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Identification of Variants in RET and IHH Pathway Members in a Large Family With History of Hirschsprung Disease


BACKGROUND & AIMS: Hirschsprung disease (HSCR) is an inherited congenital disorder characterized by absence of enteric ganglia in the distal part of the gut. Variants in ret proto-oncogene (RET) have been associated with up to 50% of familial and 35% of sporadic cases. We searched for variants that affect disease risk in a large, multigenerational family with history of HSCR in a linkage region previously associated with the disease (4q31.3-q32.3) and exome wide. METHODS: We performed exome sequencing analyses of a family in the Netherlands with 5 members diagnosed with HSCR and 2 members diagnosed with functional constipation. We initially focused on variants in genes located in 4q31.3-q32.3; however, we also performed an exome-wide analysis in which known HSCR or HSCR-associated gene variants predicted to be deleterious were prioritized for further analysis. Candidate genes were expressed in HEK293, COS-7, and Neuro-2a cells and analyzed by luciferase and immunoblot assays. Morpholinos were expressed in zebrafish embryos. Embryos were allowed to develop and stained for enteric neurons. RESULTS: Within the linkage region, we identified 1 putative splice variant in the lipopolysaccharide responsive beige-like anchor protein gene (LRBA). Functional assays could not confirm its predicted effect on messenger RNA splicing or on expression of the mab-21 like 2 gene (MAB21L2), which is embedded in LRBA. Zebrafish that developed following injection of the lrba morpholino had a shortened body axis and subtle gut morphological defects, but no significant reduction in number of enteric neurons compared with controls. Outside the linkage region, members of 1 branch of the family carried a previously unidentified RET variant or an in-frame deletion in the glial cell line derived neurotrophic factor gene (GDNF), which encodes a ligand of RET. This deletion was located 6 base pairs before the last codon. We also found variants in the Indian hedgehog gene (IHH) and its mediator, the transcription factor GLI family zinc finger 3 (GLI3). When expressed in cells, the RET-P399L variant disrupted protein glycosylation and had altered phosphorylation following activation by GDNF. The deletion in GDNF prevented secretion of its gene product, reducing RET activation, and the IHH-Q51K variant reduced expression of the transcription factor GLI1. Injection of morpholinos that target ihh reduced the number of enteric neurons to 13% ± 1.4% of control zebrafish. CONCLUSIONS: In a study of a large family with history of HSCR, we identified variants in LRBA, RET, the gene encoding the RET ligand (GDNF), IHH, and a gene encoding a mediator of IHH signaling (GLI3). These variants altered functions of the gene products when expressed in cells and knockout of ihh reduced the number of enteric neurons in the zebrafish gut.

Keywords: ENS; Neural Development; Genetic Causes of HSCR; Family Study.

Hirschsprung disease (HSCR) is a congenital disorder characterized by the absence of enteric ganglia in variable lengths of the distal gut. As a consequence, functional networks of neurons and glia, the intrinsic innervations of the gastrointestinal tract comprising the enteric nervous system (ENS), cannot be established, leading to intestinal obstruction by dysregulated smooth muscle contraction/relaxation.

HSCR is considered to be an inherited disease. This assumption is based on several lines of evidence, including familial occurrence (~5%), elevated risk of occurrence in

*Authors share co-first authorship.

Abbreviations used in this paper: bp, base pair; ENS, enteric nervous system; GDNF, glial cell–derived neurotrophic factor; GFP, green fluorescent protein; GLI1, GLI family zinc finger 1; GLI3, GLI family zinc finger 3; HEK, human embryonic kidney cells; Hh, Hedgehog; hpf, hours post fertilization; HSCR, Hirschsprung disease; IHH, Indian Hedgehog; LRBA, lipopolysaccharide-responsive beige-like anchor; MAB21L2, Mab-21-Like 2; mRNA, messenger RNA; WT, wild-type.

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WHAT YOU NEED TO KNOW

BACKGROUND AND CONTEXT
Hirschsprung disease (HSCR) arises due to failure of the enteric neurons to colonize the gut. It is an inherited disorder, but the genetic cause is unknown in the majority of cases.

NEW FINDINGS
In a Dutch multigenerational family with history of HSCR, the authors identified variants in RET, GDNF, IHH and GLI3 that disrupt the function of their encoded proteins, contributing to disease development.

LIMITATIONS
The variants identified in this family are rare and unlikely to explain the missing heritability seen in the majority of HSCR cases.

IMPACT
This study confirms RET as the major HSCR gene and shows that a combination of rare variants in GDNF, IHH and GLI3, modulates clinical expression of the disease phenotype.

siblings (relative risk as high as 200), association with chromosomal abnormalities, and the existence of many naturally occurring animal models with colonic aganglionosis. The mode of inheritance can vary from dominant with reduced penetrance, mostly found in nonsyndromic familial HSCR cases, to recessive, in families with syndromic HSCR. Sporadic HSCR cases also have been reported and are believed to be multifactorial and polygenic in nature, suggesting the involvement of several genes in concert.

