Mutational screening of splicing factor genes in cases with autosomal dominant retinitis pigmentosa

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Accessibility
Mutational screening of splicing factor genes in cases with autosomal dominant retinitis pigmentosa

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Purpose: Mutations in genes encoding proteins from the tri-snRNP complex of the spliceosome account for more than 12% of cases of autosomal dominant retinitis pigmentosa (adRP). Although the exact mechanism by which splicing factor defects trigger photoreceptor death is not completely clear, their role in retinitis pigmentosa has been demonstrated by several genetic and functional studies. To test for possible novel associations between splicing factors and adRP, we screened four tri-snRNP splicing factor genes (EFTUD2, PRPF4, NHP2L1, and AAR2) as candidate disease genes.

Methods: We screened up to 303 patients with adRP from Europe and North America who did not carry known RP mutations. Exon-PCR and Sanger methods were used to sequence the NHP2L1 and AAR2 genes, while the sequences of EFTUD2 and PRPF4 were obtained by using long-range PCRs spanning coding and non-coding regions followed by next-generation sequencing.

Results: We detected novel missense changes in individual patients in the sequence of the genes PRPF4 and EFTUD2, but the role of these changes in relationship to disease could not be verified. In one other patient we identified a novel nucleotide substitution in the 5′ untranslated region (UTR) of NHP2L1, which did not segregate with the disease in the family.

Conclusions: The absence of clearly pathogenic mutations in the candidate genes screened in our cohort suggests that EFTUD2, PRPF4, NHP2L1, and AAR2 are either not involved in adRP or are associated with the disease in rare instances, at least as observed in this study in patients of European and North American origin.

The most common form of hereditary retinal blindness is retinitis pigmentosa (RP), which affects about 1 in 4,000 people worldwide. The disease typically begins with patients experiencing night blindness, due to the early involvement of rod photoreceptors, and progresses with a decrease in the visual field and loss of central vision, due to the degeneration of cone photoreceptors [1]. Patients affected with RP display clinical heterogeneity regarding age of onset, degree of severity, rate of progression, and other secondary manifestations. These differences are partly explained by the different genes and mutations that cause RP. To date, more than 60 genes have been associated with non-syndromic RP, with about 3,000 mutations reported in total; however, a substantial fraction of cases are negative for mutations in known disease genes [2]. The inheritance mode is classically monogenic: dominant (about 30–40%), recessive (about 50–60%), X-linked (5–15%), and a smaller fraction of non-Mendelian or complex inheritance [1].

The functions of RP genes can be diverse: some genes are specific for retinal function such as phototransduction and retinal metabolism, while others have a more general function in cell development and maintenance [3]. A particular category that exemplifies the complexity of the molecular genetics of RP is represented by a few highly conserved and ubiquitously expressed pre-mRNA splicing factors.

Splicing consists of consecutive reactions occurring in the nucleus and leading to the removal of introns from pre-mRNA to form mature mRNA. A macromolecular complex, referred to as the spliceosome, ensures the fidelity and the correct timing of these reactions. The core components of the spliceosome are five small nuclear ribonucleoproteins (snRNP), U1, U2, U4, U5, and U6 [4], that assemble on the pre-mRNA in an ordered, stepwise manner. U1 snRNP first recognizes the 5′ splice site, and U2 binds to the branch point; then the U4/U6.U5 tri-snRNP complex is recruited, and finally U1 and U4 are released, leading to catalytic activation [5].
To date, six splicing factors genes have been found to be mutated in patients with adRP: *PRPF8* (RP13; ID: 10594, OMIM 607300) [6], *PRPF31* (RP11; ID: 26121, OMIM 606419) [7], *PRPF3* (RP18; ID: 9129, OMIM 607301) [8], *PAP-1* (RP9; ID: 6100, OMIM 607331) [9], *SNRNP200* (RP33; ID: 23020, OMIM 606664) [10,11], and *PRPF6* (ID: 24148, OMIM 613979) [12]. The prevalence of mutations in adRP cases is estimated to be about 8% for *PRPF31*, 2–3% for *PRPF8*, 1–4% for *PRPF3*, 1.6% for *SNRNP200*, and to be rare for *PAP-1* and *PRPF6* [1,13,14], globally accounting for more than 12% of all adRP cases.

