Presence and significance of a R110W mutation in the DNA-binding domain of GCM2 gene in patients with isolated hypoparathyroidism and their family members

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Abstract

Objective: Glial cells missing 2 (GCM2) gene encodes a parathyroid-specific transcription factor. We assessed GCM2 gene sequence in patients with isolated hypoparathyroidism (IH).

Design: Case–control study.

Methods: Complete DNA sequencing of the GCM2 gene including its exons, promoter, and 5’ and 3’ UTRs was performed in 24/101 patients with IH. PCR–restriction fragment length polymorphism was used to detect a novel R110W mutation in all 101 IH patients and 655 healthy controls. Significance of the mutation was assessed by electrophoretic mobility shift assay (EMSA) and nuclear localization on transfection.

Results: A heterozygous R110W mutation was present in DNA-binding domain in 11/101 patients (10.9%) and absent in 655 controls ($P < 10^{-7}$). Four of 13 nonaffected first-degree relatives for five of these index cases had R110W mutation. Four heterozygous single nucleotide polymorphisms were found in the 5’ region. One of the 11 patients with R110W also had T370M change in compound heterozygous form. Mutant R110W and T370M GCM2 proteins showed decreased binding with GCM recognition elements on EMSA indicating loss of function. Both wild-type and R110W mutant GCM2 proteins showed nuclear localization.

Conclusions: The present study indicates a significant association of R110W variant with IH. Absence of effect of heterozygous R110W mutation on DNA binding and presence of the same mutation in asymptomatic family members indicate that additional genetic (akin to T370M change) or nongenetic factors might contribute to the expression of diseases in IH. Alternatively, it is possible that association of R110W with IH could be due to linkage disequilibrium with the unidentified relevant genes in IH.

Introduction

Hypoparathyroidism is a heterogeneous group of disorders characterized by tetany, cataract, basal ganglia calcification, hypocalcemia, hyperphosphatemia, and subnormal serum parathyroid hormone (PTH) (1–12). Recently, Dolores Shoback has classified its pathophysiologic mechanisms into three broad categories (13). These include i) destruction of parathyroid gland due to iatrogenic causes, metastasis, heavy metal infiltration, and organ-specific autoimmunity occurring in isolation or as part of autoimmune polyendocrine syndrome type 1 (APS-1); ii) impairment of PTH secretion as seen in hyper- and hypomagnesemia, activated mutations of the calcium-sensing receptor (CaSR), or nondestructive activating CaSR autoantibodies; and iii) disorders (familial or sporadic) due to mutations of genes such as PTH, glial cells missing 2 (GCM2), HDR syndromes (GATA3), autoimmune regulator in APS-1, tubulin cofactor E in Kenny-Caffey and Sanjad–Sakati syndrome, 22q11.2 TBX-1 (DiGeorge syndrome), and mitochondrial gene defects in Kearn–Sayre syndrome (13).

Patients with isolated hypoparathyroidism (IH) also referred to as acquired or idiopathic hypoparathyroidism demonstrate the presence of CaSR autoantibodies with prevalence varying from 29 to 56% (10–12). However, they do not demonstrate increased risk of coexisting thyroid autoimmunity unlike in type-1 diabetes and premature ovarian failure (14). These facts along with reports of de novo mutations in the CaSR and PTH genes in a subset of IH indicate that later is a cluster of heterogeneous group of disorder (15–17). In our previous studies, the PTH and CaSR genes were
sequenced in 49 and 33 patients with IH respectively (18, 19). PTH gene and its 3′ UTR were normal in all (18) and only one had a heterozygous Val621Met mutation in exon 7 of the CaSR gene (19). The latter was considered benign because the same mutation was also present in her asymptomatic mother and brother. Besides, there was no increased prevalence of autoimmunity-related single nucleotide polymorphisms (SNPs) in the CTLA-4 and PTPN22 genes in our earlier studies in patients with IH (20, 21).

Recently, familial hypoparathyroidism has also been linked with mutations of GCM gene (22–27). The GCM gene encodes a glial cells-specific transcription factor in Drosophila (28) and its mammalian homologs, i.e. gcm1 and gcm2 (mouse) and GCM1 and GCM2 (humans) encode transcription factors necessary for the development of placenta and parathyroid glands in the fetus and adults respectively (29–31). The GCM2 gene located on chromosome 6p23–24 encodes a 506 amino acids protein with DNA-binding domain from 21 to 174 amino acids, and its response elements have been described in the CaSR gene (25, 27, 32).

Although there are six reports of GCM2 gene analysis in patients with familial hypoparathyroidism, only two included a total of 20 patients with IH (22, 25). GCM2 gene sequence was normal in them (22, 25). We report GCM2 gene sequence analysis in a large cohort of patients with IH (14, 18–21) and report occurrence of a new R110W mutation and its functional significance.

Materials and methods

Patients

The study included 101 patients with IH attending the endocrine and metabolic clinics of All India Institute of Medical Sciences, Delhi, during 1998–2008 (14, 18–21). The criteria used to diagnose IH included the presence of hypocalcemia, hyperphosphatemia, and an appropriately normal or subnormal level of serum-intact PTH (iPTH), normal renal function, and serum magnesium (2). Patients with post-surgical hypoparathyroidism were excluded. There was one sibling pair (brothers) in study cohort. None of the patients had clinical features of type 1 APS. Autoimmune adrenal involvement was excluded by demonstrating normal serum cortisol and plasma ACTH and the absence of adrenal cortical autoantibodies by indirect immunofluorescence (33). Serum ferritin levels measured to rule out hemochromatosis were normal in all (34).

Number of patients studied for complete GCM2 gene sequencing (n = 24) The group of 101 patients with IH was arranged in ascending order of age. The first and last 12 patients (17 males) were selected for complete sequencing of the GCM2 gene, which included all its five exons, intron–exon boundaries, and 5′ and 3′ UTRs. The 5′ upstream sequence up to −652 position from translation start site ATG included 5′ UTR of exon 1, promoter sequence, and binding sites for PAX1 and PAX9 transcription factors (25).

