ONLINE MUTATION REPORT

Rapid detection of CFTR gene rearrangements impacts on genetic counselling in cystic fibrosis

F Niel, J Martin, F Dastot-Le Moal, B Costes, B Boissier, V Delattre, M Goossens, E Girodon


Cystic fibrosis (CF) (MIM 219700) is one of the most common autosomal recessive diseases in Caucasians. It affects about 1 in 2500 births and approximately 1 in 25 individuals are heterozygotes, with marked regional variations (www.genet.sickkids.on.ca/cftr). It is caused by mutations of the cystic fibrosis transmembrane conductance regulator (CFTR) gene (MIM 602421), which is also involved in a broad spectrum of phenotypes, including male infertility by congenital bilateral absence of the vas deferens (CBAVD), disseminated bronchiectasis (DB), and chronic pancreatitis. So far, over 1000 CFTR gene mutations have been described throughout the gene, along with geographic and ethnic variations in their distribution and frequency (www.genet.sickkids.on.ca/cftr). Of these variations, 99% consist of point mutations or micro-deletions/insertions (www.genet.sickkids.on.ca/cftr) but account for 33–98% of CF alleles, depending on the population. A number of cases remain unsolved after extensive and laborious screening of the 27 exons, thus making genetic counselling difficult for the patients and their families, particularly when the CF diagnosis is not certain. Unidentified CF mutations may lie in introns or in regulatory regions which are not routinely investigated, or correspond to gene rearrangements such as large deletions at the heterozygous state which escape detection using current PCR based techniques. Deletions have been suspected in a very few situations: upon failure of PCR amplification to target particular exons when the deletions were present in CF patients in the homozygous state, or in cases of abnormal segregation of a mutation or polymorphisms in a family. Two such deletions, CFTRdels–311 and CFTRdele17a–18, which are now routinely tested for by conventional PCR using specific primers, were found in about 5% and 13% of CF alleles, respectively. Deletions still remains a challenge and quantitative PCR based methods represent an attractive approach. Very recent data have shown that 16% of unidentified CF alleles in a mainly French population consist of large CFTR gene rearrangements. Analysis of a larger and heterogeneous population using a semi-quantitative fluorescent PCR assay targeting the 27 CFTR exons, led us to identify undescribed CFTR gene anomalies and a similar but higher proportion of rearrangements. We discuss here the place of our assay in the strategy to diagnose CF and related diseases, and its implications for genetic counselling and care of CF patients and their families.

METHODS

Patients

We investigated a total of 78 unrelated French patients or parents of deceased CF patients from mixed ethnic/geographic origins and subjected them to a complete CFTR gene screening. The subjects were divided into three groups according to the results of a previous screening: (i) 43 CF patients who fulfilled the diagnostic criteria of CF and who carried a CF mutation, and seven parents of deceased CF patients, a CF mutation having already been identified in the other parent (50 unidentified CF alleles); (ii) 12 CF patients with no identified CF mutation (24 unidentified CF alleles); and (iii) 16 patients apparently homozygous for a CFTR mutation and who had CF (F508del — n = 6, 2109delC — 2109delT, S945L, S1207+1G−A, N1303K) or a CFTR related disease, that is, isolated CBAVD (D110H, R117H, L997F, R747W-D1270N) or DB (R334W, R668C-G576A-D443Y) (0–16 unidentified CF alleles). In these cases, status confirmation was not possible by family analysis. In

Key points

- Cystic fibrosis (CF), one of the most frequent hereditary diseases in the Caucasian population, is mainly due to point mutations scattered over the whole CFTR gene. CFTR gene deletions are rare, but their frequency may be underestimated as they remain undetected when using conventional PCR techniques.
- We studied 78 patients, including 62 CF patients or parents of CF patients bearing one or two unidentified CF alleles after an extensive CFTR gene study, and 16 patients apparently homozygous for a CFTR mutation.
- Making use of an assay based on semi-quantitative fluorescent PCR targeted on the 27 CFTR exons in a three multiplex format, we characterised gene rearrangements in 11 patients, including a recurrent deletion, a complete gene deletion, and the first CFTR gene duplication. Taking into account three known deletions previously characterised in other CF patients, gene rearrangements thus accounted for 20% of unidentified CF alleles and for 1.3% of all CF mutations in our population.
- The methodology is both simple and reliable, and is able to detect large rearrangements and single nucleotide deletions/insertions as well. Together these account for almost 24% of the CF mutations described, and makes this the method of choice for second line screening when frequent mutations are not found. This strategy has notable implications for genetic counselling and care of CF patients and their family.