All these genes have a high level of protein sequence conservation up to yeast and belong to the U4/U6.U5 tri-snRNP complex. The growing evidence of a major role of these particular splicing factors suggested that other partners of the complex could be meaningful candidate genes for adRP. Indeed, these mutations have been discovered through linkage analysis and positional cloning for the first two genes discovered (*PRPF8* and *PRPF31*), followed by the sequencing of other splicing factor genes in linkage intervals or in large cohorts of patients. This latter strategy, commonly referred to as the candidate gene approach [15], has been (and still is) instrumental for discovering several new RP genes. For instance, the role of the *PRPF6* gene in adRP was found with this approach, via the sequencing of the coding sequence in a cohort of 200 American patients [12].

Following the same rationale, we screened four candidate genes from the tri-snRNP complex in up to 303 patients with adRP with unknown molecular diagnosis and previously found to be negative for mutations in the most common adRP genes or hotspots. We selected the genes **EFTUD2** (ID: 9343, OMIM 603892), **PRPF4** (ID: 9128, OMIM 607795), **NHP2L1** (ID: 4809, OMIM 601304) and **AAR2** (ID: 25980), because of their physical or functional interaction with known RP-linked splicing factors. In particular, **EFTUD2** encodes for an essential GTPase, hSnu114, homolog of *Saccharomyces cerevisiae* Snu114p, which forms a stable complex with the **SNRNP200** and **PRPF8** products (i.e., hBrr2 and PRPF8, both involved in adRP) [16]. hSnu114 regulates hBrr2 at the dissociation step of U4 from U6 and is necessary for spliceosome disassembly after splicing [17]. The **AAR2** gene encodes Aar2p, which competes with hBrr2 in the binding of the C-terminal region of PRPF8 before the maturation of the U5 snRNP, supposedly regulating its assembly [18]. The 15.5-kDa protein (Snu13p in yeast), encoded by the **NHP2L1** gene, binds to the 5′-stem-loop of U4 snRNA probably playing a role in the late phase of the spliceosome assembly [19]. Finally, the PRPF4 protein forms a complex with PRPF3 in the U4/U6 snRNP complex, and its downregulation was found to induce photoreceptor defects in a zebrafish model, similarly to PRPF31 [20,21].

For the genetic screening we took advantage of a method that combines classical exon-PCR for the small genes and long-range PCR followed by next-generation sequencing for the large genes. The latter approach provides a cost- and time-effective alternative to the Sanger method and adapts well to routine genetic screenings in large sets of samples.

**METHODS**

**Samples and patients:** The subjects analyzed in this cohort belong to three groups of unrelated patients affected with autosomal dominant retinitis pigmentosa. One hundred and ninety-one samples were collected at the Berman-Gund Laboratory, Harvard Medical School, Massachusetts Eye and Ear and are mostly of North American origin. They were previously screened and found to be negative for exonic mutations by Sanger sequencing in 90% of all known adRP genes. One hundred and fifteen were collected in Spain (Servicio de Genética, IIS Fundación Jiménez Diaz University Hospital, Madrid) and were negative to a genotyping microarray that assessed known RP mutations [22]. Ninety-six were from France (INSERM U1051, Institut des Neurosciences de Montpellier, Hôpital Saint Eloi, Montpellier) and before this study were sequenced and found to be negative for the ten most frequently mutated genes or hotspots (*RHO*; ID: 6010, OMIM 180380), *RDS* (ID: 5961, OMIM 179605), *PRPF31* (ID: 26121, OMIM 606419), *RPL* (ID: 6101, OMIM 603937), *PRPF8* (ID: 10594, OMIM 607300), *IMPDH1* (ID: 3614, OMIM 146690), *NRL* (ID: 4901, OMIM 162080), *PRPF3* (ID: 9129, OMIM 607301), *NR2E3* (ID: 10002, OMIM 604485), and *SNRNP200* (ID: 23020, OMIM 601664) [23]. DNA was extracted from peripheral leukocytes and quantified. For technical reasons, only a subset of these samples could undergo the complete screening of the four genes but all (402 individuals) were analyzed for putative mutations in specific exons. Control DNA samples were obtained from 95 individuals with no history of retinal degeneration and 96 unrelated healthy individuals between age 34 and 92, purchased from the Coriell Institute for Medical Research. All subjects provided written, informed consent, and the study was conducted in adherence with the Declaration of Helsinki. This research was approved by the Institutional Review Boards of our respective Universities or Hospitals: University of Lausanne, Fundación Jiménez Diaz University Hospital, Institut des Neurosciences de Montpellier, Harvard Medical School, and the Massachusetts Eye and Ear.