The search for genes involved in HSCR has been extensive and ranged from classical linkage to genome-wide association studies and candidate gene approaches. To date, mutations in approximately 20 genes have been identified. However, the REarranged during Transfection (RET) gene is still considered to be the major HSCR gene, as 50% of familial cases and 15% to 35% of sporadic cases carry a RET mutation. Linkage analysis conducted on 12 multiplex HSCR families showed that almost every patient with HSCR has a variant in RET. Thus, RET seems to be crucial in developing HSCR, but it is also likely that one or more modifier genes, as well as environmental factors, are involved in disease pathogenesis, even when a high penetrant RET mutation is found.

Corroborated this idea. Although 11 families showed linkage to the RET locus, only half of them (6) carried a severe RET coding mutation. Intriguingly, the remaining 5 families also showed linkage to 9q31, suggesting the involvement of a modifier gene at this locus. After these early findings, subsequent studies were conducted to search for modifier loci in HSCR. Sib-pair analysis resulted in the identification of 2 additional loci at 3p21 and 19q12, haplotype sharing in a large Mennonite kindred identified a new locus on 16q23, linkage analysis in a multigenerational Dutch family identified a locus at 4q31.3-q32.3, and genome-wide association studies also have identified loci at 7q21.11 and 8p12. However, combinations of distinct rare mutations resulting in HSCR are not frequently reported.

In this article, we focus on one family in which a 12.2-Mb interval suggestive for linkage was identified on 4q31.3-q32.3 (chr4: 142,197,646–158,353,484 [Hg19]), but no pathogenic variants in the known HSCR genes have been found. Based on the pedigree, incomplete penetrance of a disease-associated variant was expected, suggesting the involvement of several genes. In an attempt to identify the genetic cause of HSCR in this family, we have now used whole-exome sequencing to search for yet unidentified pathogenic rare variants or modifier genes. We determined segregation patterns for candidate variants, and performed in vitro and in vivo studies to test the involvement of the identified candidate genes in disease pathogenesis, revealing the complex genetic nature of HSCR.

Materials and Methods

Patient Information
A multigenerational Dutch family was included in this study. This family is composed of 5 individuals diagnosed with HSCR (IV-3, V-1, V-2, V-3, and V-4), and 2 diagnosed with functional constipation (III-1 and IV-2) (Figure 1). A detailed description of the phenotypes has been previously reported. Written informed consent was obtained from the parents for diagnostic analysis.

Exome Sequencing and Variant Prioritization
Two HSCR-affected individuals (V-1 and V-4) from different branches of the family were initially selected for exome sequencing. In a later stage of the study, IV-4 and IV-5 were also included (Figure 1). Three micrograms of DNA from each of the individuals was used. Details about execution and data analysis can be found in supplementary data.

Validation of Candidate Variants and Family Screening
Genomic DNA was isolated from peripheral blood leukocytes using a standard protocol previously described. Candidate variants were validated by Sanger sequencing as previously described. Segregation analysis was performed using family members for which DNA was available (II-2, III-2, IV-1, IV-2, IV-3, IV-4, IV-5, V-1, V-2, V-3, and V-4).
Vector Design and Site Direct Mutagenesis

Vectors used are described in detail in supplementary data.

Whole-Mount In Situ Hybridization for lrba, mab21l2, and ihh in Zebrafish

lrba (lipopolysaccharide responsive beige-like anchor), mab21l2 (Mab-21-Like 2), and ihh (Indian hedgehog) genes were amplified from total mRNA collected from zebrafish embryos at 48 hours post fertilization (hpf), by reverse transcription polymerase chain reaction (RT-PCR) using a One-Step RT-PCR Kit (Qiagen, Valencia, CA). Primers used are described in Supplementary Table 1. A detailed protocol can be found in supplementary data.

lrba, mab21l2, and ihh Morphant Analysis in Zebrafish

Two splice blocking morpholinos were designed to target exon 13 (AGTGGTTTAGCTCTTACCAGAC) and exon 24 (ACTGCTACTAACCCGAGAAGAGT) of lrba. The effectiveness of these morpholinos was confirmed by RT-PCR. A previously described translation blocking morpholino for mab21l2 (ACTGTAGACCGGAGTTTCGCAGTAC) was used25 (Gene Tools, Philomath, OR). A mab21l2 mutant line (au12 allele) was also analyzed.26 The ihh morpholino (GGAGACGCATTCCACCGCAAGCG) was designed to target the transcription start site of ihh, as previously described.27 Morphants were generated by injecting 100 μM of each morpholino into 1-cell-stage zebrafish embryos. Morphant/mutant and control embryos were allowed to develop until 120 hpf and were fixed and stained for ENS neurons using the HuC/D antibody (Invitrogen, Carlsbad, CA), as previously reported.28 A p53 control morpholino (Gene Tools) was coinjected in all morphant and control embryos, to suppress apoptotic effects induced as a secondary effect of the morpholinos, as described elsewhere.29 To determine the number of enteric neurons present, a 10-segment length of the gut to the vent was counted. The numbers in the text represent percent of control ± SEM for at least 5 separate embryos per morpholino/mutant genotype. Significance was determined by the Student t test with significance assessed when $P < .0005$.

