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Loss of \textit{DIAPH1} causes SCBMS, combined immunodeficiency, and mitochondrial dysfunction

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GRAPHICAL ABSTRACT

Loss of \textit{DIAPH1} causes SCBMS, combined immunodeficiency and mitochondrial dysfunction

Combined immunodeficiency

- Susceptibility to infection and lymphoma
- SCBMS (OMIM #616632)
- Progressive Microcephaly
- Early-onset epilepsy
- Cortical blindness
- Intellectual disability

MITOCHONDRIAL DYSFUNCTION

Respiratory complex IV deficiency
RTE and naïve cells
- Activation
- Proliferation
- Adhesion
- MTOC polarization

Marginal zone and switched memory cells
- Immunoglobulins

Abbreviations

\textit{DIAPH1} - Diaphanous homolog 1
SCBMS - Seizures, cortical blindness, and microcephaly syndrome
RTE - Recent thymic emigrant
MTOC - Microtubule organizing center

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Background: Homozygous loss of \textit{DIAPH1} results in seizures, cortical blindness, and microcephaly syndrome (SCBMS). We studied 5 Finnish and 2 Omani patients with loss of \textit{DIAPH1} presenting with SCBMS, mitochondrial dysfunction, and immunodeficiency.

Objective: We sought to further characterize phenotypes and disease mechanisms associated with loss of \textit{DIAPH1}.

Methods: Exome sequencing, genotyping and haplotype analysis, B- and T-cell phenotyping, \textit{in vitro} lymphocyte stimulation assays, analyses of mitochondrial function, immunofluorescence staining for cytoskeletal proteins and mitochondria, and CRISPR-Cas9 \textit{DIAPH1} knockout in healthy donor PBMCs were used.

Results: Genetic analyses found all Finnish patients homozygous for a rare \textit{DIAPH1} splice-variant (NM\_005219:c.684+1G>A) enriched in the Finnish population, and Omani patients homozygous for a previously described pathogenic \textit{DIAPH1} frameshift-variant (NM\_005219:c.2769delT;p.F923fs). In addition to microcephaly, epilepsy, and cortical blindness characteristic to SCBMS, the patients presented with infection susceptibility due to defective lymphocyte maturation and 3 patients developed B-cell lymphoma. Patients' immunophenotype was characterized by poor lymphocyte activation and proliferation, defective B-cell maturation, and lack of naive T cells. CRISPR-Cas9 knockout of \textit{DIAPH1} in PBMCs from healthy donors replicated the T-cell activation defect. Patient-derived peripheral blood T cells exhibited impaired adhesion and inefficient microtubule-organizing center repositioning to the immunologic synapse. The clinical symptoms and laboratory tests also suggested mitochondrial dysfunction. Experiments with immortalized, patient-derived fibroblasts indicated that \textit{DIAPH1} affects the amount of complex IV of the mitochondrial respiratory chain.

Conclusions: Our data demonstrate that individuals with SCBMS can have combined immune deficiency and implicate defective cytoskeletal organization and mitochondrial dysfunction in SCBMS pathogenesis. (J Allergy Clin Immunol 2021;148:599-611.)

\textbf{Key words:} \textit{DIAPH1}, SCBMS, microcephaly, mitochondrial dysfunction, T cells, immunodeficiency

\textit{DIAPH1} encodes for the evolutionarily conserved formin diaphanos homolog 1 (\textit{DIAPH1} or mDia1), which acts downstream of Rho GTPases promoting F-actin polymerization and microtubule stabilization.\textsuperscript{13} \textit{DIAPH1} is composed of an N-terminal regulatory GTPase-binding-diaphanous inhibitory domain followed by a dimerization domain, 2 highly conserved formin homology domains (FH1 and FH2) that orchestrate actin polymerization, and a C-terminal diaphanos autoregulatory domain.\textsuperscript{5,6} Cytoskeletal dynamics are relevant for many cellular processes, and hence formins have been implicated in cell morphology, differentiation, adhesion, migration, and proliferation in several cell types.\textsuperscript{3} \textit{DIAPH1} also participates in regulating mitochondrial trafficking by inducing docking of the mitochondria to the cytoskeleton.\textsuperscript{6,7} \textit{DIAPH1} has also been implicated in several steps of brain development, including neural migration and neurite formation.\textsuperscript{8}

\textit{DIAPH1} knockout mice present with ventricular enlargement (brain atrophy) at early and postnatal stages and have marked defects in the function of several types of immune cells.\textsuperscript{9,14} \textit{DIAPH1} is the predominant isoform of the 3 diaphanous-related proteins (\textit{DIAPH1-DIAPH3}) in T cells and regulates T-cell function through effects on microtubule-organizing center (MTOC) polarization and actin accumulation at the immunologic synapse.\textsuperscript{14,15} As a result, \textit{DIAPH1}\textsuperscript{−/−} mice develop lymphopenia and show defective adherence, migration, chemotaxis, and proliferation of T cells.\textsuperscript{9,16} In addition, the aging \textit{DIAPH1}\textsuperscript{−/−} mice spontaneously develop a myeloproliferative phenotype.\textsuperscript{16}

In humans, \textit{DIAPH1} has been implicated in both cancer\textsuperscript{17,18} and heritable monogenic disease: Dominant gain-of-function variants in \textit{DIAPH1} cause sensorineural deafness with macrothrombocytopenia (DFNA1),\textsuperscript{19-21} whereas homozygous loss of \textit{DIAPH1} causes seizures, cortical blindness, and microcephaly syndrome (SCBMS). In SCBMS, the seizures typically start during the first 6 months of life and are difficult to manage. Head size can be normal at birth, but progressive microcephaly, cortical blindness, and severe intellectual disability soon become evident. Patients can also have difficulty to thrive and have reduced height and weight. In previous studies, some patients suffered bronchiectasis or recurrent respiratory infections, but no clear immunodeficiency or cause for these symptoms was shown.\textsuperscript{12,22}

Until now, the SCBMS syndrome has been reported in only 3 consanguineous families, with a total of 9 patients homozygous for damaging \textit{DIAPH1} variants (NM\_005219: c.2332C>T; p.Q778X, c.2769delT;p.F923fs, c.3145C>T;p.R1049X).\textsuperscript{12,22}

\textsuperscript*These authors contributed equally to this study.

