; 50 ng DNA, 1.5 mM MgCl₂, 0.2 mM dNTPs (Pharmacia, St Albans, Hertfordshire), 0.3 μM primer, 0.5 U Taq polymerase (ABGene, Epsom, UK) in a 10×KCl PCR buffer). PCR products were electrophoresed through 6% polyacrylamide gels (FMC Bioproducts, Rockland, ME) on an ABI 377 DNA sequencer (Applied Biosystems, Foster City, CA) and analysed using GeneScan v3.0 and Genotyper v2.1 software (PE-ABI, Foster City, CA). Linkage to candidate loci

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Figure 1 (A) Pedigree structure of the family with genotyping showing linkage to the GCM2 locus. Transmission of the phenotype is compatible with an autosomal recessive mode of inheritance. Genotype data are shown for the region encompassing markers D6S940 to D6S1653, spanning a 4.6 Mb interval. (B) Sequence chromatogram illustrating the GCM2 R47L mutation. Affected individuals carry a homozygous G→T substitution at nucleotide 140 (indicated by an asterisk). Nucleotides are numbered according to the cDNA sequence, with the adenine of the initiation codon designated +1. (C) Segregation of the mutation was tracked through the family by Hha I digestion of PCR products. Mutation carriers are detected by the presence of a 246 bp band due to loss of an Hha I site. Gel lanes correspond to the individuals numbered in the pedigree (lane 1, normal control).
was examined under the assumption that FIH was segregating as an autosomal recessive trait due to homozygous mutation inherited common by descent.

**Mutation analysis of GCM2**

The complete protein coding region and intron/exon boundaries of the GCM2 gene were amplified from all available family members and one normal control individual by PCR in 40 µl reactions. Primer sequences for PCR products spanning the five coding exons are listed in Table 2. PCR products were separated by electrophoresis through 2% LE agarose (Cambrex, East Rutherford, NJ) to test the presence of sufficient quantities for sequence analysis, and were purified using the QiAquick PCR purification kit (Qiagen, Valencia, CA). Purified PCR products were sequenced, using the same forward primers as for the PCR reactions, with the Applied Biosystems BigDye terminator kit on an ABI 377 sequencer.

The mutation identified in family 1, at nucleotide position 140 in exon 2, abolished an HhaI restriction endonuclease recognition site. We therefore independently confirmed segregation of the variant within the family by restriction analysis with HhaI (New England Biolabs, Beverly, MA), and tested a panel of chromosomes from demographically matched control individuals. An 1198 bp fragment containing exons 2 and 3 was amplified by PCR under identical conditions as those described above, using primers GCM2ex2F and GCM2ex3R. Each PCR product was digested with 10 U enzyme at 37°C for 90 min. After digestion, the DNA fragments were separated on a 3% LE agarose gel and visualised with ethidium bromide.

**Preparation of GCM constructs**

Full length human GCM2 cDNA in pBluescript was kindly donated by A Giangrande. Using this plasmid as template, we next sequenced all five coding exons and intron/exon boundaries of the GCM2 gene. The finding of homozygosity in affected individuals displaying heterozygous genotypes for all markers across this region (data not shown), was considered compatible with linkage to GCM2 (fig 1A).

**Transfection and immunoblotting**

COS cells were maintained at 37°C and 5% CO₂ in Dulbecco’s modified Eagle’s medium (DMEM) supplemented with 10% fetal calf serum and antibiotics. Cells were seeded onto 10 cm dishes and transiently transfected with 8 µg of expression plasmid using FuGene 6 reagent (Roche Molecular Biochemicals, Indianapolis, IN) according to the manufacturer’s recommendation. COS cells were harvested after 48 h and total cell extracts were prepared as described. Protein concentrations were quantified using the Bio-Rad (Hercules, CA) protein assay. Samples were separated by SDS-PAGE (10% acrylamide), transferred to nitrocellulose membrane, and stained with Ponceau S to visualise protein bands.

**RESULTS**

**Autozygosity mapping**

All available family members were typed with polymorphic microsatellite markers spanning the PTH locus over a 4.3 Mb interval. There was no evidence of linkage to PTH, with affected individuals displaying heterozygous genotypes for all markers across this region (data not shown).