Cell Culture and Transfections

Human embryonic kidney (HEK293) cells, COS-7 cells (CV-1 [simian] in origin, and carrying the SV40 genetic material), and control fibroblasts were cultured in Dulbecco’s modified Eagle’s minimal essential medium (GIBCO, Waltham, MA) containing 10% fetal bovine serum (GIBCO) and penicillin/streptomycin (GIBCO). The neuroblastoma cell line (Neuro-2a) (CCL-131; American Type Culture Collection, Manassas, VA) was cultured according to the protocol of the American Type Culture Collection. All cell lines were incubated at 37°C, and supplied with 5% CO₂. Transfection was performed as described before.30

Exon Trap Assays

The exon trap assays were performed as described before.31,32 SD6 and SA2 primers are described in Supplementary Table 1.

Luciferase Assays

Neuro-2a cells were transfected with 1 μg of SV40-P or LRBA-wild-type (WT)/mutant (Mut) vectors and cotransfected with 10 ng of internal control, pRL-SV40-Renilla Luciferase (Promega, Madison, WI). Luciferase activity was measured and
formed in 3 independent, triplicate experiments (n = 9).

**Activation of the Indian Hedgehog Signaling**

HEK293 cells cultured in a 6-well plate were transiently transfected with pCMV-IHH-FLAG-WT/Mut. After 24 hours, the medium of transfected cells (conditioned medium) was collected and filtered using a 0.45-μm filter; 200,000 to 300,000 control human fibroblast cells were cultured in a 6-well plate for 24 hours. After this period, the medium was replaced by 1 mL fresh complete medium and 500 μL conditioned medium (containing secreted IHH-WT or IHH-Mut). Conditioned medium derived from nontransfected HEK293 cells was used as a negative control. Medium supplemented with 20 μM Purmorphamine (Calbiochem, San Diego, CA) was used as a positive control for activation of the Hedgehog (Hh) signaling: 500 μL conditioned medium was concentrated using an M-10 filter (Millipore, Bedford, MA) and used for Western blot to determine the levels of IHH-WT and IHH-Mut protein secreted into the medium.

**Glial Cell–Derived Neurotrophic Factor Stimulation and Western Blot**

HEK293 cells were transiently cotransfected with pCMV-RET-WT/Mut (P399L), pCMV-GFRα1, and pNE–green fluorescent protein (GFP). After 24 hours, cells were treated with 50 ng/mL glial cell–derived neurotrophic factor (GDNF) (Peprotech EC, London, UK) for 15 minutes. To test the effect of the GDNF deletion, conditioned medium collected from HEK293 cells transfected with a GDNF WT or GDNF-Mut constructs was collected in a similar way as described for IHH, and used to stimulate HEK293 cells transfected with pCMV-RET-WT, pCMV-GFRα1, and pNE-GFP. An amount of 500 μL of conditioned medium was also concentrated as described for IHH, and used to determine the levels of GDNF-WT and GDNF-Mut protein secreted into the medium by Western blot. Cell lysis, protein quantification, and Western blot were performed as previously described.30 Primary and secondary antibodies used are described in Supplementary Table 2.

**RNA Isolation and qReal-time-PCR**

RNA isolation, complementary DNA preparation, and quantitative real-time (qRT) PCR are described in supplementary data.

**Statistical Analysis**

All results are expressed as the mean ± standard deviation or standard error of the mean. All data were analyzed using a 2-tailed Student t test or the χ² test. P < .05 was considered to be statistically significant.

**Results**

**A Putative Splice Variant in LRBA Was Found in the Linkage Interval**

Exome sequencing data collected from patients V-1 and V-4 were first analyzed to detect variants present in the linkage interval previously identified.18 Exons that were not totally covered within this region (7 exons), were Sanger sequenced. From the exome analysis, only 1 rare variant (Exome Aggregation Consortium: 0.002534, and Genome of the Netherlands database: 0.009), predicted to be deleterious was found: a putative splice variant affecting exon 20 of the LRBA gene (NM_001199282.2:c.2444A>G) (Table 1 and Supplementary Table 3). LRBA was also found to be expressed in mouse gut,44 leading us to consider it the best candidate gene for this family. Sanger sequencing confirmed the presence of the LRBA variant in all family members for which DNA was available (n = 11), and segregation patterns were determined (Figure 1; Supplementary Table 4).

**lrba Is Not Required for ENS Development in Zebrafish**

To investigate a possible role for LRBA in ENS development, we used the zebrafish as a model system. A single zebrafish ortholog for lrba was identified in an Ensemble gene search, which showed strong sequence similarity, as well as genome organization, to its human ortholog (82% homology). Whole-mount in situ hybridization revealed that lrba has a comparatively restricted expression pattern in zebrafish (Figure 2A). At 24 hpf, lrba expression was identified along the yolk sac boundary and weakly in the hindbrain. At 48 hpf, lrba was still weakly present in the hindbrain, and no apparent expression was detected elsewhere in the embryo (Figure 2A). A similar pattern of expression was detected at 72 and 96 hpf. However, at 72 hpf, lrba expression appeared in the intestinal bulb, and it was maintained at 96 hpf (Figure 2A). We also designed 2 different splice blocking morpholinos to suppress expression of this gene in zebrafish. Examination of lrba morphants at 120 hpf revealed a shortened body axis and subtle gut morphological defects. However, no significant reduction in the number of enteric neurons was detected when compared with controls, as the number of neurons in lrba morphants was 97.2% ± 4.8% of control (n = 17; Figure 2B).