Abbreviations: CBAVD, congenital bilateral absence of the vas deferens; CF, cystic fibrosis; CFTR gene, cystic fibrosis transmembrane conductance regulator gene; DB, disseminated bronchiectasis; DHOE, denaturing gradient gel electrophoresis; DHPLC, denaturing high pressure liquid phase chromatography; FISH, fluorescent in situ hybridisation; MP, multiplex PCR; QFM-PCR, semi-quantitative fluorescent multiplex PCR
addition, we considered that the genotype could not explain the observed phenotypes in CBAVD and DB patients.

When available, parents of patients in whom an abnormal pattern had been detected were studied. All the patients were referred to our laboratory between 1989 and 2004. Informed consent to CFTR studies had been previously obtained from the patients and/or their parents at the time of referral to the laboratory.

Previous extensive CFTR gene analyses with a mutation detection rate of 95% included: (i) scanning for 31 frequent mutations (CF OLA assay, Abbott, Rungis, France); (ii) scanning of the 27 exons and their boundaries using denaturing gradient gel electrophoresis (DGGE)14,15 or denaturing high pressure liquid phase chromatography (DHPLC), followed by sequencing to characterise the variants; (iii) screening for the intronic splicing 1811–1818 and CFTRdele17a–18; and (iv) screening for three previously characterised gene rearrangements using specific primers: CFTRdele2,3,16 CFTRdele17a–18,17 and CFTRdele19.18 This last step led us to identify large deletions in four former patients: CFTRdele2,3 (one allele), CFTRdele17a–18 (two alleles), and CFTRdele19 (two alleles). These patients were thus not included in the cohort of patients studied here, but the data were taken into account to determine the proportion of CFTR gene rearrangements among CF alleles.

DNA extraction
Most genomic DNAs were extracted from whole blood samples collected on EDTA using a phenol chloroform extraction protocol or a commercial kit (Nucleon, BACCC, Amersham Biosciences, Saclay, France). Some DNAs, received from other laboratories, were extracted with different protocols. DNA concentration and quality were determined for each sample.

Screening for CFTR rearrangements by semi-quantitative fluorescent multiplex PCR (QFM-PCR)
The original protocol described by Yau et al19 was adapted to screen for CFTR rearrangements. Briefly, the principle is based on comparisons of the fluorescent profiles of multiplex PCR fragments obtained from different samples, the amplification being stopped at the exponential phase. This procedure allows the detection of heterozygous deletions (twofold reduction of fluorescence intensity) and heterozygous duplications (1.5-fold increase). The 27 CFTR gene exons, a promoter region (1873118868, GenBank AC000111.1, or 940 to 803 according to the current CFTR gene numbering) and a region containing the polyadenylation signal sequence (5892059091, GenBank AC000066.1, or 60356206 according to the current CFTR gene numbering) were amplified in three fluorescently labelled multiplex reactions, denoted multiplex PCR (MP): MP 1 (promoter, polyadenylation signal sequence, exons 1–6a and 11), MP 2 (exons 7–10 and 12–16), and MP 3 (exons 6b and 17a–24). Intronic specific primers (but exonic for the exon 4); and a DNA carrying a previously identified CFTR gene deletion, fluorescent in situ hybridisation (FISH) analysis with a CFTR cDNA probe.