**Mutation analysis of GCM2**

We next sequenced all five coding exons and intron/exon boundaries of GCM2 for all available family members and identified a homozygous G to T transition at nucleotide position 140 (c.140G→T) in exon 2, present in all affected individuals. This substitution results in a change in the amino acid at codon 47, within the DNA binding domain of GCM2, from the normal arginine to leucine. All unaffected parents were heterozygous for this R47L missense mutation.

**Electrophoretic mobility shift assays**

Sequences of DNA probes containing consensus (wt) and mutant (m3) GCM recognition sites were as described in Schreiber et al. Double stranded probes were generated by annealing of complementary oligonucleotides and labelled with γ-dATP 32P using T4 polynucleotide kinase (New England Biolabs).

Electrophoretic mobility shift assays (EMSA) were performed as described using 5 µg whole cell extracts from transiently transfected COS cells. Protein samples were incubated with 0.5 ng of 32P-labelled double stranded probe for 30 min at room temperature. Samples were loaded onto native 4% polyacrylamide gels (Flowgen, Nottingham, UK) and electrophoresed in 0.5×TBE (45 mM Tris, 45 mM boric acid, 1 mM EDTA, pH 8.3) at 180 V, 4°C for 75 min.

**Table 1**

<table>
<thead>
<tr>
<th>Locus</th>
<th>Markers</th>
<th>Distance (Mb)</th>
<th>Heterozygosity</th>
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<td>PTH</td>
<td>D1S1315</td>
<td>12.7</td>
<td>0.54</td>
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<tr>
<td></td>
<td>D1S569</td>
<td>13.1</td>
<td>0.84</td>
</tr>
<tr>
<td></td>
<td>D1S1794</td>
<td>13.3</td>
<td>0.84</td>
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<tr>
<td></td>
<td>D1S861</td>
<td>14.4</td>
<td>0.70</td>
</tr>
<tr>
<td></td>
<td>D1S1981</td>
<td>17.0</td>
<td>0.83</td>
</tr>
<tr>
<td>GCM2</td>
<td>D6S940</td>
<td>9.9</td>
<td>0.66</td>
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<td></td>
<td>D6S470</td>
<td>10.1</td>
<td>0.80</td>
</tr>
<tr>
<td></td>
<td>D6S1721</td>
<td>12.8</td>
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</tr>
<tr>
<td></td>
<td>D6S1653</td>
<td>14.5</td>
<td>0.75</td>
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</tbody>
</table>

Individuals were also typed for polymorphic markers flanking the GCM2 gene. The finding of homozygosity in affected individuals for all or some of these markers was consistent with linkage to GCM2 (fig 1A).
six fragments. Figure 1B and C illustrates the R47L mutation identified and segregation of this mutation within the family. A cohort of 108 chromosomes from healthy unrelated Pakistani control subjects was screened for the presence of the mutation. All controls demonstrated a wildtype genotype, implying that the DNA variant is highly unlikely to represent a sequence polymorphism.

**Effect of R47L mutation on DNA binding ability of GCM2**

To assess whether the R47L amino acid substitution altered the DNA binding ability of the mutant GCM2 protein, we performed EMSA. Significant levels of expression of both wildtype and mutant GCM proteins following transfection were determined by means of western blotting. Normal levels of both proteins were detected in cell extracts subsequently used for EMSA experiments (fig 2C).

Using a 32P-labelled oligonucleotide containing the known DNA binding recognition site for GCM proteins, EMSA reactions were performed with extracts from COS cells transfected with full length wildtype GCM2 cDNA or full length GCM2 containing the R47L substitution. Cells transfected with empty vector (pCMV-Tag3B) were used as a negative control. Binding of GCM2 to the recognition site was readily detected for wildtype protein and was competed out with increasing amounts of unlabelled self-competitor probe, indicating the binding to be specific. Protein containing the R47L mutation was unable to bind to the GCM binding site, implying that substitution of leucine for arginine at this residue abolishes normal DNA binding ability of the GCM2 protein (fig 2D).