**Lack of Splicing Effect and Enhancing Defects for the LRBA Variant**

The LRBA variant identified in this family (NM_001199282.2:c.2444A>G) is predicted to affect mRNA splicing of exon 20 by 1 of the 5 splice site prediction programs included in the Alamut splicing prediction module (http://www.interactive-biosoftware.com/alamut-visual/). To confirm pathogenicity of this variant, exon trap assays were performed, but no splice defect was detected. Similar-size bands of spliced product were observed in both the WT and Mut situations (Figure 3A).

Within intron 42 of LRBA, another gene called Mab-21-Like 2 (MAB21L2) is found (Figure 3B). A previous study has shown that expression of MAB21L2 can be controlled in a tissue-specific manner by several enhancer elements present within LRBA.45 This led us to hypothesize that exon 20 of LRBA might work as one of these enhancers, and that the variant identified in this gene might disturb expression of MAB21L2. Because the role of MAB21L2 in ENS
### Table 1. Rare variants identified in patients V-1 (a) and/or V-4 (b)

<table>
<thead>
<tr>
<th>Sample</th>
<th>Gene</th>
<th>HGVS cDNA</th>
<th>Location</th>
<th>Effect</th>
<th>Exon</th>
<th>HGVS protein</th>
<th>dbSNP</th>
<th>Inherited from</th>
<th>ExAC</th>
<th>MAF</th>
<th>GoNLMAF</th>
<th>Linkage region</th>
<th>HSCR gene panel</th>
<th>ClinVar</th>
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<tr>
<td>a, b</td>
<td>RET</td>
<td>NM_020975.4:c.1196C&gt;T</td>
<td>E</td>
<td>MS</td>
<td>6</td>
<td>p.Pro399Leu</td>
<td>-</td>
<td>M</td>
<td>0</td>
<td>0</td>
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<td>Yes</td>
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<tr>
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<td>MS</td>
<td>7</td>
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<td>0.006</td>
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<td>No</td>
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<td></td>
</tr>
<tr>
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<td>MS</td>
<td>1</td>
<td>p.Gly62Glu</td>
<td>rs41298555</td>
<td>F</td>
<td>0.0003475</td>
<td>0</td>
<td>No</td>
<td>No</td>
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<td></td>
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<tr>
<td>a, b</td>
<td>LRBA</td>
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<td>MS, PSE</td>
<td>20</td>
<td>p.Asn815Ser</td>
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<td>M; F</td>
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<td>MS</td>
<td>1</td>
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<td>No</td>
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<tr>
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<td>MS</td>
<td>24</td>
<td>Asp1183His</td>
<td>rs201361018</td>
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<td>No</td>
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</tr>
<tr>
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<td>MS</td>
<td>16</td>
<td>p.Val899Ala</td>
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<td>MS</td>
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<td>NM_002181.3:c.151G&gt;A</td>
<td>E</td>
<td>MS</td>
<td>1</td>
<td>p.Gln51Lys</td>
<td>-</td>
<td>M</td>
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<td>No</td>
<td>Yes</td>
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<td>GLB1</td>
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<td>MS</td>
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<td>3</td>
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</tr>
</tbody>
</table>

**NOTE.** Build hg19, # public databases are 1000 Genomes, ESP6500, and Genome of the Netherlands (GoNL). All variants are heterozygous. The variants in *GLI3* and *RET* are known deleterious variants.

cDNA, complementary DNA; dbSNP, Single Nucleotide Polymorphism database; DN, de novo; E, exon; ExAC, Exome Aggregation Consortium; F, Father; HGVS, Human Genome Variation Society; IFD, in-frame deletion; M, Mother; MAF, minor allele frequency; MS, missense; PSE, putative splice effect.
that the 2 affected siblings of patient V-1 (V-2 and V-3), the
unaffected mother (IV-2), and the affected maternal uncle
(IV-3) also carry the same heterozygous \textit{RET} variant,
whereas the grandmother (III-2) does not (Figure 1,
Supplementary Table 4). Due to DNA unavailability, we
were unable to confirm the presence of this variant in the
grandfather (III-1). However, considering that both the
mother (IV-2) and the grandfather (III-1) were reported to
suffer from severe constipation in childhood, and the
grandmother (III-2) had no intestinal complaints, it is likely
that this \textit{RET} variant was inherited from the grandfather
(III-1). For patient V-4, 2 rare variants were identi-
fi ed in 2 different genes: Indian hedgehog (\textit{IHH})
(NM\_002181.3:c.151C>T, p.Q51K), and the GLI family zinc
finger 3 (\textit{GLI3}) (NM\_000168.5:c.2119C>T; p.P707S)
(Table 1 and Supplementary Table 3). Segregation analysis
 showed that both variants were inherited from the father
(Figure 1, Supplementary Table 4). The de novo analysis
performed for patient V-4 also identi-
fi ed a heterozygous in-
frame deletion in the Glial cell–derived
neurotrophic factor
gene (\textit{GDNF})
(NM\_001190468.1:c.676_681delGGA TGT)
(Figure 1, Table 1). No allelic frequencies of any of these
variants were found in the available databases.

