Common variable immunodeficiency associated with microdeletion of chromosome 1q42.1-q42.3 and inositol 1,4,5-trisphosphate kinase B (ITPKB) deficiency

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Common variable immunodeficiency (CVID) is a heterogeneous disorder characterized by hypogammaglobulinemia and impaired specific antibody response and increased susceptibility to infections, autoimmunity and malignancies. A number of gene mutations, including ICOS, TACI and BAFF-R, and CD19, CD20, CD21, CD81, MSH5 and LRBA have been described; however, they account for approximately 20–25% of total cases of CVID. In this study, we report a patient with CVID with an intrinsic microdeletion of chromosome 1q42.1-42.3, where gene for inositol 1,3,4,5-trisphosphate kinase β (ITPKB) is localized. ITPKB has an important role in the development, survival and function of B cells. In this study, the expression of ITPKB mRNA as well as ITPKB protein was significantly reduced. The sequencing of ITPKB gene revealed three variants, two of them were missense variants and third was a synonymous variant; the significance of each of them in relation to CVID is discussed. This case suggests that a deficiency of ITPKB may have a role in CVID.

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Common variable immunodeficiency (CVID) is a heterogeneous disorder of unknown etiology characterized by decreased immunoglobulin G (IgG) and additional Ig isotypes(s) and impaired specific antibody responses; they often present with increased susceptibility to recurrent infections, autoimmune diseases and malignant disorders.1–6 In contrast to monogenetic antibody deficiency disorder such as x-linked agammaglobulinemia, a single common gene defect has not been identified for CVID. Mutations in a number of genes associated with B-cell development and functions, that is, ICOS, TACI and BAFF-R, and CD19, CD20, CD21, CD81, MSH5 and LRBA have been observed in patients with CVID.7–17 However, they contribute to approximately 20% of all cases of CVID. Therefore, there is a need to identify additional gene defects associated with CVID.

To identify a potential candidate gene, we investigated a patient with CVID who had a microdeletion of chromosome 1q42.1-42.3. In this subregion, genes were reviewed and the gene for inositol 1,4,5-trisphosphate 3 kinase β (ITPKB) was identified as a potential responsible gene for the patient’s immunological defects. ITPKB is one of three inositol 1,4,5-trisphosphate (IP3) kinase isoforms that is ubiquitously expressed and has an important role in the development, survival and functions of various hematopoietic cells.18–27 ITPKB phosphorylates IP3 to inositol 1,3,4,5-tetrakisphosphate (IP4) and control signal transduction in hematopoietic cells.23,25,27 ITPKB gene has been implicated as a candidate gene in a number of human disorders, including Alzheimer’s disease, multiple sclerosis and malignant melanoma.28–30 An association of ITPKB deficiency in CVID has not been previously described.

Herein we report a 26-year-old male patient with CVID and a constellation of findings, that is, schizophrenia, developmental delay, seizures, dystonia and hyperkeratotic eczematous dermatitis, who has an interstitial deletion of chromosome 1q42.1-42.3. This subregion carries the responsible genes for schizophrenia, seizure disorder, ectodermal dysplasia and dystonia as well as the gene for ITPKB. We believe that microdeletion of 1q42.1-42.3 resulting in haplo-insufficiency of this subregion at least contributes to, if not causing, this patient’s clinical findings.

RESULTS

Case report

A 26-year-old Caucasian male patient was evaluated for recurrent skin infections due to Staphylococcus aureus. The papulo-pustular skin lesions started on his face, trunk and extremities in his early twenties. Multiple cultures were remarkable for staphylococcus, including methicillin-resistant S. aureus. He required multiple courses of antibiotics along with incision and drainage for several deep skin abscesses. The patient experienced recurrent ear infections as a child.
and was diagnosed as having allergic rhinitis, eczema, schizophrenia, dystonia, seizure disorder and developmental delay. Physical examination revealed a diffuse erythematous rash and multiple small papulopustular lesions on the face, trunk and extremities and hyperkeratotic eczematous dermatitis.