**Library preparation and next-generation sequencing:** Genes **EFTUD2** and **PRPF4** were sequenced with long-range PCR
(LR-PCR) followed by next-generation sequencing (NGS), using Illumina instruments (San Diego, CA). Five and two LR-PCRs were generated to amplify the entire 51- and 20-kb regions of each gene, respectively, for a total of 71-kb targeted region. LR-PCRs were obtained individually for each sample using Takara LA Taq polymerase (Takara Bio, Shiga, Japan) with GC buffer and 1 µM of the primers reported in Appendix 1. The following cycling conditions were used: 94 °C for 1 min followed by 30 cycles at 98 °C for 5 s and 68 °C for 15 min, and final extension of 72 °C for 10 min. For each sample, the seven LR-PCRs were pooled into a single tube, after their quantity was estimated on agarose 1% gel. They were subsequently purified using DNA Clean and Concentrator columns (Zymo Research, Orange, CA). Only the DNA samples from the three cohorts that yielded seven clear PCR bands underwent NGS, resulting in 200 samples in total.

Library preparation and sample barcoding were performed as described by Adey et al. [24] using the Nextera DNA Sample Prep Kit (Epicenter, Madison, WI) and 48 barcodes adapted to Illumina platforms [25], following the manufacturer’s instructions. Fourteen tagged samples were sequenced as a pool in one lane of the GAII instrument for testing purposes, after which two runs of the HiSeq instrument (one lane for each run) were used to sequence two pools of 48 and 47 barcoded samples each. After the Nextera products were integrated by Illumina, we processed 91 additional samples using the Nextera XT DNA Sample Preparation (Illumina) protocol, reagents, and barcodes, and sequenced the samples as a unique pool with one Miseq instrument run.

Analysis and variant calling of sequences from next-generation sequencing: We mapped the reads obtained from NGS to the reference sequence of the genes (GRCh37.p10 assembly) with the CLC Genomics Workbench package, v. 5.5 (CLC bio, Aarhus, Denmark). The parameters were in a way that a read could align only if it had at least a 90% identity for the 90% of its length. A more relaxed setting (80% identity over 70% of its length) was also tried. Single nucleotide variant calling and small insertion and deletion calling were achieved by imposing a minimum frequency of discordant bases of 20%, with minimum coverage of five nucleotides and an average base quality of 20 Phred. The analyses were performed as a batch of all individual samples (200), and the obtained variants were annotated with the hg19_snp137 track from the UCSC Genome Browser.

Analysis of variant identified: To exclude polymorphisms, we consulted the databases dbSNP, 1000 Genomes, Exome Variant Server, Complete Genomics’ 42 control individuals, and exome sequencing data from 500 individuals from the CoLaus cohort [26]. Missense changes were analyzed with the online package PON-P, which integrates the results of the most common prediction software, including PolyPhen and SIFT [27]. The effect of intronic changes was evaluated with the Shannon Human Splicing Pipeline, kindly offered to us as a free trial by Cytognomix (London, Canada) and implemented in the CLC software [28], and the NNSPLICE 0.9 algorithm [29].