\textbf{RET-P399L Disturbs Protein Glycosylation and Affects Phosphorylation on GDNF Activation In Vitro}

To determine the effect of the \textit{RET} rare variant identified in the first branch of the family (c.1196C>T, p.P399L), we
examined the glycosylation and phosphorylation status of the mutant protein and compared it with the WT. As expected, 2 bands were identified in the presence of the RET-WT–expressing vector (Figure 4A). The lower band
(~150 kDa) corresponds to the unglycosylated RET pro-
tein, whereas the upper one (~170 kDa) is the glycosylated
(mature) RET protein. In the presence of the RET-Mut (RET-
P399L) expressing vector, only the lower band was detec-
ted, suggesting that this variant disturbs protein glycosyla-
tion (Figure 4A). RET phosphorylation was also investigated
on GDNF stimulation, and in the presence of the Mut-
expressing vector, RET phosphorylation was dramatically
reduced (Figure 4A). These results confirm pathogenicity of the \textit{RET} variant identified.

\textbf{IHH-Q51K Disturbs Activation of Hedgehog Signaling In Vitro}

To study the effect of the \textit{IHH} variant identified in patient
V-4 (c.151C>T, p.Q51K), we transiently transfected HEK293
cells with \textit{IHH-WT-FLAG} and \textit{IHH-Q51K-FLAG} vectors.
Comparative expression levels of the precursor form of \textit{IHH-
WT} (~46 kDa) and IHH-Q51K were found in the cell lysates
and in the conditioned medium from transfected HEK293
cells (Figure 4B). However, a significant lower expression of the transcriptional target of Hh signaling, \textit{GLI1}, was identi-
fied by qreal time-PCR in fibroblasts cultured in the presence of conditioned medium containing the secreted form of mutant IHH (Figure 4C). This result confirms pathogenicity of the \textit{IHH} variant identified.

\textit{ihh} Is Required for ENS Development in Zebrafish

Transgenic zebrafish embryos \textit{Tg(-8.3pox2b:Kaede)}
were injected with a morpholino designed to specifically
target expression of \textit{ihh} to further study the involvement of
this gene in ENS development. Morphant and uninjected
control embryos were visualized at 120 hpf and several
differences were noticed. Morphant embryos showed a curved body, small eyes, and no swim bladder (Figure 4D). Moreover, a significant decrease in the number of enteric neurons was detected when compared with controls (Figure 4D). The number of enteric neurons in ihh morphants was $13\% \pm 1.4\%$ of that seen in controls ($n = 23$), suggesting that $ihh$ is required for normal ENS development in zebrafish.

**De Novo Deletion in GDNF Leads to Reduced Levels of Secreted Protein and Results in Impaired RET Activation**

A heterozygous de novo in-frame deletion in GDNF was identified in patient V-4 (NM_001190468.1:c.676–681delG-GATGT). Because this deletion affects 6 base pairs (bp) located just before the last codon of GDNF, a change in RNA stability is expected based on the RNAfold online software (http://rna.tbi.univie.ac.at/cgibin/RNAfold.cgi; Supplementary Figure 2 and Supplementary Table 5). To evaluate this effect, we performed qreal time-PCR on RNA isolated from HEK293 cells transfected with GDNF-WT-Myc-DDK and GDNF-Mut-Myc-DDK–expressing constructs. No significant effect on the mRNA levels was observed in the presence of the deletion (Figure 5A). To determine if the in-frame deletion identified impairs the function of GDNF, HEK293 cells transiently expressing RET and GFR-α1, were treated with conditioned medium containing GDNF-WT-Myc-DDK and GDNF-Mut-Myc-DDK. We observed that in the presence of the mutant protein, a decrease in RET expression and phosphorylation levels was observed when compared with the WT. This suggests that the deletion identified does affect the ability of GDNF to activate RET (Figure 5B). Moreover, we observed that the GDNF-Mut protein was
absent in the conditioned medium (~30 kDa), but it was still present inside the cells. The opposite situation was detected for GDNF-WT (Figure 5C). Based on our results, we concluded that the 6-bp deletion impairs secretion of GDNF, thus resulting in less RET activation.

Discussion

A complete understanding of the genetics of an inherited complex disease is a major challenge requiring substantial efforts. In this study, we used a combination of whole-exome sequencing and functional assays to find the underlying causes of HSCR in a multigenerational Dutch family.

Multiple Variants Contribute to HSCR

Finding multiple contributing variants seems logical for a disease with reduced penetrance, such as HSCR. Therefore, we were not surprised to find that 4 different genes appear to modulate disease expression in this family. In the first branch, a missense variant in RET was identified (Figure 1). This variant (c.1196C>T, p.P399L), was predicted to affect the extracellular domain of RET and result in RET dysfunction. Our in vitro studies confirmed this prediction, and showed that the variant identified was pathogenic, as it affected glycosylation and phosphorylation of RET (Figure 4A). A previous study of this family also reported that all 3 affected siblings (V-1, V-2, and V-3) inherited a common heterozygous RET risk haplotype from their father (IV-1). This haplotype is located in intron 1 of RET and has been shown to increase susceptibility for HSCR by affecting RET expression. Considering that the mother (IV-2) does not have HSCR despite carrying the pathogenic RET variant (c.1196C>T, p.P399L), it is logical to consider that the presence of the risk haplotype enhanced the penetrance of the RET variant, contributing to the development of the disease in patients V-1, V-2, and V-3.