Table 1 Statistical profiles from the analysis of patient no. 7 carrying the CFTRdele17a–17b deletion from multiplex PCR 2 (MP 2) and 3 (MP 3)

<table>
<thead>
<tr>
<th>Patient no. 7</th>
<th>Control</th>
<th>DQSCR1/SCR1</th>
<th>DQFP/FP</th>
</tr>
</thead>
<tbody>
<tr>
<td>Height value</td>
<td>565</td>
<td>502</td>
<td>1060</td>
</tr>
<tr>
<td>Control value</td>
<td>461</td>
<td>400</td>
<td>0.98</td>
</tr>
<tr>
<td>DQSCR1/SCR1</td>
<td>0.92</td>
<td>0.38</td>
<td>1.02</td>
</tr>
<tr>
<td>DQFP/FP</td>
<td>0.21</td>
<td>0.064</td>
<td>0.13</td>
</tr>
</tbody>
</table>

The DQ values indicative of the 17a–17b deletion pattern are underlined. From our study, values of the DQ were within the range 0.75–1.31 (mean 0.95) for normal control samples, 0.38–0.64 (mean 0.48) for a heterozygous deletion control, and 1.40–1.79 (mean 1.55) for a heterozygous duplication control. They were concordant with those obtained by You et al.20

As an example (indicated in bold characters), the DQ for CFTR exon 17a compared to DQSCR1/SCR1 and DQFP/FP was 0.52 (mean 0.55) for a heterozygous deletion control. They were concordant with those obtained by You et al.20

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RESULTS
Detection of CFTR rearrangements
QFEM-PCR screening led to the detection of rearrangements in 11 families (table 2). Ten of them were found in the first group of 50 patients or parents of deceased patients where a mutation had been previously identified. None was detected in the second group of 12 patients who carried two unknown mutations. One further rearrangement was identified in the third group of 16 patients, in a CBAVD patient who was apparently R117H homozygous. No rearrangement was detected in the other patients of the third group, confirming that they were homozygous for a CFTR mutation. The results obtained in the third group thus added a CF allele to the total of unidentified alleles which were investigated for the presence of rearrangements. Overall, a rearrangement was found in 11/75 (14.7%) unidentified CF alleles. Taking into account the five CF alleles bearing known deletions that were previously identified, CFTR gene rearrangements accounted for 20% of 80 so called unidentified CF alleles, where a point mutation or a short deletion/insertion has not been found.

The 11 rearrangements detected consisted of eight different patterns. Most exhibited a simple deletion pattern involving one or several consecutive exons: 1; 2; 17b; 14a–17b; 17a–17b in four unrelated cases (fig 1A and table 1). Two others consisted of a complex deletion removing exons 3–10 and 14b–16, and a whole CFTR gene deletion (fig 1B). The former was found in cis with the V754M variation (exon 13), which has been described as a CF mutation (www.genet.sickkids.on.ca/cftr). The complete deletion was identified in a patient having CBAVD, and who apparently carried two R117H–7T copies (R117H in cis with the IVS8–7T variant). Rearrangement analysis of his parents confirmed the compound heterozygosity for R117H and the deletion. The last rearrangement consisted of a duplication pattern of exons 4–8 (fig 1C).

The multiplex assay was sensitive enough to detect a number of micro-deletions/insertions within exons, which modified the fragment size, such as F508del, 394delTT, 2183AA→G, 4016insT, as well as STR variants, for example at the IVS6a(TG) and IVS8(TG)mTn polymorphic sites.

Molecular characterisation of the rearrangements
The 11 rearrangements consisted of eight different anomalies, of which six are new (table 3). The two already reported involve exon 122 and exon 2 (Mekus and Tümler, www.genet.sickkids.on.ca/cftr). We named the new rearrangements according to the nomenclature recommendations (www.hgvs.org), but the A of the ATG translation start codon was numbered +133 to be in accordance with the current CFTR gene numbering (GenBank NM_000492.2) and the CF mutation database, where the rearrangements were reported. The breakpoints of three new deletions involving intron 17b were determined. The 3’ breakpoints were concentrated in a small AT-rich region including the IVS17b(TA) microsatellite. Hence, abnormal segregation of this microsatellite was observed in four families where such a deletion was detected. The 3’ breakpoint of the partial deletion of exon 17b, 3413del355ins6, is located 9 bp after the IVS17b(TA) site, while those of CFTRdel14b–17b and CFTRdel17a–17b are located within it, leaving stretches of 13(TA) and 7(TA) repeats, respectively. The junction CFTRdel17a–17b was identical in the four patients carrying this anomaly, which was associated with the same extended haplotype (IVS1(CA), IVS6a(TG), IVS8(CA), IVS8(TG)mTn, 1540A/G, 2694T/G, IVS17b(CA); data partially shown in table 3). In all the cases characterised at the molecular level (nos. 1, 3–8), the rearrangements were inherited in a stable manner, as the breakpoints were identical in the patients and their parents.