**DISCUSSION**

FIH is known to be a heterogeneous disorder with mutations in the PTH gene, encoding parathyroid hormone, being described in both autosomal dominant and autosomal recessive cases.\(^2\)\(^-\)\(^4\) PTH secretion is normally regulated by the G protein-coupled CASR, functioning as a negative feedback loop; heterozygous defects in the CASR gene resulting in constitutive receptor activation have also been detected in autosomal dominant FIH.\(^2\) In addition to these two genes described, there has been a single report of a mutation in the Drosophila giall cells missing (gcm) human homologue, GCM2, encoding a transcription factor implicated in parathyroid gland development.

In a highly consanguineous Pakistani family within which autosomal recessive FIH is segregating, we report a novel missense mutation of the GCM2 gene. This is only the second report of a mutation of the GCM2 gene, and the first to identify a critical domain of the GCM2 protein necessary for control of parathyroid tissue development. We used autozygosity mapping, initially to exclude linkage to a known gene causative of autosomal recessive FIH, namely the PTH locus. We next identified a region of homozgyosity extending over an interval of 180 kb, proximal to the GCM2 gene (fig 1A). Direct sequence analysis of all coding GCM2 exons showed all three affected individuals to be homozygous for an Arg47Leu amino acid substitution, the first missense mutation to be reported in this gene which encodes a transcription factor. Unaffected parents were heterozygous for the mutation, which co-segregated with the disease phenotype and was absent from normal controls, producing compelling evidence that this missense mutation represents the inherited basis of hypoparathyriodism in this kindred (fig 1B and C). The only previously reported mutation of the GCM2 gene in FIH is a large homozygous deletion of exons 1–4.\(^1\)\(^-\)\(^3\) The present study demonstrates that a missense mutation within the conserved DNA binding domain of GCM2 is sufficient to cause an FIH phenotype.

The substituted arginine residue is conserved amongst its mouse and Drosophila homologues, indicating a potentially important and functional role in GCM2 activity (fig 2A). Arginine residues are positively charged, polar amino acids, which play a significant role in structure. They are frequently involved in salt bridges, where they pair with negatively charged amino acids to form stable hydrogen bonds, important for protein stability.\(^9\) The replacement of arginine with the similarly positively charged lysine in the GCM1 isoforms provides further evidence of an important role for this amino acid residue within the GCM DNA binding domain. The affected individuals in our FIH kindred have a homozygous substitution of leucine for arginine at position 47. The amino acid leucine, in contrast to arginine residues, is aliphatic and hydrophobic, preferring to be situated within protein hydrophobic cores. In addition, this highly non-reactive amino acid favours a position within alpha helices, rather than in beta strands.\(^1\)\(^-\)\(^3\) Recently, Cohen et al.\(^1\) solved the crystal structure of the GCM domain-DNA complex, defining the amino acid residues that make contact with the DNA. The GCM domain exists as two beta sheet domains, which form a clamp, seizing the DNA from two sides of the major groove. The upper jaw of the clamp is formed by the beta sheet of the larger domain, with its strands orientated orthogonally to the DNA axis. Analysis of the predicted protein structure of GCM2 indicates that the arginine residue substituted in this hypoparathyroidism family is not involved directly in DNA binding (fig 2B). However, EMSA analysis has demonstrated abolition of DNA binding activity when the arginine to leucine mutation is introduced at amino acid position 47 (fig 2D). This residue lies in the large beta sheet domain, but is located on the outer surface of the protein, and does not contact the DNA substrate. Taken together, these data

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**Table 2** Primer sequences for GCM2 gene amplification