In the second branch of this family, 2 missense variants located in IHH (NM_002181.3:c.151C>A) and GLI3 (NM_000168.5:c.2119C>T; p.P707S), and 1 de novo deletion in GDNF (c.676–681delGGATGT), have been found to underlie HSCR pathogenesis in patient V-4 (Figure 1). IHH and GLI3 encode members of the Hh pathway, whereas GDNF encodes a RET ligand. Hh signaling is known to be essential for the development of a variety of tissues and
organs and is required for normal ENS development in zebrafish. Despite a previous suspicion of the involvement of IHH in HSCR, the Hh signaling was only recently linked to this disease, when mutations in the GLI family of transcription factors, known as effectors of Hh signaling, were found in a series of patients with HSCR. Our functional studies support this involvement, as they confirmed the pathogenic nature of the IHH variant identified (Figure 4C), and showed that the absence of ihh in zebrafish leads to an HSCR-like phenotype (Figure 4D). The same effect has been previously observed in mice. However, only 50% of Ihh knockout mice showed aganglionosis, suggesting that deletion of this gene is not fully penetrant, and disruption of additional genes is required for the intestinal phenotype observed. To date, it is still unclear how IHH affects ENS development, and further studies are required to determine if intestinal aganglionosis is due to a failure of migration of enteric neural crest cells from the vagal neural crest region into and along the gut tube, or whether IHH is required for proliferation of enteric neural crest cells once they enter the gastrointestinal tract. For GLI3, we found that the variant identified in patient V-4 and her father (c.2119C>T; p.P707S) has also been reported in patients with Greig cephalopolysyndactyly syndrome (MIM 175700), a rare disorder characterized by craniofacial abnormalities, polydactyly, and syndactyly of hands and feet. Previous studies have shown that this variant is pathogenic, as it leads to abnormal subcellular localization of GLI3 and reduced transcriptional activity. However, neither IV-4 nor V-4 have any of the features seen in patients with Greig cephalopolysyndactyly syndrome, leading us to conclude that this is a low-penetrance variant, likely requiring additional factors to modulate disease expression. Finally, a de novo variant in GDNF was also identified comprising an in-frame 6-bp deletion that led to the loss of 2 amino acids (c.676–681delGGATGT). Our results showed that this deletion has a pathogenic effect, as it impairs GDNF secretion and leads to reduced RET activation (Figure 5B and 5C). Mutations in GDNF have been previously reported in a few HSCR cases. However, it has been postulated that they are not sufficient to cause HSCR on their own, and require additional contributing factors. In this particular case, we hypothesize that the variants identified in IHH and GLI3 are these additional factors, especially because they are found in a heterozygote state in this family. Previously, we have proposed a model for disturbed ENS development, in which harmful and protective factors balance on a fulcrum representing a disease-specific genetic predisposition. In this model, mild variants that are harmless by themselves can lead to a disease phenotype if found together. For patient V-4, we believe that the deletion in GDNF is the one predisposing for HSCR, as it is the only variant present exclusively in patient V-4 and not in her healthy father (IV-4). However, it is the additive effect of the variants identified in IHH and GLI3 that triggers HSCR development in this patient.
Based on the previously performed linkage analysis, we were expecting to find the causative gene for HSCR in this family on chromosome 4. Therefore, we initially focused our efforts on LRBA, as this was the only gene in the linkage region that showed expression in mouse gut. Our functional studies failed to confirm a direct involvement of LRBA in HSCR pathogenesis, and could not support a direct role for lrba in ENS development in zebrafish (Figures 2 and 3). Within LRBA, another gene can be found, MAB21L2, specifically located in intron 42 of LRBA. MAB21L2 is known to play a role in neural development, and here we show that this gene is required for ENS development in zebrafish (Figure 3C). Based on this evidence, MAB21L2 was considered to be a possible candidate gene for HSCR in this family, but because we could not identify any pathogenic variant in this gene in any of the affected members, and failed to show an effect of the LRBA variant identified on MAB21L2 expression, we were unable to link MAB21L2 to HSCR. Therefore, although we believe that MAB21L2 could play a role in HSCR pathogenesis based on its function, the risk allele on chromosome 4 for this family cannot be attributed to MAB21L2 or LRBA, and remains to be identified.

Consequences for Genetic Counseling

Complex inheritance in families with variable expression and incomplete penetrance is to be expected in HSCR. However, searching for multiple variants that in concert can explain disease variation and penetrance within such families is rare. Common practice in diagnostic laboratories is to search for mutations in the major known disease-associated gene. For HSCR, this means screening the RET gene. If a mutation is identified, the search for additional causing genes stops. However, in some families, this may not represent the full genetic etiology of the disease, leading to a miscalculation of the real genetic risk. Using the family described in this study as an example, the extensive genetic analysis was performed only because the RET variant (c.1196C>T, p.P399L) was missed in the initial screening. One could argue that for the branch in which this variant was found, the additional screen hardly
adds any useful information, as RET probably determines most of the penetrance. However, in the RET negative branch, the additional genetic screening proved to be necessary. Finding a de novo GDNF deletion, in combination with 2 inherited variants in members of the Hh pathway (IHH and GLI3), changed genetic counseling, as we now predict a low recurrence risk for this branch of the family. Based on our findings, we believe that an extensive genetic screen can change genetic counseling of a complex genetic disease, especially if a de novo search is added. However, one should be cautious to counsel based only on the presence of a de novo variant, because it is difficult to assess the contribution of such variants to the overall disease risk.