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\textbf{Abbreviations used}

\begin{itemize}
  \item CV: Complex IV
  \item MMP: Mitochondrial membrane potential
  \item MTOC: Microtubule-organizing center
  \item PBL: Peripheral blood lymphocyte
  \item SCBMS: Seizures, cortical blindness, and microcephaly syndrome
  \item WES: Whole-exome sequencing
  \item WT: Wild-type
\end{itemize}

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Here, we report 5 Finnish patients homozygous for a previously unpublished pathogenic \textit{DIAPIH} splice-donor variant (c.684+1G>A), as well as 2 additional Omani patients homozygous for the previously described p.F923fs variant. In addition, we extend the clinical and molecular phenotype of SCBMS by showing that patients with SCBMS can present with combined immunodeficiency, lymphoma, and mitochondrial dysfunction, and provide evidence for the role of \textit{DIAPIH} in the function of mitochondria and the human immune system.

**METHODS**

**Sequencing and genomic analyses**

DNA and RNA extraction, whole-exome sequencing (WES) and capillary sequencing, genotyping, and data analysis are described in this article’s Methods section in the Online Repository at www.jacionline.org. Primers are listed in Table E1 in this article’s Online Repository at www.jacionline.org.

**Cell isolation and culture**

Fibroblast cultures were established from skin biopsies at the Department of Clinical Genetics of Oulu University Central Hospital. Fibroblasts were immortalized by a retroviral vector that expresses the E7 gene of type 16 human papilloma virus and a retroviral vector that expresses the protein component of human telomerase. \textsuperscript{23} PBMCs were isolated from heparin blood using Ficoll-Paque PLUS (GE healthcare, Chicago, IL) gradient centrifugation. Peripheral blood lymphocytes (PBLs) were collected after 3- to 16-day monocyte attachment to culture flasks. Culture media are listed in this article’s Methods section in the Online Repository.

**Cloning and lentiviral transduction**

Full-length human wild-type (WT)-\textit{DIAPIH} cDNA was amplified from control fibroblasts by RT-PCR and ligated into a Gateway-compatible pLXSH-puro lentiviral vector (Invitrogen/ThermoFisher, Waltham Mass). Forty-eight hours after transfection of a Phoenix packaging cell line, lentivirus-containing medium was collected and used in mixture with 4 mL polybrene to transduce fibroblasts as described elsewhere.\textsuperscript{24}

**Immunophenotyping**

Clinical immunophenotyping and T-cell receptor-repertoire analyses were performed by the laboratories of Oulu University Hospital, Helsinki University Hospital, Turku University Hospital, and the Royal Hospital and Sultan Qaboos University Hospital Oman. Phenotyping of IL-17–positive T\textsubscript{H}17 cells and regulatory T cells is described in more detail in this article’s Methods section in the Online Repository. Neutrophil oxidative burst was analyzed with dihydrodorhamidine test.

**Lymphocyte proliferation assays**

Lymphocyte proliferation was measured with 3H-thymidine incorporation (as described elsewhere).\textsuperscript{25} EU incorporation according to manufacturer’s recommendations (Invitrogen Click-t-EDU), or by imaging-based estimation of cell confluence and cell counting (see this article’s Methods section in the Online Repository). PBMCs/PBLs were stimulated in the presence of 10 to 20 ng/ml IL-2 (Peprotech, Rocky Hill, NJ) in RPMI media with 10% FBS. Stimulations were performed with PHA (Sigma-Aldrich, St Louis, Mo), concanavalin A, pokeweed mitogens, 1:1 or 1:2 cell-bead ratio of Gibco Dynabeads Human T-Activator CD3/CD28 beads (ThermoFisher, Waltham, Mass), or 1 $\mu$g/mL soluble anti-CD3 (OKT3) and anti-CD28 (CD28.2) (Invitrogen) for a maximum of 3 days, after which culture was continued in media with IL-2.

**Activation marker analysis**

Cells were stimulated as described above, and expression of activation markers analyzed by flow cytometry after 16 to 48 hours. Combinations of the following antibodies were used: BV605-CD3 (#563217), BV421-CD4 (#562425), PE-Cy7-CD8 (#335822), BV786-CD69 (#563834), and PE-CF594-CD25 (#562525) (all from BD Biosciences, Franklin Lakes, NJ) and BV570-CD8 (#301038; BioLegend, San Diego, Calif). DRAQ7 (BD Biosciences) and eFluor 660 (ThermoFisher) were used to gate out dead cells. For DIAP1H staining, samples were fixed and permeabilized in methanol for 30 minutes, washed, stained for 60 minutes at room temperature for surface markers and rabbit monoclonal DIAP1H antibody (1:200; ab129167; Abcam, Cambridge, UK), washed, and stained with AF488 goat antirabbit secondary antibody (1:10000; #A11008; Invitrogen). Samples were run on the iQue Screener PLUS flow cytometer and analyzed with ForeCyt software (Sartorius, Gottingen, Germany).