<table>
<thead>
<tr>
<th>Exon</th>
<th>Primer name</th>
<th>Primer sequence (5'→3')</th>
<th>Amplicon size (bp)</th>
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<td>1</td>
<td>GCM2ex1F</td>
<td>TAACCATTTGCCCAACCTTIC</td>
<td>361</td>
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<tr>
<td></td>
<td>GCM2ex1R</td>
<td>TCCGGACACCTTCAAGAAC</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>GCM2ex2F</td>
<td>TGCCATTGGGCTTTGGAC</td>
<td>498</td>
</tr>
<tr>
<td></td>
<td>GCM2ex2R</td>
<td>CACCGCTGAGTGACAGATG</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>GCM2ex3F</td>
<td>GAGTCCTCTGTCACCAATAATTTTGT</td>
<td>315</td>
</tr>
<tr>
<td></td>
<td>GCM2ex3R</td>
<td>GACCTGGGTGCTTTATTTTGG</td>
<td></td>
</tr>
<tr>
<td>4</td>
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<td>TACAGTGAAATACAAACCTTG</td>
<td>410</td>
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<tr>
<td></td>
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<td>TCAGATGGATACAAAACCTTG</td>
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</tr>
<tr>
<td>5</td>
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<td>GCM2ex5R</td>
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<tr>
<td></td>
<td>GCM2ex5bF</td>
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</tr>
<tr>
<td></td>
<td>GCM2ex5bR</td>
<td>CCTGAAATCAGGCCATGTT</td>
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</tbody>
</table>
Figure 2  (A) Sequence alignment of human (GCM1, GCM2), mouse (mGcm1, mGcm2), rat (rGcm1), and fly (dGCM, dGCM2) proteins in the DNA binding domain. Conserved amino acids are boxed; numbers indicate amino acid positions of human GCM2 protein. The arrow identifies the position of the R47L substitution. (B) Predicted structure of normal GCM2 protein backbone, with arginine residues highlighted in ball-and-stick format. The arrow identifies the predicted DNA binding region. Position of the native arginine residue at position 47, substituted for leucine in affected individuals, is indicated. (C) Western blot demonstrating expression of wildtype and mutant GCM2, indicated by the horizontal arrow. Size ladder is shown in kDa. (D) Electrophoretic mobility shift assay showing binding ability of normal and mutant proteins to radio labelled probe containing the GCM DNA binding site. Contents of lanes are indicated above the gel image. Competition assays were performed with 1-, 10-, 20-, and 50-fold molar excess of self and non-self competitors. The R47L mutation abolishes DNA binding ability of the GCM2 protein. Figure indicates DNA-protein complexes (C) and free probes (F).
suggest DNA binding activity of GCM2 may be dependent on complex formation with one or more additional proteins, and we hypothesise that disruption of this protein-protein interaction represents the molecular mechanism leading to FIH in this family.

Although the function of human GCM2 remains unknown, studies using mouse Gcm2 and Drosophila GCM2 provide some insight into the expression patterns and transcriptional activity of this protein. In Drosophila, GCM proteins are transiently expressed in glial precursors and act as a binary switch between neuronal and glial cell determination.22-24 From sequence homology, indicating a potential conservation of function, mammalian GCM proteins may be expected to be involved in gliogenesis.25 However, expression studies have shown murine Gcm1 and Gcm2 to be expressed in trophoblast cells during placentation and in developing parathyroid glands, respectively.16,17 Despite containing two separate transactivation domains, Gcm2 is a poor transcriptional activator when compared to Gcm1, and is unable to initiate the neuron-glia transformation when expressed as a transgene in the developing nervous system of Drosophila.22,24 Targeted deletion of the mouse Gcm2 gene results in absence of parathyroid glands and undetectable PTH expression in the thyroid and neck of homozygous mice.17 These mice develop hypoparathyroidism but with normal serum PTH levels, insufficient to correct the hypocalcaemia. This compensatory PTH is synthesised in the thymus, where PTH positive cells are shown to express Gcm1 and Casr.17 Of interest, affected members in the family we investigated each had detectable but sub-normal levels of circulating PTH.

In summary, the present study reinforces the critical role of GCM2 activity in human parathyroid gland development through molecular analysis of an autosomal recessive FIH family. Detailed characterisation of GCM2 mutations associated with FIH is warranted and will likely provide insight into the molecular pathways necessary for PTH secreting cells. These findings have more immediate relevance for the diagnosis and management of families presenting with isolated hypoparathyroidism.

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Competing interests: none declared

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