Conclusions
HSCR is a complex disorder in which several genes are known to play a role (Figure 6). Although in 20% of the cases the genetic cause relies on the presence of a single deleterious mutation in a specific gene,45 for most patients it is likely that rare mutations affecting more than 1 gene are involved in disease pathogenesis. In this study, we report such a family, in which mutations in members of the major disease-associated pathway, RET and GDNF, in combination with mutations in GLI3 and in a previously unrelated HSCR gene, IHH, are likely to modulate the clinical expression of the disease phenotype (Figure 6). In addition, our results show that even familial cases can have a high genetic complexity, something that should be taken into account when counseling and performing genetic tests for disorders with a presumed multifactorial etiology.

Supplementary Material
Note: To access the supplementary material accompanying this article, visit the online version of Gastroenterology at www.gastrojournal.org, and at https://doi.org/10.1053/j.gastro.2018.03.034.

References


Author names in bold designate shared co-first authorship.

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Conflicts of interest
The authors disclose no conflicts.

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Supplementary Material and Methods

Exome Sequencing and Variant Prioritization

Three micrograms of DNA from each of the individuals was sheared using acoustic technology (Covaris, Inc, Woburn, MA). Target enrichment for V-1 and V-4 was performed with the SureSelect Human All Exon 50 Mb Targeted exome enrichment kit v4, and for the trio (IV-4, IV-5, and V-4) the Agilent Sureselect CRE capture kit (Agilent Technologies, Inc., Santa Clara, CA) was used. Captured fragments were sequenced (paired-end 101-bp read length) on the Illumina HiSeq2000 (Sureselect V4) and HiSeq2500 (CRE) sequencers (Illumina, San Diego, CA). Demultiplexing, alignment to the human genome build 19 (Hg19) reference genome, and curation of low-quality reads were done as described by our in-house developed NARWHAL pipeline.\(^1\) BAM-files were generated with SAMtools version 0.1.12a,\(^2\) and variant calling was performed with the Bayesian genotyper incorporated in the genome analysis toolkit version 1.2.9.\(^3\) Variant files generated of VCFv4 format were uploaded into Cartagenia Bench NGS version 5.0 (Cartagenia Inc, Boston, MA) for filtering with previously described settings.\(^4\)

Vector Design and Site Direct Mutagenesis

The genomic region of LRBA containing exon 20 and its flanking sequence (approximately 400 bp), was amplified from control and patient DNA to obtain WT and Mut (NM_001199282.2:c.2444A>G) alleles, respectively, using primers described in Supplementary Table 1 (LRBAF and LRBAR). PCR products obtained, LRBA-Enh-WT and LRBA-Enh-Mut, were inserted into the pCR 2.1-TOPO vector, subsequently digested with XhoI and KpnI restriction enzymes, and cloned into a pGL3-SV40 promoter (SV40-P) upstream of the luciferase gene (Promega, Madison, WI), to generate the pGL3-SV40p-Luc-LRBA-Enh-WT and pGL3-SV40p-Luc-LRBA-Enh-Mut vectors. The same LRBA PCR products, LRBA-Enh-WT and LRBA-Enh-Mut, were also directly cloned into the exon trapping vector pSPL3 (Invitrogen, Carlsbad, CA) to generate the pSPL3-LRBA-WT and the pSPL3-LRBA-Mut vectors. The pRc/CMV-RET-WT vector\(^5\) and pCMV6-Entry-GDNF-Myc-DDK vector (OriGene, Rockville, MD) were used to create pCMV-IHH-FLAG-Mut (Q51K) and pCMV6-Entry-GDNF-Mut (Gly226_Cys227del)-Myc-DDK, respectively, by site-directed mutagenesis, according to the manufacturer’s instructions (Stratagene and New England Biolabs, Ipswich, MA). All inserts were Sanger-sequenced to confirm the presence of the WT and Mut variants, as well as the orientation of the inserted fragments. Primers used (RET-MutF; RET-MutR; IHH-MutF, IHH-MutR, GDNF-MutF, and GDNF-MutR) are described in Supplementary Table 1.

Whole-Mount In Situ Hybridization for lrba, mab21l2, and ihh in Zebrafish

lrba, mab21l2, and ihh genes were amplified from total mRNA collected from zebrafish embryos by RT-PCR. Amplified bands were gel-purified and sub-cloned into TOPO TA PCRII vector (Thermo Fisher, Waltham, MA). Digoxigenin-labeled antisense probes (Roche, Basel, Switzerland) were generated using SP6 polymerase (Roche) after linearizing the plasmid templates using NotI restriction enzyme (New England Biolabs). Embryos were collected and processed for whole-mount in situ hybridization as previously described.\(^7\) Digoxigenin-labeled probes were visualized with NBT/BCIP coloration reactions.