**PAGE and western blotting**

Blots were probed by the following primary antibodies: SDHA #ab14715, UQCRCC2 #ab14745, COX IV #ab14744, ATP5A #ab14748, and DIAP1H #ab129167 (Abcam); NDUF9A #A21344 (Life Technologies/ThermoFisher, Waltham, Mass); and GAPDH #258 (ThermoFisher). Secondary detection was performed with Goat Anti-Mouse IgG HRP #1031-05 (SouthernBiotech, Birmingham, Ala), Goat Anti-Rabbit IgG H&L #ab97080 (Abcam) or Swine Anti-rabbit Ig/HRP #P0399 (Dako/Agilent, Santa Clara, Calif), and ECL reagents (Pierce, Appleton, Wis). Total protein was detected with No-stain Protein Labeling Reagent (Invitrogen/ThermoFisher). Imaging was performed with the ChemiDoc MP Imaging System (Bio-Rad, Hercules, Calif), and relative intensity of bands was calculated using Image J software or ImageLab 6.0 (Bio-Rad). Blotting methods are described in more detail in this article’s Methods section in the Online Repository.

**Immunocytochemistry**

Detailed methods for immunofluorescence stainings are described in this article’s Methods section in the Online Repository. Briefly, 1- or 10-day cultured T cells were plated on ICAM-1 and CD3 antibody or CD3/CD28 antibody–coated surface, let attach for 1 hour, and fixed with 2% or 4% formaldehyde in PBS. Cells were stained with either (a) Mitotracker Deep Red (#M22426; ThermoFisher; staining of live cells before fixation) or AF647 Phalloidin (#A22287; Invitrogen) and AF555-conjugated α-Tubulin antibody (#MA1-38000-A555; ThermoFisher) and Hoechst 33342 (#14533; Sigma-Aldrich) or (b) CytoPainter Phalloidin iFluor 488 Reagent (#ab176753; Abcam) and Hoechst. Cells were imaged with Olympus Fluoview FV1000 confocal microscope or PerkinElmer Opera Phenix high-content confocal microscope at 60× or 63×, respectively. Identical exposure time and offsetting was used for all samples. Images were exported and further analyzed with Harmony 4.9 software in 3D or Fiji.\textsuperscript{27} Parameters are listed in Table E2 in this article’s Online Repository at www.jacionline.org.

**CRISPR-Cas9 knockout of \textit{DIAPIH} in healthy donor PBMCs**

\textit{DIAPIH} Alt-R CRISPR-Cas9 cDNA guides (listed in Table E1; IDT) were combined 1:1 with Alt-R CRISPR-Cas9 tracrRNA (IDT, 1072533), annealed at 95°C for 5 minutes, and cooled to room temperature. RNPs were produced by complexing 2 \textit{DIAPIH} guides (guide 1 + 2 or guide 1 + 3, each at 100 pmol/sample) with Alt-R S.p. Cas9 Nuclease V3 (IDT; 1081059; 100 pmol) and incubated at room temperature for 15 minutes. Healthy donor PBMCs were stimulated in complete RPMI media with ImmunoCult Human CD3/CD25 T Cell Activator (STEMCELL Technologies, Vancouver, British Columbia, Canada) and 3 ng/mL IL-7 and IL-15 (Peprotech) for 3 days. Cells were resuspended at 1 million cells/20 µL in 1 mol electroporation buffer and electroporated using Lonza 4D Nucleofector X unit (Lonza, AAF-1002X), electroporation program “EO-115,” and “Primary-Cell-P3” solution. After
TABLE I. Summary of phenotypic characteristics of the studied patients

<table>
<thead>
<tr>
<th>Characteristic</th>
<th>Patient 1</th>
<th>Patient 2</th>
<th>Patient 3</th>
<th>Patient 4</th>
<th>Patient 5</th>
<th>Patient 6</th>
<th>Patient 7</th>
</tr>
</thead>
<tbody>
<tr>
<td>Age (y)</td>
<td>9</td>
<td>6</td>
<td>3</td>
<td>29</td>
<td>—</td>
<td>3</td>
<td>—</td>
</tr>
<tr>
<td>Age of death (y)</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td>Sex</td>
<td>Male</td>
<td>Male</td>
<td>Male</td>
<td>Female</td>
<td>Female</td>
<td>Female</td>
<td>Male</td>
</tr>
<tr>
<td>Cause of death</td>
<td>B-cell lymphoma</td>
<td>Status epilepticus</td>
<td>Progressive (from −2.5 SD at 1.5 y to −5.5 SD)</td>
<td>Progressive (from −1.0 SD at birth to −5.5 SD)</td>
<td>Progressive (from −3.7 SD at birth to −7.6 SD at 4 y 5 mo)</td>
<td>Progressive (from −1.4 SD at birth to −6.3 SD at 2 y 1 mo)</td>
<td>Progressive (from −2.0 SD at 10 wk to −4.8 SD at 3 y 2 mo)</td>
</tr>
<tr>
<td>Microcephaly</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Brain imaging</td>
<td>Abnormal signal intensities in occipital white matters; thin chiasm and optic nerves</td>
<td>Abnormal signal intensities in occipital white matter; thin chiasm and optic nerves</td>
<td>Abnormal signal intensities in occipital white matter; thin chiasm and optic nerves</td>
<td>Normal at the age of 5 d</td>
<td>Occipital atrophy at age 27 y, encephalitis at age 29 y</td>
<td>Brain atrophy</td>
<td>Partial agenesis of corpus callosum, occipital atrophy</td>
</tr>
<tr>
<td>Intellectual disability</td>
<td>Profound</td>
<td>Profound</td>
<td>Profound</td>
<td>Profound</td>
<td>Profound</td>
<td>Profound</td>
<td>Profound</td>
</tr>
<tr>
<td>Epilepsy onset</td>
<td>2 mo</td>
<td>2 mo</td>
<td>2.5 mo</td>
<td>2 d</td>
<td>1 mo</td>
<td>2 mo</td>
<td>15 d</td>
</tr>
<tr>
<td>Visual impairment</td>
<td>Cortical blindness</td>
<td>Cortical blindness</td>
<td>Cortical blindness</td>
<td>Cortical blindness</td>
<td>Cortical blindness and optic nerve atrophy</td>
<td>Cortical blindness and optic nerve atrophy</td>
<td>Cortical blindness</td>
</tr>
<tr>
<td>Muscles</td>
<td>Muscular atrophy, increased fat and number of mitochondria</td>
<td>Muscular atrophy, increased fat and number of mitochondria</td>
<td>Mild muscular hypotonia, muscle biopsy not taken</td>
<td>Normal muscle tone, muscle biopsy not taken</td>
<td>Normal muscle tone, muscle biopsy not taken</td>
<td>Muscular hypotonia, muscle biopsy not taken</td>
<td>Mild muscular hypotonia, muscle biopsy not taken</td>
</tr>
<tr>
<td>Severe/ recurrent infections</td>
<td>Bacterial otitis media, candida, mycobacteria, VZV, HSV, EBV, Molluscus contagiosus</td>
<td>Respiratory infections, Molluscus contagiosum</td>
<td>Otitis media and respiratory infections</td>
<td>Recurrent watery diarrhoea, respiratory infections</td>
<td>Rubella vaccine strain skin infection, JCV encephalitis</td>
<td>Candida, Staphylococcus haemolyticus, Elizabethkingia meningoseptica, EBV, CMV</td>
<td>Otitis media, Streptococcus pneumonia, MRSA, RSV bronchiolitis</td>
</tr>
<tr>
<td>Lymphoma (B cell)</td>
<td>Diffuse large B-cell lymphoma</td>
<td>Hodgkin-like (detected in autopsy)</td>
<td>No</td>
<td>No</td>
<td>No</td>
<td>No</td>
<td>No</td>
</tr>
</tbody>
</table>