Following detection of a new mutation (R110W) in exon 2, PCR–restriction fragment length polymorphism (RFLP) analysis was performed in all the 101 patients. To determine the prevalence of SNPs in the 5′ UTR, DNA sequencing of this region was undertaken in all the remaining 77 patients with IH. The P1 and P2 promoter regions of the CaSR gene (−606 to −323 and −300 to −90 from transcription start site at +1, accession number AF116081–82) were also sequenced in all the 11 patients with R110W mutation, and in 10 IH patients without R110W mutation for analysis of GCM response elements in these promoters (−451 to −441 relative to transcription start site at +1 in P1 and −166 to −156 in P2) (27). Complete sequencing of all the GCM2 exons was performed in eight additional patients detected to have R110W mutation on PCR–RFLP analysis.

Controls

The controls included 655 apparently healthy North Indian volunteers including school teachers, students, and other staff who were previously enrolled for the assessment of vitamin D deficiency, thyroid autoimmunity, and relationship of vitamin D receptor (VDR) polymorphisms with bone mineral density (35). All the controls had normal serum total calcium and inorganic phosphorus values. None of them had subnormal serum iPTH levels (35). Identification and genotyping of R110W mutation were performed by PCR–RFLP analysis in all the 655 controls. DNA sequencing of the 5′ UTR of GCM2 and the P1 and P2 promoters of the CaSR gene was performed in a limited number of controls (n = 53 and 10 respectively).

The local institutional ethics committee approved the study protocol including genotyping among the control group. Written consent was obtained from all the study subjects.

Relatives

Thirteen nonaffected first-degree family members of 5 of the 11 index patients with R110W mutation (Fig. 1) could be investigated for clinical and biochemical features of hypoparathyroidism. Sequencing of exon 2 of the GCM2 gene and its 5′ and 3′ UTRs was performed in all the relatives. Complete sequencing of the GCM2 gene and promoters of the CaSR gene was also performed in four relatives detected to have R110W mutation.
Methods

DNA sequence analysis Genomic DNA was extracted from the peripheral leukocytes (19). The first seven pairs of primers used to amplify GCM2 gene (Table 1) were the same as used by Thomeé et al. (24), and their sequences and conditions for amplification were provided to us by one of the authors (Dr Abramowicz) on request. The primers used to amplify 3' and 5' UTRs of the GCM2 gene and P1 and P2 promoter regions of CaSR gene were designed using software (biotools.umassmed.edu/bioapps/primer3_www.cgi). All the PCR were carried out in 40 μl reaction volume using 100 ng genomic DNA (GenAmp 9700, Applied Biosystems, Foster City, CA, USA), and the amplified fragments were then excised from the agarose gel, purified (Qiaex II gel extraction kit Qiagen Inc.), and directly sequenced by Big Dye v3.1 cycle sequencing chemistry on the ABI PRISM 310 Genetic Analyzer (Applied Biosystems). The nucleotide sequences were compared with the published sequence of human GCM2 gene (GenBank accession no. NT_007592) using Blastn algorithm (http://www.ncbi.nlm.nih.gov) and also deposited in the GenBank databases (accession no. FJ655842–49).

PCR–RFLP analysis The presence of C–T substitution at nucleotide 4711 in exon 2 (GenBank accession no. NC_000006) created a restriction site for HinflII enzyme (Fig. 2a). For the RFLP analysis, a 153 bp DNA fragment of exon 2 containing R110W mutation was amplified using forward (5'-gcaacaccaaccaacact-3') and reverse (5'-ttgcttcttttctctttgt-3') primers, and then digested with HinflII restriction enzyme. The digestion fragments were then separated using 3% agarose gel electrophoresis.

Figure 1 Pedigrees of 5 of the 11 index patients with R110W mutation whose 13 nonaffected first-degree family members were studied. The nucleotides (numbered from translation initiation site) observed at five variable sites in the GCM2 gene sequence are shown in rectangular box (from above to below). The possible alleles at these position were: —252 G/T, —248 G/C, —149 G/A, —44 T/C, and C/T substitution at nucleotide 4711 in exon 2 leading to R110W mutation in codon 110. The nucleotide positions are according to GenBank accession no. NC_000006.
Table 1 Primer sequences used to amplify various regions of the GCM2 gene, two promoters of the CaSR gene (P1 and P2), and for the PCR–restriction fragment length polymorphism (RFLP) analysis of R110W mutation.