**Chromosom analysis**

Cytogenetic and fluorescent in situ hybridization analysis were performed because patient has microcephaly and developmental delay. Cytogenetic analysis shows additional material attached to the long arm of chromosome 1 (G banding): 46,XY,add (1)(q42.1). This may represent a deletion or an interchromosomal rearrangement. Fluorescent in situ hybridization analysis using whole chromosome paint 1 (wcp1) probe and subtelomere probe specific for chromosome 1q (D1S3738) revealed the presence of hybridization signal over the entire abnormal chromosome 1 (Figure 1, top panel) and the presence of subtelomere region (Figure 1, bottom panel). The abnormality is therefore interpreted to represent an interstitial deletion of the long arm of chromosome 1 (ish del (1)(wcp1+, D1S3738+).

**Immunological studies**

Immunological features of the patient are shown in Table 1. Serum levels of IgG and IgA were decreased and IgM levels were normal. The patient did not respond to any of the 14 serotypes of *Streptococcus pneumoniae* following Pneumovax-23 vaccination. Lymphocyte sub-

**Figure 1** Fluorescent in situ hybridization analysis showing heterozygotic microdeletion of chromosome 1q42.1-42.3 (arrows). The top panel shows the wcp1 staining, and the bottom panel shows the presence of subtelomere region.

**DISCUSSION**

CVID, excluding selective IgA deficiency, is the most common primary immunodeficiency in adults, with a prevalence of approximately 1 in 10,000–50,000. It is a heterogenous disorder characterized by recurrent infections and an increased risk for autoimmune and malignant disorders. Most cases are sporadic in origin but autosomal-dominant and autosomal-recessive inheritance patterns have been recognized in some families. Several family studies have also identified susceptibility loci in the major histocompatibility complex region. The immune system defect is characterized by hypogammaglobulinemia, impaired specific antibody response and impaired cell-mediated responses in up to 50% of patients. T-cell abnormalities may include CD4+ lymphopenia, diminished lymphoproliferative responses to antigens and mitogens and impaired cytokine production. Our patient also displayed low CD3+ T cells and markedly impaired response T-cell responses to recall antigens, suggesting a combined T- and B-cell defects. Furthermore, our patient has severe deficiency of Treg cells. Similar deficiency of Treg has been reported in patients with CVID. Although some of the molecular defects in CVID have been identified, including mutations of ICOS, TACI and BAFF-R, and CD19, CD20, CD21,
Table 1 Immunological features of a patient with CVID

| Lymphocyte subsets (%) | Patient | Reference ranges |
|------------------------|---------|-----------------|
| CD3+                   | 744 (62%) | 844–2395 (65–80%) |
| CD3+CD4+               | 504 (42%) | 437–1597 (31–56%) |
| CD3+CD8+               | 204 (17%) | 281–1125 (17–34%) |
| CD4+/CD8+ ratio        | 2.57    | 0.78–2.21       |
| CD19+                  | 60 (5%)  | 32–399 (4–16%)  |
| CD3-CD56+CD16+         | 36 (3%)  | 120–424 (4–16%) |

Lymphocyte proliferation to antigens and mitogens (c.p.m.)

| Serum immunoglobulins (mg dl\(^{-1}\)) | Patient | Reference ranges |
|-----------------------------------------|---------|-----------------|
| IgG                                    | 516     | 694–1618        |
| IgA                                    | 44      | 68–378          |
| IgM                                    | 95      | 65–263          |
| IgE (IU l\(^{-1}\))                   | 110     | 10–150          |

Specific antibodies

| Streptococcus pneumoniae (µg ml\(^{-1}\), 14 serotypes) | 0.0–0.3\(^a\) | >1.3\(^b\) |

Complement

| C10 (µl ml\(^{-1}\)) | 267 | (101–300) |
|----------------------|-----|-----------|
| C3 (mg dl\(^{-1}\))  | 113 | (88–201)  |
| C4 (mg dl\(^{-1}\))  | 31  | (16–47)   |

Oxidative respiratory burst (MFI)

| Unactivated | 54 | 70 |
|-------------|----|----|
| PMA-activated| 404| 873|

Abbreviations: ConA, concanavalin A; CVID, common variable immunodeficiency; Ig, immunoglobulin; MFI, mean fluorescence intensity; PMA, phorbol myristate acetate; PPD, purified protein derivative; PWM, pokeweed mitogen.