CMV, Cytomegalovirus; HSV, herpes simplex virus; JCV, John Cunningham virus; MRSA, methicillin-resistant Staphylococcus aureus; RSV, respiratory syncytial virus; VZV, varicella-zoster virus.

RESULTS
Identification of patients with DIAPH1-related disease
We studied 7 patients with SCBMS originating from Finland and Oman, who presented with a global developmental delay with progressive microcephaly, drug-resistant early-onset epileptic seizures, cortical blindness, and deficiency of cellular immunity (Table I). To identify a genetic cause for the disease, we acquired WES of all patients. WES data were analyzed for rare (frequency <0.01), exonic or splice region variants that followed de novo or compound heterozygous inheritance, as well as for de novo variants. WES identified a homozygous, previously published pathogenic NM_005219:c.684G>A variant in all Finnish patients, although the families were not known to share recent ancestry. The variant was validated by targeted capillary sequencing (see Fig E1 in this article’s Online Repository at www.jacionline.org). In the 2 Omani patients, diagnostic WES analyses found a homozygous, previously published pathogenic NM_005219:c.2769delT:p.F923fs variant (Fig 1, A and B).22 No other

Statistics and data visualization
Welch t test (fluorescence intensity) and Student t test (western blot band intensities, imaging data) were used to calculate P values between groups. Data were handled and plotted with R (4.0.3) using the ggplot2 package in Rstudio (v1.3.1093).

Study approval
This study was approved by the Regional Ethics Committee of the Northern Ostrobothnia and the Research and Ethics Review and Approval Committee in Ministry of Health, Oman, and conducted according to the principles of the Helsinki Declaration. Written informed consents were obtained from caregivers of the patients, their family members, and healthy controls.

electroporation, 80 μL/sample of RPMI with 1% FBS and IL-2 at 500 U/mL, was added and cells were allowed to rest at 37°C for 15 minutes, followed by transfer into 24-well plate in 400 μL medium. Cells were since cultured at a concentration of 0.5 to 2 × 10^6/mL. Five days after electroporation, cells were restimulated either as before electroporation or with 1:2 ratio of CD3/CD28 beads (ThermoFisher). After 16 and 40 hours, cells were collected for activation marker analysis by flow cytometry.
pathogenic variants were identified. Other variants surviving filtering in families 1, 4, and 5 are listed in Table E3 in this article’s Online Repository at www.jacionline.org.

Analysis of patient-derived cDNA showed that the c.684+1G>A variant resulted in aberrant splicing of DIAPH1 (Fig 1, C; see Fig E2 and capillary sequencing results in this article’s Online Repository at www.jacionline.org). Only WT transcript was detected in heterozygotes, possibly due to dosage compensation and preferential PCR amplification of the more abundant WT transcript. Western blot of immortalized fibroblast and PBMC total protein extracts indicated total loss of the DIAPH1 protein in patients (Fig 1, D). In control fibroblasts, only the 141-kDa full-length DIAPH1 was detected, whereas unstimulated control PBMCs contained very little of the full-length protein and higher amounts of a shorter isoform of approximately 75 kDa. In healthy donor PBMCs in response to stimulation (stim) by anti-CD3/CD28, blotted, and probed for DIAPH1. Numbers below bands indicate relative band volume intensity after total protein normalization, with the average of the 0-day samples set to 1.