RNA Isolation and qReal time-PCR

RNA isolation was performed with the RNeasy mini kit (Qiagen, Valencia, CA) according to the manufacturer’s instructions. cDNA preparation was done with the iScrip cDNA synthesis kit (Bio-Rad, Hercules, CA), using 1 μg RNA isolated from fibroblasts treated with Purmorphamine and conditioned medium containing IHH-WT and IHH-Mut. GLI1 expression levels were determined by quantitative real-time (qreal-time) Sybr Green PCR, using the 7300 Real-time PCR platform system (Applied Biosystems, Foster City, CA). The same procedure was used to determine levels of GDNF in HEK293 cells transfected with GDNF-WT and GDNF-Mut vectors. CLK2 was used as a housekeeping gene to normalize GLI1 expression levels, while GAPDH and ACTB were used for GDNF (primer details in Supplementary Table 1). qreal time-PCR data were analyzed using a method previously described,\(^9\) and presented as fold changes. These assays were performed in 3 independent triplicates (n = 9).
**Supplementary Figure 1.** *mab21l2* expression pattern in zebrafish. In situ hybridization showing that *mab21l2* has a strong expression in the hindbrain *(black arrows)* and pharyngeal arches *(white arrows)* through all time points (24–96 hpf). From 48 hpf onward, a strong expression is also detected in the gut mesoderm (*). 

**Supplementary Figure 2.** A decrease in RNA stability is predicted in the presence of the de novo deletion in *GDNF*, by in silico analysis. Secondary structures of *GDNF* WT and Mut RNA determined using RNAfold software, showed that a change in both the minimum free energy (MFE) and the centroid secondary structures are predicted to occur in the presence of the deletion identified *(arrowheads)*. Each color indicates the probability of individual nucleotides to participate in the structure, and range from the highest *(red)* to the lowest probability *(blue-violet)*.
### Supplementary Table 1. List of Primers Used in This Study

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### Supplementary Table 2. List of Antibodies Used for Western Blot

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### Supplementary Table 3: In Silico Prediction of the Pathogenic Nature of the Rare Variants Identified in Patients V-1 (a) and V-4 (b)

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**NOTE.** The following thresholds were used to evaluate conservation: PhyloP ≥ 0.95; GERP++ ≥ 2; SiPhy ≥ 5; PHAST conservation score ≥ 0; Grantham distance ≥ 60. To predict deleteriousness the following thresholds were used: Mutationtaster ≥ 0.51; Pph2 hvar ≥ 0.909 (complex disease) or Pph2 hdiv ≥ 0.956 (Mendelian disease); Mutation assessor ≥ 1.91; FATHM ≤ -1.50; SIFT ≤ 0.049; LRT: deleterious; BLOSUM62 ≤ 0; CADD Phred ≥ 20 (mutations in the splice interval can have lower values). BLOSUM, Blocks Substitution Matrix; GERP, Genomic Evolutionary Rate Profiling; LRT, likelihood ratio test; PolyPhen, Polymorphism Phenotyping v2. *-, unknown.
**Supplementary Table 4.** Segregation Analysis of Candidate Variants Identified by Exome Sequencing in the Family Members

<table>
<thead>
<tr>
<th>Gene</th>
<th>II-2</th>
<th>III-2</th>
<th>IV-1</th>
<th>IV-2</th>
<th>IV-3</th>
<th>IV-4</th>
<th>IV-5</th>
<th>V-1</th>
<th>V-2</th>
<th>V-3</th>
<th>V-4</th>
</tr>
</thead>
<tbody>
<tr>
<td>LRBA (c.2444A&gt;G)</td>
<td>+</td>
<td>+</td>
<td>–</td>
<td>+</td>
<td>+</td>
<td>–</td>
<td>+</td>
<td>+</td>
<td>+</td>
<td>+</td>
<td>+</td>
</tr>
<tr>
<td>RET (c.1196C&gt;T)</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>+</td>
<td>–</td>
<td>–</td>
<td>+</td>
<td>+</td>
<td>+</td>
<td>–</td>
</tr>
<tr>
<td>IHH (c.151C&gt;A)</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>+</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>+</td>
</tr>
<tr>
<td>GLI3 (c.2119C&gt;T)</td>
<td>NI</td>
<td>NI</td>
<td>–</td>
<td>–</td>
<td>NI</td>
<td>+</td>
<td>–</td>
<td>–</td>
<td>Ni</td>
<td>Ni</td>
<td>+</td>
</tr>
</tbody>
</table>

+, present; -, absent; NI, not investigated.

**Supplementary Table 5.** Differences in Minimum Free Energies and Ensemble Diversity of Predicted Secondary Structures of GDNF WT and Mut RNA

<table>
<thead>
<tr>
<th></th>
<th>GDNF WT</th>
<th>GDNF Mut</th>
</tr>
</thead>
<tbody>
<tr>
<td>Minimum free energy</td>
<td>192.80 kcal/mol</td>
<td>18.40 kcal/mol</td>
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<td>Free energy of</td>
<td>-202.30 kcal/mol</td>
<td>-197.50 kcal/mol</td>
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<td>thermodynamic ensemble</td>
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<tr>
<td>Ensemble diversity</td>
<td>109.20</td>
<td>100.24</td>
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<tr>
<td>Minimum free energy</td>
<td>-177.30 kcal/mol</td>
<td>-171.10 kcal/mol</td>
</tr>
<tr>
<td>(centroid secondary structure)</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Supplementary References