<table>
<thead>
<tr>
<th>Serial no.</th>
<th>Site</th>
<th>Sense primer</th>
<th>Antisense primer</th>
<th>Annealing temperature and time</th>
<th>Amplicon (bp)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1*</td>
<td>Exon 1</td>
<td>5'-tcataacattgtccccag-3'</td>
<td>5'-tgtatgttcgtccga-3'</td>
<td>55 °C, 1 min</td>
<td>376</td>
</tr>
<tr>
<td>2*</td>
<td>Exon 2</td>
<td>5'-tgtagattgtgcattg-3'</td>
<td>5'-gagtagttgggaacagc-3'</td>
<td>55 °C, 1 min</td>
<td>516</td>
</tr>
<tr>
<td>3*</td>
<td>Exon 3</td>
<td>5'-ccgagcagttgtttt-3'</td>
<td>5'-tgaagctgtatgg-3'</td>
<td>55 °C, 1 min</td>
<td>292</td>
</tr>
<tr>
<td>4*</td>
<td>Exon 4</td>
<td>5'-actagttgggaagcga-3'</td>
<td>5'-tgatgttgatg-3'</td>
<td>52 °C, 1 min</td>
<td>410</td>
</tr>
<tr>
<td>5*</td>
<td>Exon 5a</td>
<td>5'-ttgctattggtggtg-3'</td>
<td>5'-cagttgaacgacagt-3'</td>
<td>53 °C, 1 min</td>
<td>553</td>
</tr>
<tr>
<td>6*</td>
<td>Exon 5b</td>
<td>5'-ttaacgcttgaaggg-3'</td>
<td>5'-gcttttacagttgag-3'</td>
<td>53 °C, 1 min</td>
<td>502</td>
</tr>
<tr>
<td>7a</td>
<td>Exon 5c</td>
<td>5'-atactagttggtcag-3'</td>
<td>5'-aagagttgaacctccag-3'</td>
<td>56 °C, 1 min</td>
<td>422</td>
</tr>
<tr>
<td>8</td>
<td>5' UTR</td>
<td>5'-ccggccagatgcagttg-3'</td>
<td>5'-tgtcttcacccgagca-3'</td>
<td>60 °C, 30 s</td>
<td>506</td>
</tr>
<tr>
<td>9</td>
<td>5' UTR</td>
<td>5'-ccctgttccctgagttg-3'</td>
<td>5'-gatgtgcatccttggagccag-3'</td>
<td>60 °C, 30 s</td>
<td>435</td>
</tr>
<tr>
<td>10</td>
<td>3' UTR</td>
<td>5'-gcatgtgtacaacagccagga-3'</td>
<td>5'-gccagctctggatgg-3'</td>
<td>60 °C, 30 s</td>
<td>374</td>
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<td>11</td>
<td>2' UTR</td>
<td>5'-caactctctggtgatgctcaaa-3'</td>
<td>5'-gaagcttttaatgtgactg-3'</td>
<td>60 °C, 30 s</td>
<td>407</td>
</tr>
<tr>
<td>12</td>
<td>R110W RFLP</td>
<td>5'-gacaaacccacacacacacact-3'</td>
<td>5'-tggtctgcctgcctg-3'</td>
<td>55 °C, 30 s</td>
<td>153</td>
</tr>
</tbody>
</table>

For all PCR reactions: initial denaturation at 94 °C for 6 min followed by 40 cycles of denaturation at 94 °C for 30 s, annealing as shown in table, extension at 72 °C for 30 s, and final extension at 72 °C for 7 min.

*Primers nos 1–7 have been described earlier by Thomeé et al. (Ref. (24)).

Assessment of intragenic deletion in GCM2 allele in subjects with R110W mutation

To assess the possibility of intragenic deletion within the other GCM2 allele in 11 patients with heterozygous R110W mutation, an 8.09 kb fragment of the GCM2 gene incorporating all the five exons and four intervening introns was amplified by long PCR enzyme mix (Cat no. K0181, Fermentas, Lithuania) and primers 5'-tcataacattgtccccag-3' and 5'-acaaggtgaatctcc-3'. Conditions for PCR amplification were: initial denaturation at 94 °C for 3 min, followed by 22 cycles of denaturation at 94 °C for 20 s, annealing at 55 °C for 30 s, extension at 68 °C for 7 min, and final extension at 68 °C for 10 min. The contribution of both the alleles in the 8.09 kb PCR product was confirmed by performing a RFLP analysis for R110W mutation in the 153 bp product amplified using the 8.09 kb product as the template.

Cloning, expression, and purification of wild-type and mutant GCM2 proteins

Preparation of wild-type GCM2 clone A wild-type cDNA encoding full-length GCM2 protein was prepared from the RNA extracted from parathyroid adenoma tissue obtained after informed consent from a patient undergoing parathyroidectomy using the RNA-binding columns (Eppendorf AG-22331, Hamburg, Germany). The first strand of cDNA was synthesized using the random hexamers and M-MuLV RT (RevertAidH Minus, Fermentas). The sense (5'-agcgcgctgtacgccgACccagttc-3') and antisense (5'-tcctgctctgcgctttggca-3') primers were used to prepare double-stranded cDNA. The Sall and Xhol restriction sites (underlined) in the two primers were created by changing the normal nucleotide sequence (in capitals) of the GCM2 cDNA (GenBank accession no. NM_004752). The PCR conditions for preparing double-stranded GCM2 cDNA were: 50 μl reaction volume; 5 μl single-stranded cDNA template; 1 mM MgSO4; 0.3 μM of each of the primers; 0.3 mM dNTPs and 2.5 units of high-fidelity proof reading DNA polymerase enzyme (platinum pfx); initial denaturation at 94 °C for 7 min, followed by 40 cycles of denaturation at 94 °C for 1 min, annealing at 65 °C for 1 min, extension at 68 °C for 90 s, and final extension at 68 °C for 15 min. The 1593 bp GCM2 cDNA product was gel purified (Qiagen Inc.). The plasmid expression vector pPROEX HTc (Invitrogen Corp.) with sequence 6× histidine (His6) residues proximal to Sall restriction site was used to facilitate affinity purification of the recombinant protein. The expression vector pPROEX HTc and GCM2 cDNA insert were cut with the Sall and Xhol restriction enzymes and then digested using 2.5 units of T4 DNA ligase (Fermentas) in 3:1 ratio (V/V) at 22 °C for 6 h. The ligated product was used to transform Escherichia coli (DH5α) by heat shock method at 42 °C for 90 s (36). The recombinants were screened by colony PCR using primers 5'-agcgctgtacgccgACccagttc-3' and 5'-agcgcgctgtacgccgACccagttc-3'. Sequence of the GCM2 insert in positive clone was checked by DNA sequencing.
Preparation of GCM2 clone containing R110W mutation and protein expression

A C–T transition at nucleotide 4711 position (GenBank accession no. NC_000006) was made, to create R110W mutation, using 5'-ctgcgaaccatatgctgtgcag-3' primers (nucleotides changed are in capitals) and the wild-GCM2-pPROEX HTc using quick change site-directed mutagenesis kit (Stratagene, La Jolla, CA, USA). The presence of mutated cDNA was confirmed by sequencing. The plasmids with wild-type or mutated GCM2 cDNA inserts were then transformed into E. coli C43 (DE3) strains. Cells were then grown in two 500 ml flasks, and protein expression was induced with isopropylthiogalactoside (0.6 mM) and culture grown for 20 h at 30°C. The recombinant proteins were purified by affinity chromatography under nondenaturing conditions from the soluble fraction of E. coli using the Ni-NTA agarose column (Qiagen Inc.), and identity of the protein was checked by western blot (Fig. 3) using anti-GCM2 antibody (Santa Cruz Biotechnology, Inc., Santa Cruz, CA, USA).