**FIG 1.** Genetics and effects of DIAPH1 variants. A, Pedigrees of studied families. For F1, only those siblings who participated in segregation analysis are displayed. B, DIAPH1 protein structure showing published SCBMS-causing variants. Variants found in patients in this article are marked in red. C, Gel separation of PCR amplicons spanning the variant from patient-derived and parental cDNA. D, Total protein from patient and healthy control–derived fibroblasts or PBMCs was run on SDS-PAGE gel, blotted, and probed for DIAPH1. GAPDH was used as a loading control. E, Total protein from PBL of 2 healthy controls was collected every 2 days since stimulation (stim) by anti-CD3/CD28, blotted, and probed for DIAPH1. Numbers below bands indicate relative band volume intensity after total protein normalization, with the average of the 0-day samples set to 1. Black line indicates samples were run on the same gel but were noncontiguous. F, Lengths of shared haplotype segments around the c.684+1G>A variant in phased array data. Data from patients (GSA-chip) are shown as dark gray bars, and data from heterozygous carriers (PCC1-20, CoreExome-chip) are shown as light gray bars. Numbers next to bars represent haplotype arm lengths around the variant (black vertical line) in megabases (Mb). G, MDS plot (first 2 dimensions) was constructed to visualize genetic distances between 20 variant carriers in a Finnish population cohort. Gray dots: noncarrier, yellow dots: DIAPH1 c.684+1G>A heterozygote. GAPDH, Glyceraldehyde-3-phosphate dehydrogenase; HC, healthy control; MAT, maternal haplotype; MDS, multidimensional scaling; PAT, paternal haplotype.
### TABLE II. Immunophenotype of patients with SCBMS

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Patient</th>
<th>Reference values</th>
</tr>
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<tbody>
<tr>
<td><strong>Age at sampling (y)</strong></td>
<td>9</td>
<td>4</td>
</tr>
<tr>
<td><strong>Leukocytes</strong></td>
<td>8.0</td>
<td>11.0</td>
</tr>
<tr>
<td><strong>Neutrophils</strong></td>
<td>4.8</td>
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<tr>
<td><strong>Lymphocytes</strong></td>
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<td>5.1</td>
</tr>
<tr>
<td><strong>CD19⁺ B cells</strong></td>
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<tr>
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<tr>
<td><strong>Naive CD27⁺ IgD⁻ IgM⁺</strong></td>
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<tr>
<td><strong>Memory CD27⁺</strong></td>
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<td><strong>Marginal zone</strong></td>
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<tr>
<td><strong>Switched memory</strong></td>
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<tr>
<td><strong>Plasmablasts CD38⁺ IgM⁺</strong></td>
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<td><strong>Activated CD3⁴⁺CD21⁻</strong></td>
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<td>3315</td>
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<td><strong>T17⁺: IFN-γ in PMA-stimulated cells</strong></td>
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<tr>
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(Continued)
to stimulation with soluble anti-CD3/CD28 or with PHA, the amount of full-length DIAPH1 increased, suggesting that DIAPH1 is relevant for proliferating lymphocytes (Fig 1; see Fig E3 in this article’s Online Repository at www.jacionline.org).

The novel DIAPH1:c.684+1G>A disease variant is enriched in the Finnish population

Comparison of variant frequency between populations in the Genome Aggregation Database revealed that the c.684+1G>A variant is enriched in the Finnish population at an allele frequency of 0.001125. In genotype data from approximately 11,400 individuals from Finnish population cohorts (FINRISK and TWIN studies), the variant was present at a similar allele frequency. To investigate whether the c.684+1G>A variant had arisen from a single mutational event, we carried out haplotype analysis for 20 unrelated, heterozygous, variant carriers in the cohort. The analysis indicated that the c.684+1G>A variant lied on a shared ancestral haplotype with a median length of 8.8 Mb for shared haplotype segments (Fig 1F; see Tables E4 and E5 in this article’s Online Repository at www.jacionline.org). Average pairwise identity-by-descent-sharing coefficients (PI-HAT) were 0.0038 for the whole cohort and 0.0067 for variant carriers, with values ranging from 0 to 0.03 between distinct patient sample pairs (see Table E6 in this article’s Online Repository at www.jacionline.org), indicating greater than average genomic sharing between some but not all carriers. Similarly, on a multidimensional scaling plot, some of the variant carriers clustered together whereas others exhibited comparatively low genomic sharing (Fig 1G). This suggests that the mutational event has not taken place very recently. Using a previously published approach that uses the information on the haplotype arm lengths and assuming a correlated genealogy, the age of the mutation was estimated at 17.9 generations (95% CI from 4.3 to 32.5 generations).

Clinical characteristics of patients with SCBMS

Detailed clinical descriptions for each patient can be found in this article’s Online Repository at www.jacionline.org. Shortly, all studied patients had microcephaly, developmental delay, epilepsy, and cortical blindness characteristic to the SCBMS syndrome (Table 1). Brain magnetic resonance imaging of patients F1.P1, F1.P2, and F2.P3 demonstrated thin chiasm and optic nerves, and T2-hyperintense white matter and cortical signal abnormalities in bilateral occipital lobes (see Fig E4, A, in this article’s Online Repository at www.jacionline.org). The clinical presentation of F4.P5 and brain magnetic resonance imaging have been previously described. In autopsy, neuropathological examination of F1.P2 and immunohistochemical stainings revealed several morphological abnormalities (Fig E4, B and C). In family 1, mitochondrial disease was suspected on the basis of progressive brain atrophy, mildly elevated lactate/pyruvate ratio in blood, and increased number of mitochondria and mild increase in fat in muscle biopsies. F2.P3, F5.P6, and F5.P7 also presented with muscular hypotonia. Moreover, the patients showed signs of immunodeficiency. F1.P1 and F1.P2 suffered recurrent respiratory infections as well as persistent and extensive Molluscum contagiosum lesions. In addition, F1.P1 had recurrent oral herpes simplex virus and fungal infections throughout his childhood. At 19 years, he had EBV viremia and subsequently developed and succumbed to diffuse large B-cell lymphoma. F1.P2 died of nonimmune causes (status epilepticus) at the age of 6 years, but autopsy revealed a subclinical Hodgkin-type lymphoma. In addition, patient F5.P6 died of EBV-positive B-cell lymphoma at age 3 years (see Fig E5 in this article’s Online Repository at www.jacionline.org). Patient F4.P5 suffered from persistent vaccine strain Rubella skin infection and progressive multifocal leukoencephalopathy positive for John Cunningham virus. These clinical findings are consistent with poor T-cell immunity.