Sanger sequencing and restriction analysis: The genes NHP2L1 and AAR2 were screened with Sanger sequencing of the coding exons. PCR reactions were obtained with the GoTaq polymerase (Promega, Madison, WI) standard protocol and 0.25 µM of the primers reported in Appendix 2. Reactions were purified from excess primers and nucleotides with ExoSAP-IT (Affymetrics, Santa Clara, CA) and subjected to sequencing reactions using the Big Dye V1.1 Terminator Kit (Applied Biosystems, Foster City, CA) and an ABI automated DNA sequencer (Applied Biosystems). Sequences were analyzed using the CLC Genomics Workbench (CLC bio). The same procedure was applied to validate the novel changes in specific exons identified with NGS, cosegregation analysis, and screening of controls and additional patients. Primers used for these purposes are listed in Appendix 2. In some instances, controls and additional patients were tested using restriction enzymes when a particular nucleotide change abolished or created a restriction site. In particular, exon 5 of PRPF4 was tested with MscI, exon 8 of EFTUD2 with Hahl, and exon 1 of NHP2L1 with MluI (New England Biolabs, Ipswich, MA).

RESULTS

Screening of PRPF4 and EFTUD2: We obtained LR-PCR products spanning the genes PRPF4 and EFTUD2 for a total of 200 unrelated individuals diagnosed with adRP (Table 1). Seventy-nine patients were from North America, 71 from France, and 50 from Spain. Following multiplexed runs of NGS instruments, we analyzed the sequencing reads by alignment to the reference genomic sequences of the targeted genes. Since different instruments were used, different samples had different coverage depths. Specifically, the samples sequenced with HiSeq had higher coverage than the ones sequenced with MiSeq, due to the lower throughput and higher number of samples sequenced with the latter (Appendix 3). With the exception of a few samples, the targeted region was optimally covered for reliable variant calling. This consisted in the detection of single nucleotide variations and small insertions and deletions by the CLC Genomics algorithm. After merging the results obtained individually for each sample, we obtained a total figure of 1,195 variants identified, 591 of which are annotated variants...
present at different frequencies in the analyzed cohort. By restricting the analysis to exonic changes, we identified in total six missense variants, of which one was later found to be a false positive due to low coverage, as ascertained with Sanger sequencing (not shown). The remaining five variants are listed in Table 2.

Within the PRPF4 sequence, we identified two annotated variants, p.His78Arg and p.Pro187Ala (Table 2). The first one corresponded to dbSNP entry rs1138958 and was present in 60 European heterozygotes from the Exome Variant Server database; therefore, we considered the variant to be non-pathogenic. The second variant, found in a single individual (ID: 001–417), involved nucleotide c.559C (NM_004697.3, exon 5), which was flagged in dbSNP as entry rs187531407 and referred to a CCC>TCC (p.Pro187Ser) change, found only in two non-validated 1000 Genomes reports. We ascertained that one of these reports (a low-coverage genome in an African sample) was a false positive, following validation with direct Sanger sequencing on the original DNA sample (ID: NA18933, Coriell DNA repository). Moreover, although the nucleotide is the same, the base change in the patient in our cohort was different compared to rs187531407. More specifically, we identified a CCC>GCC change, which resulted in p.Pro187Ala. Proline 187 is not fully conserved across different species and, according to predictions with different tools, the likelihood of pathogenicity of p.Pro187Ala is uncertain (Table 3). We followed up this change by analyzing controls and available relatives. Public databases, as well as sequencing of in-house controls, did not reveal the presence of this change. We then screened an additional 202 patients with adRP from the same cohorts for this specific variant, but this change was not found in any additional individuals. The affected sibling (ID: 226–1953) of the index patient also carried the same change, but other family members were not available for further segregation analysis. Since the base change is located within exon 5, at a 5-bp distance from the donor splice site, we also checked if splicing of this exon was affected. Bioinformatic prediction was negative, and reverse-transcription (RT)–PCR of patient’s cDNA did not reveal missplicing events. In the absence of additional elements, we could neither exclude nor validate this change as a potential mutation.