Functional analysis of R110W mutation

Electrophoretic mobility shift assay

Electrophoretic mobility shift assay (EMSA) was performed to assess the DNA-binding ability of the wild-type GCM2 protein and its R110W mutant (Fig. 4) using biotin-labeled DNA probes (5'-gatccggattcgggtgca-3' and complementary) containing GCM2 recognition element (underlined) (37). The 3' end of the oligonucleotides were labeled with biotin using a commercial kit (Thermo Scientific, Rockford, IL, USA) and then annealed at 42°C for 1 h.

The EMSA reactions were carried out by incubating 1.4 ng DNA probes with varying concentrations of wild-type (2.5 and 5 µg) or mutant (2.5, 5.0, and 10 µg) GCM2 protein on ice for 30 min in a 20 µl reaction mixture. The mixture contained 10 mM HEPES (pH 8.0), 5% glycerol, 50 mM NaCl, 5 mM MgCl2, 2 mM dithiothreitol, 0.1 mM EDTA, 1 µg BSA, and 1 µg poly(dI−dC). The mixture was loaded on 4% native PAGE in 0.5× TBE buffer, transferred to a positively charged nylon membrane (Hybond N+, Amersham Biosciences) at 390 mA for 45 min, and cross-linked using u.v. cross linker at 120 mJ/cm² for 1 min (Amersham Biosciences). DNA probe and its shift were detected using streptavidin–HRP conjugate and chemiluminescent luminol (Thermo Scientific) and X-ray films. Specificity of the shift in the EMSA was confirmed by competition with unlabeled DNA probe (Fig. 4).

Presence and significance of a R110W mutation

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Figure 2 (a) Electropherogram of exon 2 region of GCM2 gene from a patient with IH showing the presence of C–T transition (upper arrow, R110W mutation) leading to a new site for restriction (Hin1II (box CATG)). Normal electropherogram of the same region is shown below (down arrow). (b) PCR–RFLP analysis of R110W mutation after overnight digestion of 153 bp amplicon with 5 units of Hin1II restriction enzyme using 2.5% agarose gel electrophoresis. Patients with C/T genotype showed the presence of three bands 153, 130, and 23 bp (last could not be visualized) (lanes 1 and 2). Subjects with the normal CC genotype (lanes 3 and 4) showed an intact band of 153 bp. A 100 bp DNA ladder is in lane 5. (c) Absence of intragenic deletion of GCM2 alleles in patients and their relatives with R110W mutation. A single band of 8.09 kb amplified from GCM2 gene including exon 1–5 with intervening introns in subjects with R110W mutation (lanes 2–11, patients with IH; lanes 12–15, relatives of IH with R110W, lanes 16 and 17, healthy controls). (d) Corresponding lanes of (c) showing heterozygous nature of the 8.09 product as revealed by the RFLP analysis of R110W mutation on the 153 bp product amplified using the 8.09 kb product. RFLP analysis for R110W was performed as shown in (b).

Preparation of GCM2 clone containing R110W mutation and protein expression

A C–T transition at nucleotide 4711 position (GenBank accession no. NC_000006) was made, to create R110W mutation, using 5'-ctgcgaaccatatgctgtgcag-3' and its complementary 5'-gctgtttcagccattgccttgtcgcag-3' primers (nucleotides changed are in capitals) and the wild-GCM2-pPROEX HTc using quick change site-directed mutagenesis kit (Stratagene, La Jolla, CA, USA). The presence of mutated cDNA was confirmed by sequencing. The plasmids with wild-type or mutated GCM2 cDNA inserts were then transformed into E. coli C43 (DE3) strains. Cells were then grown in two 500 ml flasks, and protein expression was induced with isopropylthiogalactoside (0.6 mM) and culture grown for 20 h at 30°C. The recombinant proteins were purified by affinity chromatography under nondenaturing conditions from the soluble fraction of E. coli using the Ni-NTA agarose column (Qiagen Inc.), and identity of the protein was checked by western blot (Fig. 3) using anti-GCM2 antibody (Santa Cruz Biotechnology, Inc., Santa Cruz, CA, USA).

Figure 3 Immunoblot analysis showing 61 kDa histidine-tagged wild-type (lane 2, 10 µg protein) and R110W mutant GCM2 proteins (lane 3, 10 µg protein) expressed in E. coli. Staining was performed with anti-GCM2 antibody in 1:500 dilutions. Lane 1 contains molecular weight marker.
checked by i) competition assay using a 100-fold excess of unlabeled DNA probe and ii) super shift of the DNA–GCM2 protein complex with anti-histidine tag antibody (positive control) and an unrelated antibody (negative control) i.e. VDR MAB (Catalog no. V2130X, US Biologicals, Swampscott, MA, USA). For the demonstration of super shift, DNA probe–GCM2 protein (2.5 μg) was incubated with 1 μg anti-histidine tag or anti-VDR antibody for 30 min at 4 °C.

EMSA reaction was also carried out using biotin-labeled DNA probes containing GCM recognition sequence (underlined) present in the P1 (5'-gtgctggctgaggaggtcctcagcgacctg-3') and P2 (5'-aagagccgctcagtacagcccg-3') promoters of the CaSR gene (27).

Transfections to assess the subcellular localization of R110W mutant pcDNA3.1(+) expression vector (Invitrogen Corp.) with full-length wild-type or mutant
GCM2 cDNA inserts (pcDNA–GCM2) was constructed to assess nuclear translocation of the wild and mutant GCM2 protein in HeLa cells. The wild-type and mutant double-stranded GCM2 cDNA inserts were prepared as described above in the construction of GCM2 cDNA used for the EMSA except the forward primer (5'-ctatttttcGgaTcctggcggaaage-3'), which resulted in the amplification of cDNA containing 35 nucleotides proximal to translational initiation site to incorporate minimal Kozak sequence. The restriction site in the forward primer was BamH1 (underlined) and the changed nucleotides are in capital. Cells were transfected using TransFast reagent (Promega) as per the manufacturer’s protocol.