B-cell maturation defects

Complement activity, natural killer cell, and neutrophil counts and oxidative burst were normal in all tested patients. However, 5 of the 7 patients were deficient with at least 1 major immunoglobulin class. CD19+ B cells were very low in 1 patient (F5.P6), and immunophenotyping showed that proportions of memory B cells, marginal zone CD27- IgD- IgM- and switched memory CD27+ IgD+ IgM- B cells were low in the other 4 patients from whom PBMCs were available for analysis (Table II). Proportions of transitional CD38+IgM+ B cells in turn were elevated.

DIAPH1 is required for T-cell function

Lymphocyte differentials indicated abnormalities in the T-cell compartment: CD3+ T-cell counts were low or normal and showed skewing of the CD4/CD8 ratio below 1. Patients consistently showed defective T-cell maturation with low naive CD4+CD3+ and CD8+CD3+ (CD45RA+CCR7+) T-cell populations and nearly absent CD45RA+CD62L+CD31+ recent thymic emigrant cells. Proportion of IFN-γ and IL-17–positive CD4+ T-cell counts were high, indicating Th1 and Th17 activity, respectively.

All patients from whom PBMCs were available for analysis repeatedly showed a poor or absent lymphocyte proliferation response to stimulation by concanavalin A, PHA, or anti-CD3/CD28–coated beads (Table II; Fig 2, A and B). However, responses to soluble antibodies or pokeweed mitogens varied
from normal to absent between patients. Similarly, in flow cytometric analysis after in vitro stimulation with PHA or anti-CD3/CD28 beads, patient-derived T cells exhibited poor upregulation of the activation markers CD69 and CD25, especially in the CD8\(^+\)-cell subset (Fig 2, C and D). Stimulation with soluble anti-CD3/CD28 resulted in a more variable result: poor upregulation of both markers in F3.P4, otherwise normal response except for weak CD25 upregulation in CD8\(^+\) T cells in F4.P5, and a WT-like response in F2.P3. Of note, F2.P3 showed high spontaneous lymphocyte activation similar to what is sometimes seen with chronic herpes simplex virus infection, but test results for herpes simplex virus and EBV were negative.

To confirm reduced proliferation instead of increased apoptosis of activated lymphocytes, the percentage of apoptotic cells was estimated in 2 patients via an imaging-based AnnexinV-binding assay. Neither patient showed increased activation-induced cell death after stimulation by PHA or anti-CD3/CD28, although baseline percentage of AnnexinV-positive cells was higher in the F2.P3 sample than in controls (see Fig E6 in this article’s Online Repository at www.jacionline.org).
Knockout of DIAPH1 in healthy donor PBMCs replicates the SCBMS patient T-cell phenotype

To confirm that the T-cell activation defect was due to lack of DIAPH1, we generated DIAPH1 knockout cells from PBMCs of 2 healthy donors with the CRISPR-Cas9 method. Seven days after electroporation, 20% to 40% of cells in each replicate sample were negative for DIAPH1 protein (DIAPH1<sup>−/−</sup>) as estimated by flow cytometry (Fig 2, E). Samples were stimulated with anti-CD3/CD28 beads or soluble antibody tetramers to assay upregulation of activation markers and proliferation. At 16 and 40 hours after stimulation, the percentage of cells positive for CD69 and CD25 was markedly reduced in DIAPH1<sup>−/−</sup> cells compared with DIAPH1<sup>+/+</sup> cells from the same donor (Fig 2, F). In addition, after gating of CD69<sup>+</sup> or CD25-positive cells, median fluorescence intensities of CD69 and CD25, respectively, were significantly lower for DIAPH1<sup>−/−</sup> cells at most time points (see Fig E7 in this article’s Online Repository at www.jacionline.org). Hence, knockout of DIAPH1 in healthy

**FIG 3.** Analysis of T-cell adhesion, shape, and cytoskeletal organization. A-C, A total of 25,000 T cells were plated on 8-well chamber slide coated with CD3 and CD28 antibodies, let attach for 1 hour, fixed, and stained for F-actin. Imaging was done with Olymmpus Fluoview FV1000 confocal microscope at 60×. A, The number of adhered cells counted from 6 replicate wells (<3-7 images/well) was lower for patient samples than for healthy controls (P = .001 for F2.P3/control; P = .016 for F4.P5/control II). B, Cell circularity index (where 1 = perfect circle) of 12 to 17 cells per study subject was measured using Fiji image analysis software. The circularity index was higher in patient cells compared with control cells although only significantly so for F2.P3 (P = .003). Error bars = SD. C, Representative microscopic fields of patient and control cells. Blue = Hoechst (nucleus), green = Phalloidin (F-actin). D, T cells from 3 healthy donors and 2 patients (F2.P3 and F4.P5) were stained for α-tubulin to visualize the MTOC. The MTOC distance from ICAM-1 anti-CD3-coated surface was measured in 3D in 300 cells/sample with Harmony 4.9 software, and average distances were compared between patients and controls. Error bars = SD of the mean. E, Representative microscopic fields of patient and control cells. Yellow = α-tubulin (MTOC), Red (upper panel) = MitoTracker Deep Red (mitochondria), Red (lower panel) = Phalloidin AF647 (F-actin), Blue = Hoechst (nucleus). Student t test: *P < .05, **P < .01, ***P < .001.
donor PBMCs reproduced the T-cell activation defect detected in patients lacking DIAPH1.