### Table 1. Genes analyzed in this study and methods.

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Protein</th>
<th>snRNP complex</th>
<th># exons</th>
<th>Screening method</th>
<th># screened patients</th>
</tr>
</thead>
<tbody>
<tr>
<td>EFTUD2</td>
<td>Elongation factor Tu GTP binding domain containing 2-116 kDa</td>
<td>U5 [13]</td>
<td>28</td>
<td>Nextera-NGS</td>
<td>200</td>
</tr>
<tr>
<td>PRPF4</td>
<td>PRP4 pre-mRNA processing factor 4 homolog – 60 kDa</td>
<td>U4/U6 [17]</td>
<td>14</td>
<td>Nextera-NGS</td>
<td>200</td>
</tr>
<tr>
<td>NHP2L1</td>
<td>NHP2 non-histone chromosome protein 2-like 1-15.5 kDa</td>
<td>U4/U6.U5 [16]</td>
<td>4</td>
<td>Sanger</td>
<td>303</td>
</tr>
<tr>
<td>AAR2</td>
<td>AAR2 splicing factor homolog</td>
<td>U5 [15]</td>
<td>4</td>
<td>Sanger</td>
<td>187</td>
</tr>
</tbody>
</table>

### Table 2. Variant output from NGS screening of PRPF4 and EFTUD2 after filtering for coding changes.

<table>
<thead>
<tr>
<th>Gene</th>
<th>Sample count</th>
<th>Genomic Position</th>
<th>Coding region change</th>
<th>Amino acid change</th>
<th>DATABASE</th>
</tr>
</thead>
<tbody>
<tr>
<td>PRPF4</td>
<td>3/200</td>
<td>9:116049532</td>
<td>NM_004697.4:c.233A&gt;G</td>
<td>NP_004688.2:p.His78Arg</td>
<td>rs1138958</td>
</tr>
<tr>
<td>PRPF4</td>
<td>1/200</td>
<td>9:116053770</td>
<td>NM_004697.4:c.559C&gt;G</td>
<td>NP_004688.2:p.Pro187Ala</td>
<td>rs187531407</td>
</tr>
<tr>
<td>EFTUD2</td>
<td>1/200</td>
<td>17:42953357</td>
<td>NM_004247.3:c.814A&gt;G</td>
<td>NP_004238.3:p.Thr272Ala</td>
<td>rs150633454</td>
</tr>
<tr>
<td>EFTUD2</td>
<td>1/200</td>
<td>17:42956968</td>
<td>NM_004247.3:c.658C&gt;T</td>
<td>NP_004238.3:p.Arg220Cys</td>
<td>-</td>
</tr>
<tr>
<td>EFTUD2</td>
<td>1/200</td>
<td>17:42963986</td>
<td>NM_004247.3:c.238A&gt;C</td>
<td>NP_004238.3:p.Ile80Leu</td>
<td>-</td>
</tr>
</tbody>
</table>

Genomic coordinates refer to assembly GRCh37.p10. Numbering of coding region starts at A of the ATG. Human variation database search included dbSNP 137, 1000 Genomes Project, Exome Variant Server, Complete Genomics control samples and 500 exomes from the CoLaus cohort.
Of the three missense changes found in the EFTUD2 gene two were novel and present in single individuals (p.Arg220Cys and p.Ile80Leu) while one (p.Thr272Ala) was a rare variant found in two heterozygote control African samples from Exome Variant Server (rs150633454; Table 2). The p.Arg220Cys change (ID: 001–492) was confirmed with Sanger sequencing and predicted to be damaging by several prediction tools (Table 3). The residue is in fact highly conserved, from human to yeast. The change was not found in public variation databases, in 150 in-house controls tested, and in the remaining patients from the other cohorts consisting of the 202 patients with adRP. Although we verified that the patient’s healthy sister (ID: 226–2008) and son (ID: 226–2009) did not carry this change, the unavailability of other family members prevented us from investigating this variant further. The novel p.Ile80Leu missense and the rare p.Thr272Ala were predicted to be neutral, based on conservation and strength of change, and considered non-pathogenic. Moreover, for the p.Thr272Ala change it was possible to perform cosegregation analysis, and the results were negative.

Since with LR-PCRs we amplified coding and non-coding regions of the target genes, we tested whether any novel variant identified could affect sequences important for splicing signals, including those located in deep intronic regions. We analyzed 1,088 variants in exons and introns of the EFTUD2 and PRPF4 genes with the Shannon Human Splicing Pipeline [28]. Only single nucleotide substitutions, but not insertions or deletions, could be tested with this method. No change inactivated or reduced the strength of the natural splice sites. Four hundred and thirty-four variants were predicted to alter the sequence information of cryptic splice sites. By filtering for variations that were not polymorphic and that resulted in the creation of a donor or acceptor splice site with greater strength than the natural splice site, only five variants remained (Appendix 4). Two were likely false positives because they were present only in one read out of fivefold coverage. For the remaining three, other predictions were made using the NNSPLICE algorithm and did not agree with the one of the Shannon pipeline. According to NNSPLICE, in fact, in two cases the new cryptic splice sites were still weaker than the natural ones, and in one case the already existing cryptic site was weakened by the change. We therefore concluded that there were insufficient elements to study these variants further.