**Immunofluorescence** HeLa cells maintained in DMEM with 10% FCS were seeded on cover slips in six-well plates (10^5 cells/well) and grown to 70–80% of confluence and transfected with 2 μg wild or mutant pcDNA–GCM2 vector per well. After 36 h of transfection, cells attached to the cover slips were rinsed with PBS (pH 7.4), fixed with 4% paraformaldehyde for 15 min, and then washed three times (5 min each) with PBS containing 100 mmol glycine. Cells were permeabilized with 0.1% Triton X-100 in PBS for 4 min, washed three times (5 min each) with PBS (pH 7.4), blocked with 5% BSA for 30 min, and then incubated with anti-GCM2 antibody raised in goats (1:400 dilution in 1% BSA; Santa Cruz Biotechnology, Inc.) for 1 h at room temperature. This was followed by three washings of 5 min each with PBS and 30 min incubation with rabbit anti-goat IgG–FITC conjugate (1:150 dilution, Bangalore Genei P. Ltd., Bangalore, India). After three washings with PBS of 5 min each, cover slips were counterstained with 2 ml Hoechst dye (10 μg/ml) for localization of the nucleus for 20 min, rinsed with PBS, and then mounted on glass slides using 90% glycerol in bicarbonate buffer and antifade para-phenylenediamine (0.1%). Slides were scanned using a fluorescent microscope (ECLIPSE 80i, Nikon Instruments Inc., NY, USA), and the Hoechst and FITC signals were merged using a software NIS-Elements version 2.2 (Nikon Instruments Inc., Melville, NY, USA; Fig. 6). The negative controls included i) HeLa cells transfected with pcDNA vector without GCM2 insert and stained as above and ii) untransfected HeLa stained only with rabbit anti-goat IgG–FITC conjugate with no prior GCM2 antibody staining.

**Structure of mutant GCM2 protein by construction of three-dimensional homology modeling**

To study the effect of R110W mutation, the structure of mutant protein was compared with that of wild-type protein. Homology modeling of the DNA-binding domain of wild-type and mutant human GCM2 proteins was based on the X-ray crystal structure of the murine DNA-binding domain of GCM1 protein complexed with octameric DNA (PDB id: 1ODH) (38). Murine and human species have a sequence identity of 69% in the region (residues 19–173). The three-dimensional model for the native and mutant R110W structures was constructed using the Modeller 8.2 module (39) of Discovery Studio 1.7 (http://accelrys.com). The position of the two zinc ions present in the template was retained in both the modeled structures. The complex structure was generated by assuming that the interface for GCM–DNA interaction was similar to that in mouse. Several models were built for wild and mutant GCM2 protein and subjected to energy minimization. The model with the most favorable energy constraint was selected in each case. Molecular dynamics simulation with the standard dynamics cascade protocol was also carried out for the mutant protein. The final structures were evaluated for their stereochemical quality using the program PROCHECK (40).

**Biochemical estimation**

The serum total calcium, phosphorus, alkaline phosphatase, urine calcium, and magnesium levels were measured using standard procedure in our laboratory (41). The intact iPTH was measured using a commercial kit using an IRMA (DiaSorin, Inc., Stillwater, MN, USA), minimum detection amount 0.7 ng/l, normal range, 13–54 ng/l till 2006, and then afterwards by electrochemiluminescence immunoassay kits autoanalyzer (Elecys-2010, Roche Diagnostics, normal range, 1.6–6.9 pmol/l).

**Statistical analysis**

The difference in the frequency of various alleles in patients and controls was analyzed using Fisher’s exact test and is shown in Table 2. The differences in the clinical and biochemical characteristics of the patients with and without R110W mutation were analyzed using Student’s ‘t’-test, and data are shown as mean ± s.d. in Table 3. The haplotype analysis using four SNPs, i.e. −252 G/T, −248 G/C, −149 G/A, and −44 T/C was performed using the SHEsis software program (http://analysis.bio-x.cn/myAnalysis.php). The P value <0.05 was considered significant.

**Results**

**DNA sequencing of the GCM2 gene in 24 patients with IH**

DNA sequencing of 24 patients with IH revealed the presence of five different types of single nucleotide substitutions in the GCM2 gene (Table 2). Four of
these five substitutions were in region 5' upstream to the translation initiation site and one was in exon 2.

Three of the four substitutions in the 5' upstream region were in the 5' UTR and included G–C transition at −248 (n=4), G–A transition at −149 (n=3), and T–C transition at −44 (n=1) position. In addition, there was a G–T transversion at −252 position (n=1). One patient with T–C transition at −44 also had a G–A transition at −149 position.

The C–T transition (Fig. 2a) observed in the exon 2 led to the change in CGG–TGG (n=3) at codon 110 and therefore a change from arginine to tryptophan (R110W). The nucleotide sequence in the 3' UTR was normal in all the 24 subjects.

Table 3 Clinical and biochemical characteristics at presentation in patients with isolated hypoparathyroidism who did not show R110W mutation in comparison to 11 patients who showed mutation.