The precise characterisation of the other rearrangements was hampered by various difficulties: (i) the size of the complete CFTR gene deletion, which was not detected by

Table 2 Phenotype and genotype data of patients carrying CFTR rearrangements

<table>
<thead>
<tr>
<th>Patient no.</th>
<th>Gender</th>
<th>Current age</th>
<th>Age at diagnosis</th>
<th>Pancr. status</th>
<th>Lung disease</th>
<th>Other</th>
<th>Sweat test</th>
<th>Allele 1</th>
<th>Allele 2</th>
<th>Allele rearrangement involving exon(s)</th>
<th>Parental</th>
<th>Geographic</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 M</td>
<td>10 years</td>
<td>1 month</td>
<td>PI</td>
<td>Severe</td>
<td>114</td>
<td>F508del</td>
<td>1</td>
<td>ND</td>
<td>F508del</td>
<td>17a–17b</td>
<td>Father</td>
<td>North eastern Italy</td>
</tr>
<tr>
<td>2 M</td>
<td>16 years</td>
<td>Birth</td>
<td>PI</td>
<td>Severe</td>
<td>130</td>
<td>A561E</td>
<td>2</td>
<td>ND</td>
<td>F508del</td>
<td>17a–17b</td>
<td>Father</td>
<td>Southern Italy</td>
</tr>
<tr>
<td>3 M</td>
<td>10 years</td>
<td>1 year</td>
<td>PI</td>
<td>Severe</td>
<td>+</td>
<td>R553X</td>
<td>17b</td>
<td>ND</td>
<td>F508del</td>
<td>17a–17b</td>
<td>Father</td>
<td>France</td>
</tr>
<tr>
<td>4 F</td>
<td>13 years</td>
<td>4 years</td>
<td>PI</td>
<td>Severe</td>
<td>NP</td>
<td>F508del</td>
<td>14b–17b</td>
<td>ND</td>
<td>F508del</td>
<td>17a–17b</td>
<td>Father</td>
<td>France</td>
</tr>
<tr>
<td>5 F</td>
<td>24 years</td>
<td>1 month</td>
<td>PI</td>
<td>Severe</td>
<td>100</td>
<td>F508del</td>
<td>17a–17b</td>
<td>ND</td>
<td>F508del</td>
<td>17a–17b</td>
<td>Father</td>
<td>France</td>
</tr>
<tr>
<td>6 F</td>
<td>21 years</td>
<td>Childhood</td>
<td>PI</td>
<td>Moderate</td>
<td>+</td>
<td>F508del</td>
<td>17a–17b</td>
<td>ND</td>
<td>F508del</td>
<td>17a–17b</td>
<td>Father</td>
<td>France</td>
</tr>
<tr>
<td>7 M</td>
<td>35 years</td>
<td>1 year</td>
<td>PI</td>
<td>Severe</td>
<td>103</td>
<td>F508del</td>
<td>17a–17b</td>
<td>ND</td>
<td>F508del</td>
<td>17a–17b</td>
<td>Father</td>
<td>France</td>
</tr>
<tr>
<td>8 F</td>
<td>2 F</td>
<td>Deceased at 2 and 6 months</td>
<td>Birth</td>
<td>PI</td>
<td>Severe</td>
<td>ND</td>
<td>F508del</td>
<td>17a–17b</td>
<td>ND</td>
<td>F508del</td>
<td>17a–17b</td>
<td>Father</td>
</tr>
<tr>
<td>9 F</td>
<td>Deceased at 5 years</td>
<td>3</td>
<td>PI</td>
<td>Severe</td>
<td>300</td>
<td>1812–1921A–G</td>
<td>1–10, 14b–16†</td>
<td>PD</td>
<td>F508del</td>
<td>17a–17b</td>
<td>Mother</td>
<td>Kabylie (Algeria)</td>
</tr>
<tr>
<td>10 M</td>
<td>37 years</td>
<td>3 months</td>
<td>PS</td>
<td>None</td>
<td>90</td>
<td>G542X</td>
<td>1–24</td>
<td>ND</td>
<td>F508del</td>
<td>17a–17b</td>
<td>Mother</td>
<td>France</td>
</tr>
<tr>
<td>11 M</td>
<td>37 years</td>
<td>31 years</td>
<td>PI</td>
<td>Severe</td>
<td>130</td>
<td>8176R–77T</td>
<td>4–8</td>
<td>ND</td>
<td>F508del</td>
<td>17a–17b</td>
<td>Mother</td>
<td>Eastern France</td>
</tr>
</tbody>
</table>
conventional cytogenotyping but confirmed by FISH analysis (data not shown); (ii) the lack of DNA or cDNA to study the complex CFTR dele3–10,14b–16 deletion, which removes at least 54 kb, and the CFTR dup4–8 duplication, which is predicted to extend over a minimum of 11 kb.