\(^a\)After Pneumovax-23 response. Patient did not respond to any of the 14 serotypes.

\(^b\)3 fold increase following Pneumovax-23 against at least 70% serotypes.

CD81, MSH4 and LRBA genes,\(^7\)–\(^17\) the genetic basis for this disorder still remains to be elucidated. In view of the heterogenous clinical features and absence of a single gene defect, CVID appears to represent different genetic disorders that have yet to be characterized.

The present case provides an opportunity to assess the genotype-phenotype relationship in patient with haploinsufficiency of chromosome 1q42.1-42.3 and CVID. Chromosome 1 is the largest human chromosome. Chromosome 1 spans about 249 million nucleotide base pairs and represents about 8% of the total DNA in human cells. Chromosome 1 is currently thought to have 4316 genes. Using the Online Mendelian Inheritance in Man (OMIM) database, the individual genes located on chromosome 1q42.1-42.3 were reviewed, and ITPKB was identified as a potential responsible gene for the immunological defect in CVID.

The mammalian IP3 kinases consist of a family of three isoforms, A, B and C.\(^18\)\(^,\)\(^19\) These three isoforms share a relatively well-conserved catalytic domain and specifically convert IP3 to IP4. An isoform (gene localized on chromosome 15q14) is associated with cytoketone, where C isoform appears exclusively localized to cytoplasm. In contrast, B isoform (ITPKB) is associated with plasma membrane, cytoskeleton and found in the endoplasmic reticulum.\(^21\) More recently, Naïsmowski et al.\(^41\) have identified subnuclear localization of ITPKB. They showed that ITPKB is enriched at nuclear invagination. They also showed that ITPKB is involved in the regulation of both cytoplasmic and nuclear calcium signaling.

ITPKB is a ubiquitously expressed enzyme that has an important role in the development and functions of hematopoietic cells. In the T cells, ITPKB appears to have a role in thymic selection and T-cell calcium signaling.\(^20\) In the B cells, ITPKB regulates B-cell selection, tolerance, survival and negatively regulate B-cell signaling.\(^23\)–\(^25\) ITPKB also has a role in myelopoiesis and negatively regulates neutrophil signaling.\(^26\)\(^,\)\(^27\)

In mice, disruption of the ITPKB gene results in decreased IP4 and block in thymocyte-positive selection and to a severe T-cell deficiency. A mouse strain with nonsense mutation of ITPKB gene shows a complete block in positive selection of T lymphocytes at double-positive stage in the thymus and impaired T-cell receptor signaling.\(^23\)

Our patient had only modest decrease in CD3+ T cells and in mitogen responses; however, his T-cell responses to antigens were severely compromised. This modest quantitative and functional T-cell deficiency in our patient may explain lack of opportunistic infection. Mice lacking ITPKB shows normal B-cell development in the bone marrow but low number of splenic B cells.\(^25\) ITPKB−/− B cells displayed impaired response to BCR signal, but normal response to CD40 cross-linking and LPS, therefore resembling tolerant B cells. Furthermore, these mice showed impaired IgG3 response to T-independent antigens. In CVID, various alterations in B-cell differentiation and impaired antibody responses have been reported.\(^42\)\(^,\)\(^43\) These include expansion of CD21\(^b\) and deficiency of switched memory B cells. Our patient shows markedly impaired response to T-independent pneumococcal polysaccharide antigens and expansion of CD21\(^b\) B cells; however, switched memory B cells were comparable to healthy controls.

In the patient, both RT-PCR and qRT-PCR showed significantly \((P<0.03)\) reduced expression of ITPKB mRNA. Furthermore, ITPKB at the protein level was also markedly decreased.

After gene sequencing revealed three variants in ITPKB gene in our patient, do these gene variants have a role in immunological defects in CVID? As two missense variants are considered benign and are frequently observed in the general population, it is unlikely that they would be contributing to CVID. The third variant is a synonymous.