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Mutation absent (n=90)</th>
<th>Mutation present (n=11)</th>
<th>P value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Male/female</td>
<td>49/41</td>
<td>6/5</td>
<td>0.75</td>
</tr>
<tr>
<td>BMI (kg/m²)</td>
<td>20.2±4.3</td>
<td>24.5±5.5</td>
<td>&lt;0.01</td>
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<tr>
<td>Age at presentation of symptoms (year)</td>
<td>24.2±13.7</td>
<td>32.0±16.6</td>
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<tr>
<td>Age at presentation to the hospital (year)</td>
<td>31.4±13.9</td>
<td>40.4±15.7</td>
<td>0.05</td>
</tr>
<tr>
<td>Serum total calcium (mmol/l)</td>
<td>1.38±0.28</td>
<td>1.28±0.2</td>
<td>0.67</td>
</tr>
<tr>
<td>Serum PO₄ (mmol/l)</td>
<td>2.23±0.42</td>
<td>2.06±0.29</td>
<td>0.21</td>
</tr>
<tr>
<td>Serum iPTH (pmol/l)</td>
<td>0.69±0.82</td>
<td>1.23±1.97</td>
<td>0.41</td>
</tr>
<tr>
<td>Frequency of basal ganglia calcification (%)</td>
<td>62/84 (73.8%)</td>
<td>8/11 (72.7%)</td>
<td>0.60</td>
</tr>
<tr>
<td>Cataract (%)</td>
<td>46/84 (54.80%)</td>
<td>6/10 (60.0%)</td>
<td>0.49</td>
</tr>
</tbody>
</table>

Data are shown as mean±s.d. Normal range for serum calcium (Ca) = 2.12–2.59 mmol/l; inorganic phosphorus (PO₄) = 0.81–1.45 mmol/l; intact parathyroid hormone (iPTH) = 1.6–6.8 pmol/l; ionized calcium (iCa) = 1.10–1.38 mmol/l.
mutation using 8.09 kb product as template for PCR. As expected, all the patients with hypoparathyroidism and relatives were heterozygous for the R110W change indicating the presence of normal and mutant alleles in the 8.09 kb product.

The presence of T370M was confirmed by RFLP analysis in a patient who showed both R110W and T370M changes by amplifying a 502 bp product incorporating T370M variation. The product was amplified using primer pair no. 6 (Table 1). RFLP analysis was performed using 10% PAGE after digestion of 502 bp product with 5 units of HinIII enzyme (Fig. 5a). None of the other 100 patients with IH and 117 healthy controls assessed for T370M variation showed this change. To differentiate compound heterozygous mutation versus the presence of two mutations in the single allele in the lone patient with IH who had both R110W and T370M changes, a simple allele discriminating PCR assay was performed as described by Bui & Liu (42) to study the origin of mutations in the GCM2 alleles. Briefly, a 3.01 kb fragment of the GCM2 gene including nucleotides corresponding to R110W change in exon 2 and T370M change in exon 5 and all intervening introns was amplified using two alleles-specific forward primers and a common reverse primer (Table 1, exon 5b antisense). The 5'-ccatctgcaagc T C -3' amplified wild-type allele and 5'-ccatctgcaagc T T -3' amplified R110W allele. Subsequently, using internal primers (Table 1, pair no. 6), a second PCR was performed using wild and mutant 3.01 kb DNA product as template to amplify a 502 bp fragment, which included the nucleotides corresponding to the T370M change. The presence of T370M change in the wild-type and R110W alleles was checked by RFLP in the 502 bp products. The T370M change was observed in the 502 bp PCR product obtained from the wild allele but not from R110W mutant allele indicating compound heterozygous nature of the mutations (Fig. 5b & c).

Prevalence of various SNPs in 5' upstream region in IH and healthy controls

To determine the prevalence of various SNPs in the 5’ upstream region, DNA sequencing was performed instead of PCR–RFLP because two of the four SNPs, i.e. −44 T/C and −252 G/T did not create any site for restriction enzyme. Moreover, all these substitutions were within a span of 250 nucleotides that could be sequenced by a single set of primer. The frequency of various SNPs in the 5’ upstream region was not significantly different between patients and the controls (−248 G/C, 22 (21.8%) versus 8 (15.1%), P = 0.43; −149 G/A, 5 (5.0%) versus 5 (9.4%), P = 0.31; −44 T/C, 2 (1.9%) versus 4 (7.5%), P = 0.2). The −252 G/T change was not observed in any of the control subjects.
Haplotype analysis using four SNPs in the 5' UTR region of GCM2 gene

Haplotypes were constructed using four SNPs, i.e. −252 G/T, −248 G/C, −149 G/A, and −44 T/C of the GCM2 gene. GGGT was the most common haplotype observed in patients with (n = 11) and without (n = 10) R110W mutation, their 13 relatives, and 10 healthy controls.

Presence of R110W mutation and SNPs in the 5' UTR in first-degree relatives

Four of the 13 family members (Fig. 1) had heterozygous R110W mutation. On DNA sequencing of all the coding exons in these four relatives, there was no other sequence variation observed. However, all these family members were clinically asymptomatic and had normal serum total calcium, inorganic phosphorus, and serum iPTH. The −248 G/C transversion in 5' UTR was also observed in 2 of the 13 relatives.

DNA sequencing of promoters of CaSR gene

Sequencing of the P1 and P2 promoter regions including GCM recognition elements was normal in patients with (n = 11) and without (n = 10) R110W mutation, their 13 relatives, and 10 healthy controls.

Electrophoretic mobility shift assay

With synthetic oligonucleotides containing octameric GCM response elements Wild-type GCM2 protein led to complete DNA probe shift (Fig. 4, lane 2). The protein–DNA complex showed super shift with antihistidine antibody but not with VDR antibody (Fig. 4a, lanes 3 and 4 respectively). When the wild and mutant GCM2 proteins were added in different concentrations in EMSA reaction, the latter bound with much lower efficacy (Fig. 4b). EMSA reaction carried out to evaluate the dominant negative effect of heterozygous R110W mutation with a mixture of 2.5 μg wild-type GCM2 protein and 2.5 μg mutant GCM2 protein revealed no attenuation of DNA–protein signal (Fig. 4c, lane 4). In contrast, there was complete attenuation of DNA–protein complex when EMSA was carried out with 100-fold excess of unlabeled DNA probe (Fig. 4a, lane 5).