T cells from patients with SCBMS exhibit impaired cytoskeletal regulation

To investigate whether the mechanism of the T-cell activation defect was related to the role of DIAPH1 in regulation of the cytoskeleton, we studied cell morphology and adhesion, as well as F-actin and α-tubulin organization by immunofluorescence staining and microscopic imaging of T cells from patients and healthy donors. When seeded on CD3/CD28 antibody–coated surface, fewer patient than control cells were able to adhere (Fig 3, A). In addition, patient cells seemed more circular than control cells (Fig 3, B and C). Measurement of the MTOC distance from surface in T cells seeded on ICAM-1 and CD3 antibody–coated wells indicated less efficient MTOC reorientation to the immunologic synapse in patient-derived T cells than control cells (Fig 3, D and E). These results suggest altered cytoskeletal regulation in T cells lacking DIAPH1. No consistent changes were found in amount or localization of F-actin or mitochondria. We also tested chemotaxis of T cells cultured for 10 days after stimulation with soluble CD3/CD28 antibodies, but found no difference in SDF1-α–driven chemotaxis between patients (F2.P3 and F4.P5) and controls (see Fig E8 in this article’s Online Repository at www.jacionline.org).

DIAPH1 regulates mitochondrial respiration through complex IV

In F1 patient–derived immortalized fibroblasts, we examined the levels of mitochondrial respiratory chain complexes of the mitochondrial oxidative phosphorylation system. Blue Native Polyacrylamide Gel Electrophoresis analysis for complexes I to V (CI–CV) revealed isolated deficiency of complex IV (CIV) (Fig 4, A and B). To confirm the link between DIAPH1 and CIV by complementation, we introduced a full-length WT-DIAPH1 expression construct into immortalized patient and control fibroblasts by lentiviral gene transfer. Surprisingly, instead of normalizing the amount of fully assembled CIV, DIAPH1 overexpression resulted in a dramatic decrease in CIV amount in both control and patient total cell pools (Fig 4, C). In addition, overexpression of DIAPH1 led to a decrease in actin levels (see Fig E9 in this article’s Online Repository at www.jacionline.org). On examination of individual patient fibroblast overexpression clones, all clones showed higher DIAPH1 expression than WT fibroblasts (Fig 4, D). The expression of COXIV (an individual subunit of complex IV) and the amount of fully assembled CIV varied among separate clones expressing WT-DIAPH1 (Fig 4, D and E). One of the clones (C4) had reached the normal amount of fully assembled complex IV after the complementation and thus the CIV defect was rescued by the expression of WT-DIAPH1. Altogether this finding confirms that the CIV deficiency detected in patient fibroblasts originally was due to the lack of normal expression of DIAPH1.

FIG 4. DIAPH1 affects CIV abundance. A, BN-PAGE for mitochondrial respiratory complexes indicated selective deficiency of CIV in patient-derived immortalized fibroblasts. B, 2D-SDS-PAGE querying amount of CIV (COX1 staining) and complex II (CI, SDHA staining) in patient and control fibroblasts. WT-DIAPH1 expression construct was introduced to patient and healthy control–derived immortalized fibroblasts, and expression of several proteins and respiratory complexes was queried by western blotting in (C) BN-PAGE for CIV and CII. D, SDS-PAGE for DIAPH1 and COX4 (CIV subunit) in individual WT-DIAPH1-expression clones; GAPDH was used as a loading control; E, BN-PAGE for mitochondrial respiratory complexes in individual clones. Bars represent mean band intensity and error bars SD from 3 separate sample preparations. Vertical black lines indicate the lanes were run on the same gel but were noncontiguous. BN-PAGE, Blue Native Polyacrylamide Gel Electrophoresis; Relat., relative. P values were calculated using Student t test: *P < .05, **P < .01, ***P < .001.
By immunocytochemistry, we studied the distribution of the mitochondrial network in the immortalized fibroblasts using antibodies against Tom20, a mitochondrial outer membrane protein, and MT-CO1, a subunit of complex IV (see Fig E10 in this article’s Online Repository at www.jacionline.org). Staining for DIAPH1 showed a lack of DIAPH1 in patient fibroblasts and clear overexpression of the protein after the complementation in both patient and control fibroblasts. In WT cells, most of the DIAPH1 protein localized to the cytoplasm and there was no colocalization with mitochondrial markers. Interestingly, in patient-derived fibroblasts overexpressing WT-DIAPH1, MT-CO1 had a strong perinuclear localization, but based on staining for Tom20, the overall distribution of the mitochondrial network was not changed.

**Mitochondrial function in T cells lacking DIAPH1**

Because we had detected reduced CIV in patient fibroblasts, we hypothesized that the immunodeficiency in patients with SCBMS could also be linked to altered mitochondrial function. Hence, we analyzed mitochondrial membrane potential (MMP) of patient- and control-derived lymphocytes by treating the cells with tetramethylrhodamine ethyl ester, a dye that accumulates in mitochondria, based on their negative MMP. Although results from CD4\(^{+}\) cells were comparable between patients and controls, the tetramethylrhodamine ethyl ester signal-profile differed markedly between control and patient CD8\(^{+}\) T cells (see Fig E11, A, in this article’s Online Repository at www.jacionline.org). In control CD3\(^{+}\)CD8\(^{+}\) cells, 2 populations with different peak fluorescence intensities were detected, whereas patient (F2.P3 and F3.P4) CD3\(^{+}\)CD8\(^{+}\) cells showed only 1 population with an MMP signal localizing between those of the populations detected in controls.