A synonymous substitution, often called a silent substitution, is a substitution of one base for another in an exon of a gene coding for a protein, such that the produced amino-acid sequence is not modified. Synonymous substitutions affecting noncoding DNA are often considered silent; however, this is not always the case.\(^44\)–\(^48\) Synonymous changes may not be neutral because certain codons are translated more efficiently than others. Synonymous mutations can affect transcription, splicing, mRNA transport and translation, any of which could render the synonymous mutation non-silent.\(^46\) Another reason why synonymous changes are not always neutral is the fact that exons sequences close to exon–intron borders function as RNA splicing signals. When the splicing signal is destroyed by a synonymous mutation, the exon does not appear in the final protein. This results in a truncated protein.\(^49\)\(^,\)\(^50\) It is possible that the synonymous variant in our patient may be contributing to the decreased transcription of ITPKB gene, and decreased expression of ITPKB at the protein level, which would be mostly due to haploinsufficiency as a result of chromosomal deletion. As patient does not know whereabouts of his parents, we could not establish whether deletion was a \(de novo\) deletion.
In addition to T-cell development, the IP3–IP4 calcium pathway has been shown to be important for other immune functions, including proliferation, cytokine production, cytotoxicity and respiratory burst. The formation of oxygen-free radicals has been shown to be in part dependent on the onset and magnitude of the cytosolic calcium signal. The activation of neutrophil oxidase is dependent on free cytosolic calcium.

In this study, we have shown that microdeletion of chromosome 1q42.1-42.3 results in decreased expression of ITPKB gene. Given the importance of calcium signaling for generation of reactive oxygen species as well as the role of ITPKB in neutrophil functions and impaired DHR and impaired T-cell functions in our patient, we considered that defective calcium signaling in neutrophils and lymphocytes can result in abnormal respiratory burst and impaired humoral and cell-mediated responses. With the exception of CVID, the clinical and immunological findings for the present case were not consistent for any other well-defined disorders. We considered the possibility of Chediak–Higashi syndrome because the gene for this disorder, Lyst, resides on the 1q42.1-42.3 segment and because our patient presented with pyogenic infections and seizures, which are consistent features of this syndrome. However, other important diagnostic features, such as neutrophil giant granules and partial oculocutaneous albinism were not present. We also entertained the possibility of chronic granulomatous disease (CGD) as these patients present with recurrent infections and abnormal respiratory burst functions. However, patients with CGD have a much more profound defect in respiratory burst. Diagnostic criteria for CGD requires respiratory burst to be <5% of control, which was not the case of our patient. Furthermore, other consistent features of CGD, including granulomas and hepatosplenomegaly, were absent in our patient. It is unclear whether modest impairment of oxidative burst contributed to the susceptibility to staphylococcal skin infections observed in this instance.

In addition to CVID, this patient presented with a constellation of other clinical disorders, including, seizures, dystonia and schizophrenia; the susceptibility genes for each of these disorders have been identified and mapped to the q42.1-q42.3 subregion of chromosome 1 (OMIM). DISC1 and DISC2 genes for schizophrenia are localized at 1q42.1,51 and gene for myotonic dystrophy (CDC42BPA, MRCA, PK-428) localized to 1q42.11.52,53 Although we did not investigate the
expression of these genes, it is likely that haploinsufficiency of this subregion results in decreased expression of the responsible genes for those disorders.

We conclude that haploinsufficiency of chromosome 1q42.1-q42.3, resulting in ITPKB deficiency may be responsible for the impaired antibody and cell-mediated immune responses and also for the attenuated respiratory burst in neutrophils in our patient with CVID.

METHODS

Subjects

PBMCs were isolated from the blood of patient and healthy subjects by Ficoll-hypaque density gradient (Mediatech, Inc., Manassas, VA, USA). Protocol was approved by the Human Subject Committee of the Institution Review Board (Human), University of California, Irvine, CA, USA. Informed consent was obtained from the patient.

For T-cell subsets, antibodies used were CD4 PerCP (peridinin chlorophyl protein) and CD8 PerCP, CD45RA APC (allophycocyanin), CCR7 FITC (fluorescein isothiocyanate), CD3 PerCP and CD278 (ICOS) PE (phycoerythrin). All antibodies were obtained from BD Pharmingen (San Jose, CA, USA).

Chromosome analysis and fluorescent in situ hybridization

Cytogenetic analysis was performed using G banding (Genzyme Genetics, Pasadena, CA, USA). Fluorescent in situ hybridization was carried out by WCP1 probe and DIS3736 subtelomere probe specific for chromosome 1.