Figure 6 Immunofluorescence microscopy (40×) following transfection of HeLa cells showing nuclear localization (arrow) of wild-type GCM2 protein (a) and R110W mutant protein (b), the absence of nuclear fluorescent signal in cells transfected with pcDNA3.1 vector without GCM2 insert (c) and untransfected cells (d). Upper panel (a–d) shows FITC-stained images and lower panel (A–D) shows merging of the FITC- and Hoechst-stained images.

Figure 7 Structural model of (a) wild-type and (b) R110W mutant GCM2 proteins indicating the arginine and tryptophan residues (ball-and-stick) in the native and mutant protein respectively. The resultant conformational change (encircled) from helix (black; amino acid residues 107–115) to the random coil (light grey) structure in the protein backbone at the site of mutation can be observed. The β-sheet is represented in dark grey. The zinc ions are indicated as grey spheres. The figure was made using PYMOL software (www.pymol.org).
With oligonucleotides containing GCM response elements in the P1 and P2 promoter regions of CaSR

The wild-type GCM2 protein resulted in significant shift of DNA probe designed from the P1 and P2 promoter regions of the CaSR gene. In contrast, mutant GCM2 protein did not shift P1 or P2 probes (Fig. 4d and e).

EMSA with T370M protein

The EMSA experiments were also carried out using T370M-recombinant protein, which was prepared using site-directed mutagenesis as described above for R110W protein. The protein–DNA binding obtained with T370M mutant protein was comparable to that obtained with R110W mutant protein (Fig. 4a, lanes 3 and 4). When a mixture of both R110W and T370M was added in equimolar concentration (1.25 μg each) to mimic the compound heterozygous state observed in the patient, there was a significant reduction in the DNA–protein complex (Fig. 4f, lane 5) when compared to that observed with wild-type protein. There was no dominant negative effect of T370M mutations on wild-type GCM2 protein (Fig. 4f, lane 7).

Immunofluorescence

Both the wild-type GCM2 protein and its R110W mutant showed localization to the nucleus and there was no difference in the intensity of FITC fluorescence signal. Both the negative controls showed no GCM2 protein signal in the HeLa cell nuclei (Fig. 6).

Effect of R110W mutation on structure of GCM2 protein

The presence of R110W mutation led to a structural change in the backbone conformation of amino acid residues 107–115 from a helical to a random coil structure (Fig. 7). This change would result in impairment in the DNA-binding ability of the GCM2 protein. In addition, no hydrogen bond was observed between W110 and backbone carbonyl oxygen A104 (Fig. 7).

Discussion

The pathogenesis of IH has been a subject of interest since 1966, when Blizzard et al. first identified parathyroid autoantibodies in 33% of their patients using indirect immunofluorescence. Organ-specific CaSR autoantibodies have been reported in patients with IH (10–12). Söderbergh et al. could not find any evidence of CaSR autoantibodies in hypoparathyroidism associated with type 1 APS (43). On the other hand, there are reports of CaSR gene mutations in a subset of patients with IH (15, 16). Thus, IH is a heterogeneous group of disorders with variable etiopathogenesis; in the absence of complete understanding of pathogenetic mechanisms, many patients are classified as idiopathic.

The present study was conducted in view of the recent reports of mutations in the GCM2 gene in patients with familial hypoparathyroidism (22–27). The gene knock-out mice have revealed a key role of the GCM protein in...
fetal parathyroid development (30). The GCM2 gene is also expressed in adult human parathyroid gland (32) and has response elements in the P1 and P2 promoters of the CaSR gene (27). Silencing of the GCM2 gene by shRNA in human parathyroid cells led to a decreased expression of the CaSR, but had no significant effect on the PTH, VDR, 25-hydroxyvitamin D (3)-1α-hydroxylase, and proliferating cell nuclear antigen expression (44). Interestingly, the result of EMSA experiments carried out in the current study revealed that the presence of R110W GCM2 mutation led to a binding abnormality with the P1–P2 GCM response elements of the CaSR. A down-regulation of CaSR by mutant GCM2 and decreased expression of CaSR would result in increased PTH secretion, unlike observed in patients with IH. The above fact coupled with the observation that relatives of patients with the same R110W heterozygous mutation were asymptomatic indicates that the binding defects on CaSR response elements due to the mutation of GCM2 alone would not explain the pathophysiology of hypoparathyroidism. Alternatively, this may suggest that GCM2 may interact with genes other than the CaSR.

To date, there are six reports assessing mutations in the GCM2 gene in patients with familial hypoparathyroidism. In five of these reports, mutations were observed in 14 patients. The homozygous mutations observed included a deletion of exons 1–4 (22), missense R47L (23), and G63S (24). All heterozygous family members were unaffected in these studies (22–24). The heterozygous mutations observed included c.1389delT (26, 27) or c.1399delC mutation (26). Two of the above studies also included 20 IH patients and reported normal GCM2 gene sequence in all of them (22, 25).

In the current study, the presence of R110W change did not affect the nuclear translocation of the mutant protein. However, normal nuclear translocation would not exclude impaired DNA binding and transactivation. In fact, GCM2 protein with R47L and G63S mutations has been reported to demonstrate normal nuclear localization but impaired transcriptional activity (23, 24). Though transactivation experiments could not be performed in the current study, results of the EMSA experiments indicated that under homozygous conditions, the presence of R110W mutation led to a significant reduction in DNA binding with GCM response element. Reduction in DNA-binding capacity was not observed in R110W heterozygous condition. However, the presence of coexistent compound mutation even in heterozygous state such as R110W and T370M observed in one of our patients could result in significant loss of DNA-binding function of the GCM2 protein.