To investigate whether there were differences in mitochondrial mass between samples, lymphocytes were stained with nonylacridine orange, a reagent that enters mitochondria independently of MMP. Patients, especially F2.P3, had a higher number of lymphocytes with a slightly lower mitochondrial mass (Fig E11, B).

We also assayed upregulation of cellular and mitochondrial calcium after activation with anti-CD3/CD28 beads in PBLs loaded with the fluorescent Ca\(^{2+}\) indicators Fluo-4 AM and Rhod-2 AM, respectively. To account for differences in reagent loading between samples, we analyzed signal intensity fold induction in response to stimulation. Patient PBLs exhibited a significantly weaker upregulation of mitochondrial Ca\(^{2+}\) in response to stimulation than controls (Fig E11, C).

**DISCUSSION**

In 5 patients from 4 unrelated Finnish pedigrees, we found homozygosity for a rare DIAPH1 splice variant (c.684+1G>A) that leads to SCBMS via loss of the DIAPH1 protein. This variant is enriched in the Finnish population at an allele frequency of roughly 0.1%, and haplotype analysis implied a common ancestral origin for the variant. The DIAPH1 c.684+1G>A variant is responsible for all cases of SCBMS identified in Finland thus far and is, to our knowledge, the first disease-causing variant in DIAPH1 to have population-level impact. In addition, 2 additional patients originating from Oman with no known relation to previously published patients were found homozygous for the DIAPH1:c.2769delT:p.F923fs variant.22

The SCBMS syndrome seems to be readily identifiable by the hallmark symptoms of microcephaly, early-onset refractory epileptic seizures, cortical blindness, and intellectual disability exhibited by all patients.12,22 In addition, all patients reported here had findings supporting immunodeficiency and some had signs of mitochondrial dysfunction. Clinically, the patients suffered from infection susceptibility and B-cell lymphomas, both of which are common occurrences in immunodeficient patients.35,36 Immunologic investigations revealed that the patients were severely deficient in naïve T-cell populations. This implies that similar problems in T-cell egression from the thymus take place in patients with SCBMS as have been demonstrated in DIAPH1\(^{−/−}\) mice.14 Moreover, upregulation of activation markers and proliferation of patient T cells in response to stimulation by mitogens or anti-CD3/CD28 was markedly reduced similarly to what has been seen in the DIAPH1\(^{−/−}\) mouse model.15,16 This defect was reproduced by CRISPR-Cas9 knockout of DIAPH1 in healthy donor PBMCs, indicating that depressed T-cell immunity in patients is directly caused by lack of DIAPH1. Variation in the severity of the T-cell activation defect between patients and between healthy donor cells subjected to CRISPR-Cas9 knockout of DIAPH1 suggests modifying genetic factors.

While investigating the mechanism behind the functional T-cell defect, we found that patient-derived T cells exhibited impaired adhesion and inefficient MTOC translocation to the immunologic synapse. This cytoskeletal reorganization is essential for T-cell function.37 An MTOC repolarization defect has also been demonstrated previously in a Jurkat DIAPH1 knockdown model.15 Considering these and previously published results on functions of DIAPH1 in actin nucleation and microtubule organization, immune presentations in patients with SCBMS are not surprising, because mutations in several genes involved in regulation of the cytoskeleton cause primary immunodeficiency.38

DIAPH1 has previously been demonstrated to regulate mitochondrial motility and distribution.6,7 However, the mitochondrial network in SCBMS patient-derived fibroblasts seemed normal based on Tom20 staining. Instead, these cells showed deficiency of CIV, an integral part of mitochondrial respiration and regulator of mitochondrial oxidative phosphorylation.9 CIV deficiency is one of the most common mitochondrial diseases and can be caused by mutations in several genes encoding for CIV subunits or assembly factors.10,11 Typical pathology is somewhat dependent on the affected genes and tissues, but invariably includes encephalopathy, which is also a significant symptom of SCBMS. In patient T cells, we found changes in mitochondrial membrane potential and calcium. Changes in MMP in patient’s CD8\(^{+}\) cells could reflect alterations in CD8\(^{+}\) naive to experienced cell ratio, mitochondrial energy production, or both.41,42 Patient PBL also showed attenuated elevation of mitochondrial calcium in response to T-cell receptor engagement. This could be secondary to impairment of MTOC localization, because activation of calcium influx at the immunologic synapse is dependent on cytoskeletal reorganization.53 Because, however, mitochondrial localization and bioenergetics are a major regulator of immune cell function,44,48 immunometabolism in patients with SCBMS would be an interesting target for future investigations.
Conclusions

Our observations suggest that biallelic loss of **DIAPH1** negatively affects T-cell function and can lead to combined immunodeficiency. Hence, clinicians treating patients with SCBMS should be aware of a higher risk for developing severe or recurrent infections and lymphoma. Furthermore, our findings indicate that the pathogenetic mechanism of SCBMS may be linked to impaired regulation of cytoskeletal organization and to mitochondrial dysfunction. However, the exact mechanistic links between **DIAPH1** and the cytokeratin, mitochondrial function, CIV, and T-cell responses warrant further investigations.

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**Key messages**

- Clinicians treating patients with SCBMS should be aware of a higher risk for persistent infections and lymphoma.
- Loss of **DIAPH1** can result in aberrant B- and T-cell maturation and reduction in T-cell functionality due to defects in cytoskeletal organization.
- Mitochondrial dysfunction may underlie aspects of **DIAPH1**-related disease.

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