Finally, a second run of variant calling was performed on alignments obtained with less stringent criteria, to exclude the possibility of false negatives due to too rigid mapping parameters. This analysis increased by two times the number of known SNPs identified (999 versus 476) and by three times the number of non-reported changes (3,752 versus 1,195), indicating a gain in sensitivity but also a decrease in specificity (Appendix 5). In fact, when we analyzed only the coding changes, in addition to the variants found with previous mappings, we obtained eight false positives, all found in the same sample and localized in a stretch of wrongly aligned reads, as became clear from inspection of the mapping.

Screening of NHP2L1 and AAR2: Two additional genes, NHP2L1 and AAR2, were also selected. Because of their relatively small size, they were screened by Sanger sequencing (Table 1). NHP2L1 consists of two coding exons and two alternative 5′ untranslated regions (UTRs) containing the start codon. Sequencing of the four exons in 303 patients (182 from the United States, 90 from France, and 31 from Spain) revealed only one novel change introducing an ATG start codon in the 5′ UTR, which was found in one patient (ID: 001–245) and not in the control population. This change was potentially interesting because it creates an upstream open

<table>
<thead>
<tr>
<th>Patient’s origin</th>
<th>Gene</th>
<th>Change</th>
<th>Polyphen prediction</th>
<th>PON-P prediction</th>
<th>Controls</th>
<th>Segregation</th>
</tr>
</thead>
<tbody>
<tr>
<td>German</td>
<td>PRPF4</td>
<td>p.Pro187Ala</td>
<td>Probably damaging</td>
<td>Unclassified, Probability of pathogenicity: 0.27</td>
<td>0/189</td>
<td>Positive</td>
</tr>
<tr>
<td>American Indian-French Canadian/Irish</td>
<td>EFTUD2</td>
<td>p.Arg220Cys</td>
<td>Probably damaging</td>
<td>Pathogenic, Probability of pathogenicity: 0.91</td>
<td>0/150</td>
<td>Positive</td>
</tr>
<tr>
<td>Italian</td>
<td>NHP2L1</td>
<td>chr22:42078408 NM_005008.2:c.-46G&gt;A Creation of upstream out of frame ORF</td>
<td>Benign</td>
<td>Neutral, Probability of pathogenicity: 0.02</td>
<td>Not available</td>
<td>Not available</td>
</tr>
</tbody>
</table>

Prediction of pathogenicity was made using Polyphen and PON-P [22]. In addition to database consultation, in-house controls were performed by direct Sanger sequencing (PRPF4) or restriction enzymes (EFTUD2 and NHP2L1).
while the current article was under review, mutations in PRPF4 were identified as a cause of dominant RP in a Chinese cohort of patients, highlighting in fact a possible population-specific effect [42].
APPENDIX 1. PRIMERS USED FOR LONG-RANGE PCR.
To access the data, click or select the words “Appendix 1.”

APPENDIX 2. PRIMERS USED FOR SHORT RANGE PCR AND SEQUENCING
To access the data, click or select the words “Appendix 2.”

APPENDIX 3. SUMMARY OF METRICS OF NGS SCREENING RUNS AND PER SAMPLE STATISTICS.
To access the data, click or select the words “Appendix 3.”

APPENDIX 4. RESULTS OF SPLICE SITES ANALYSIS USING THE SHANNON HUMAN SPLICING PIPELINE.
To access the data, click or select the words “Appendix 4.”

APPENDIX 5. TOTAL NUMBER OF VARIANTS IDENTIFIED BY TWO ALIGNMENTS WITH DIFFERENT MAPPING CRITERIA.
To access the data, click or select the words “Appendix 5.”

ACKNOWLEDGMENTS
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