B-cell subsets

B-cell subsets were analyzed on whole blood by incubating various combinations of monoclonal antibodies, including anti-human CD19 PerCP, anti-IgM APC, CD27 FITC, CD38 FITC, anti-IgD PE, CD21 PE, CD70 PE, CD27 APC, CD24 FITC, CD38 PE, CD183 PE (BD Pharmingen) and CD43 APC (Biolegend, San Diego, CA, USA) monoclonal antibodies, and corresponding isotypes. After staining, blood was lysed by 1× lysing solution (BD Pharmingen) and washed with phosphate-buffered saline and analyzed. Flow cytometry was performed using FACSCalibur (Becton-Dickenson, San Jose, CA, USA) equipped with argon ion laser emitting at 488 nm (for FITC, PE and APC excitation). Forward and side scatters were used to gate and exclude cellular debris. Ten thousand cells were acquired and analyzed using the Flowjo software (Tree star Inc., Ashland, OR, USA).

Detection of Treg cells

Cells were stained with CD4 PerCP, CD25 FITC and CD127 Alexa647 monoclonal antibodies and corresponding isotypes (BD Pharmingen), according to the manufacturer’s protocol. Followed by Foxp3 intracellular staining with Foxp3 PE monoclonal antibody, isotype control (Mouse IgG1 κ-PE) was used to evaluate nonspecific staining. Staining procedures was performed according to the manufacturer’s recommendations. Treg cells were identified as CD4+CD25+CD127loFoxP3+ and analyzed with FACSCalibur (BD Biosciences, San Jose, CA, USA). Treg were calculated as percent positive of total foxp3 cells in CD4 population = (CD4+) × (CD25 high CD127 low) × (foxp3+ve)/(10 000).

Respiratory oxidative burst in neutrophils

Oxidative burst was measured with DHR123 using flow cytometry. DHR123 is a nonfluorescent dye but it becomes highly fluorescent when oxidized by
In each PCR reaction, 18S ribosomal RNA was co-amplified with the target cDNA (mRNA) to serve as an internal standard and to allow correction for any differences in starting amounts of total RNA. For the 18S amplification, we used the Alternate 18S Internal Standards (Ambion), which yields a 324-bp product. The 18S primers were mixed with competimers at an optimized ratio 1:30, depending on the abundance of the target mRNA. Inclusion of 18S competimers was necessary to bring down the 18S signal, which allows its linear amplification to the same range as the co-amplified target mRNA (Relative RT-PCR Kit protocol, Ambion). The PCR reactions were carried out in the presence of 2 mM MgCl₂ by using standard PCR buffer ( Gibco), 0.1 mM dNTP each, 1 μM specific primer set, 0.5 μM 18S primer–competimer mix and 0.75 unit of DNA Taq polymerase (Gibco) in 25 μl total volume. A Perkin-Elmer DNA thermocycler (Norwalk, CT, USA) was used for PCR amplification, with 38 cycles of denaturation at 95 °C for 45 s, annealing at 55 °C for 45 s, extension at 70 °C for 45 s and extension for 10 min at 70 °C after last cycle. In all, 10 μl of PCR products were run on 2% agarose gels (Sigma) with TBE buffer, visualized with ethidium bromide and photographed. Signal quantification was conducted by laser-scanning densitometry. ITPKB mRNA signal was normalized to its corresponding 18S.