The present study revealed a heterozygous C–T transition in the exon 2 leading to a change of 110th codon from CGG→TGG in 10.9% of the patients with IH. The disparity between the results of the previous studies showing the absence of mutation in 20 patients with IH and the current study showing 10.9% prevalence of R110W in 101 patients could be because of the differences in the race or sample size. Occurrence of this R110W change in 10.9% patients with IH and its absence in 655 unrelated healthy controls from same ethnic North Indian background indicate that the nucleotide change is not a simple SNP. Though patients with IH recruited in the current study were from unrelated families, in the absence of complete information of family tree, we cannot exclude the possibility of common ancestor. The haplotype analysis performed using four polymorphic variables in the 5′UTR region of the GCM2 revealed no significant difference in patients with and without R110W and controls; however, further haplotype analysis using microsatellite markers flanking the GCM2 gene would help to identify the possibility of founder effect as the cause of high prevalence of R110W mutation in our cohort of patients with IH.

The R110W missense mutation in the DNA-binding domain is likely to be relevant because arginine at codon 110 in GCM2 protein is part of a conserved peptide sequence in different species (Fig. 8) (45). Theoretically, it can be hypothesized that replacement of positively charged polar amino acid arginine with nonpolar amino acid tryptophan might affect the DNA-binding ability of the R110W GCM2 protein. A mutation resulting in similar amino acid change (R47W) in the PAX9 gene led to reduced binding of PAX9 transcription factor with the DNA response element (46). In fact, EMSA experiment in the current study showed a significant reduction in the DNA-binding ability of the mutant GCM2 protein. Moreover, the molecular modeling of the GCM2 protein revealed change in the structure from helical to a random coil with R110W mutation at amino acid residues 107–115. This mutation also results in the loss of the hydrogen bond, which was present in the wild-type protein due to the polar side chain of R110 and backbone carbonyl oxygen of A104. The conformational change as well as the disruption of hydrogen bond would result in impairment in the DNA-binding ability of the GCM2 protein (Fig. 4). A similar molecular mechanism involving the loss of polar interactions due to a single-point mutation at residue R110 has been predicted earlier (47). Based on molecular interactions of the wild-type and mutant structural models, 21 amino acid residues were predicted as candidates where a point mutation would affect the activity of GCM2 and cause hypoparathyroidism (47). A detailed analysis of the polar side chain interaction to other protein residues, DNA, or the bound zinc ions revealed that the nature of interactions between the present model structure and that reported in the earlier study (47) was similar.
had normal serum PTH values. The variable expression of the clinical syndrome in subjects with same heterozygous mutation can occur with i) parental genetic imprinting; ii) dominant negative effect of mutation; and iii) compound, digenic, or polygenic mutations. The genetic imprinting is unlikely to be the cause because experimental evidences do not favor paternal or maternal imprinting in GCM2 alleles (29). Moreover, a theoretical possibility of imprinting in GCM2 gene in human could also be ruled out because of the lack of family history in our study, which is usually present in genetically imprinted disorders (48).

Similarly, family history is a characteristic feature of dominant negative heterozygous mutations (26, 27). Moreover, the results of the EMSA experiments in the current study did not support dominant negative effect of R110W mutant protein.

Individuals with heterozygous R110W genotype might also express clinical hypoparathyroidism if they have multiple mutations in the same (compound) or other genes with synergistic effect (digenic) (49, 50). Thus, if individuals with heterozygous R110W mutation in the DNA-binding region of GCM2 gene have additional mutations in its DNA-binding elements, the effect of digenic mutation might result in complete loss of transcription ability of the GCM2 protein. In the current study, only 1 of the 11 patients with IH and R110W had compound mutation in the GCM2 gene (T370M), and none had mutation in the natural response elements of the GCM2 (i.e. CaSR gene). Interestingly, the patient showing compound heterozygous mutation was a 48-year-old male who also had HLA-B27-positive ankylosing spondylitis and was reported earlier (51). Results of the EMSA experiments in the current study indicate possibility of significant loss of GCM2 protein function in this patient.

The variable expression of a heterozygous mutation has been reported in several other disorders such as hyperthyroidism due to the activating mutation of TSH receptor (52), myotonia congenita (53), retinitis pigmentosa (54), classical (55), and nonclassical congenital adrenal hyperplasia (56). The variability in phenotypic expression of heterozygous mutation may be conditioned by polygenic mechanism or by environmental factors (57, 58). Among the polygenic factors, possibilities include mutations in the parathyroid gland-related transcription factor proteins other than GCM2 such as PAX1, PAX9, GATA3, Hoxa3, TBX1, and SOX3 (6, 9, 59–62).

While the present study demonstrates R110W change in 10.9% of patients with IH and none of the controls, the study has limitations. Complete sequencing of the open-reading frame of the GCM2 gene was carried out in only 32 patients because of the cost factors. Sequencing of the GCM2 gene in all the 101 patients might have revealed additional changes in the coding regions.

To conclude, the results of the present study indicate that 10.9% of the patients with IH had a heterozygous R110W mutation in the DNA-binding region of GCM2 protein. The mutation was seen only among patients with hypoparathyroidism and their family members and not in any of the 655 healthy controls. The R110W mutant represented the loss of function in homozygous form or in compound heterozygous state with T370M change in EMSA experiments. Further studies using genome-wide scan may identify digenic/polygenic mutations or the presence of unique environmental factors as the cause of variable expression of disease in those with R110W mutation.

Declaration of interest
The authors declare that there is no conflict of interest that could be perceived as prejudicing the impartiality of the research reported.

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Author contribution statement
All authors have contributed in the study and accepted responsibility for the content of the manuscript. Neeraj Tomar performed the major work of the manuscript including experiments related to EMSA, contributed in writing of the manuscript, and analyzed the sequence of the GCM2 gene. Hema Bora performed sequencing of the GCM2 gene. Transfection experiments were jointly conducted by Ratnakar Singh and Dr Shyam Singh Chauhan. Nandita Gupta performed IP/PTH, and 25OHD assays for the study subjects. Punit Kaur performed the molecular modeling of the mutant GCM2 protein and contributed in the writing of the manuscript. Dr Yagya Dutta Sharma contributed in the analysis of the GCM2 gene and editing of the manuscript. Ravinder Goswami planned the study and contributed in the supervision, analyzing the results of functional and immunofluorescence studies, and writing of the manuscript.

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References


Presence and significance of a R110W mutation