Real-time qRT-PCR of ITPKB gene from PBMC RNA. qRT-PCR was performed on RNA extracted from PBMCs from four healthy donors and from three separate samples donated by the patient on three different occasions. One microgram of total RNA was reverse transcribed to cDNA by using the High Capacity cDNA Reverse Transcription Kit (Life Technologies, Applied Biosystems, Grand Island, NY, USA) with random hexamers as primers following the manufacturer’s instructions. The cDNA was amplified by PCR in a 20-μl reaction mixture containing 2 μl of 1 μM forward and reverse primers, 10 μl of SYBR Green 1 Master Mix (Roche Life Science, Indianapolis,
and 4 μl of either cDNA diluted 10× for ITPKB, cDNA diluted 300× for ACTB or water as a negative control. Initial denaturation of DNA was carried out at 95 °C for 10 min; 40 amplification cycles were performed, each cycle consisting of denaturation (95 °C, 30 s) and annealing with extension (65 °C, 1 min). Each sample was amplified in triplicate, and results were normalized with ACTB gene expression as 'housekeeper. A 4-log absolute standard curve dilution series was run using each primer pair at optimal concentration, and amplification efficiencies and slope were calculated. The fold changes of differential expression between healthy donors and the patient subject were calculated using the ratios of ITPKB to ACTB. Primers for ITPKB and ACTB were purchased from http://www.RealTimePrimers.com. Statistical analysis was performed by Student’s t-test.

Western blotting for ITPKB protein. PBMCs were lysed with lysis buffer (Cell Signaling, Danvers, MA, USA). Aliquots of cell lysates containing 50 μg of total protein were resolved by sodium dodecyl sulfate-polyacrylamide gel electrophoresis and transferred onto membranes (Millipore, Bedford, MA, USA) by electroblotting. The membranes were blocked for 1 h at room temperature in
TBS-T buffer with 5% nonfat dried milk and incubated with 1µg ml⁻¹ primary anti-ITPKB antibody (Sigma-Aldrich, St Louis, MO, USA) and anti-GAPDH antibody as loading control (abcam Cat. No: ab8245, Cambridge, MA, USA) used dilution 1:5000 overnight at 4. anti-ITPKB specific antibody recognizing 67.4 kDa band of ITPKB. The blots were washed three times for 20 min with TBS-T buffer and then incubated with horseradish peroxidase-conjugated secondary antibodies (1:5000–1:10000 dilution) for 1 h at room temperature. After washing three times for 20 min in TBS-T buffer, blots were developed using enhanced chemiluminescence reagents (ECL, Thomas Scientific, Rockford, IL, USA) and exposed to clear blue X-ray film.

DNA sequencing of ITPKB gene. Eight Exons and the adjacent introns of the ITPKB gene were amplified by PCR. ITPKB gene cloning and DNA sequencing primers are shown in Table 3. Exons 1, 2d, 2e, 3, 4, 5, 6, 7 and 8 of the ITPKB gene were amplified by PCR in a 25-µl reaction mixture containing 2 µl of 10 µM forward and reverse primers, 2 µl of 25 mM MgCl₂, 2.5 µl of 10 x buffer, 1 µl of 10 µM dNTPs, 50 ng of genomic DNA and 0.2 µl of 1 µM ⁻¹ AmpliTaq Gold DNA polymerase (Life Technologies, Applied Biosystems). PCR conditions were as follows: 94°C for 5 min, followed by 35 cycles of 95°C for 30 s, 60°C for 45 s, and 72°C for 45 s with a final 10-min extension period at 72°C. Certain regions of exons 2a, 2b and 2c are GC rich (74% of GC). These gene were amplified by PCR in a 25-µl reaction mixture containing 2 µl of 10 µM forward and reverse primers, 2 µl of 25 mM MgCl₂, 2.5 µl of 10 x buffer, 1 µl of 10 µM dNTPs, 50 ng of genomic DNA and 0.2 µl of 1 µM ⁻¹ AmpliTaq Gold DNA polymerase (Life Technologies, Applied Biosystems). PCR conditions were as follows: 94°C for 5 min, followed by 10 cycles of 95°C for 30 s, 60°C for 45 s, and 72°C for 45 s; followed by 20 cycles of 95°C for 30 s, 60°C for 45 s, and 72°C for 30 s, with a final 7-min extension period at 72°C.

PCR products were separated by electrophoresis and purified (Zymocell gel DNA Recovery Kit, Zymo Research, Orange, CA, USA). The eight exons and adjacent intronic regions were sequenced by Retrogen, Inc. (San Diego, CA, USA). DNA sequences were analyzed for bi-directional sequence with DNASTAR Lasergene, Edit Sequence (DNASTAR, Inc., Madison, WI, USA) and the Sequence Scanner Software 1.0 (Life Technologies, Applied Biosystems).

CONFLICT OF INTEREST

The authors declare no conflict of interest.

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