DISCUSSION

CFTR rearrangements account for 20% of unidentified CF alleles

In the population studied, CFTR rearrangements were identified in 11 unrelated families. All these rearrangements were characterised in families where a CF mutation had been previously identified. Taking into account the number of alleles bearing one of the three known deletions (CFTR dele3–3, CFTR dele17a–17b, and CFTR dele14b–17b) in our population, large CFTR gene rearrangements represented 20% of CF alleles, where a point mutation or a short deletion/insertion has not been found, and 1.3% of overall CF anomalies. These figures indicate a slightly higher proportion of CFTR rearrangements in our larger and probably more heterogeneous population than in that studied by Audrezet et al.2 Screening for CFTR gene rearrangements should especially benefit populations where the rate of point mutations is particularly low compared to that studied here. The remaining unsolved cases could be explained by mutations that escaped DGGE or DHPLC screening, or by splicing anomalies located within introns. Alternatively, it is possible that a number of patients who were diagnosed with CF but who had no identified mutation after extensive gene screening have been indeed misdiagnosed. One allele referred to a gene other than CFTR could account for their CF-like disease.19

Audrezet et al documented heterogeneity in five large deletions,19 in terms of location, extent, and mutational mechanism. We further document this heterogeneity, as we identified eight different rearrangements, of which six are new. They include deletions or indels involving one exon (1, 2, 17b) or several contiguous exons (14b–17b, 17a–17b), a complex deletion (CFTR dele3–10,14b–16), the first described deletion of the whole gene, and the first described CFTR duplication (CFTR dup4–8). Although the functional consequences of the identified rearrangements have not been evaluated, we can postulate that they preclude CFTR expression and are thus null mutations, in keeping with the observed phenotypes. Likewise, given the classical CF phenotype of patient no. 11, who carries a duplication of exons 4–8, we hypothesise that the duplicated region is located inside the CFTR gene and interferes with the transcription or translation process, thus resulting in a null mutation.

The breakpoints of three new deletions were determined. Interestingly, CFTR dele17a–17b was found in four unrelated patients originating from Eastern France and is probably associated with the same haplotype, which suggests a founding effect. It would be interesting to screen for this particular deletion in patients from neighbouring countries. In this deletion and in those involving exon 17b and exons 14b–17b, an AT-rich environment together with a short repeat at the breakpoints, may have favoured non-homologous recombination by slipped mispairing (table 3), as the 3’ breakpoint is located within this site. The number of AT repeats, however, has thus been determined by sequencing.

The linked haplotype was demonstrated in case nos. 5 and 6 and hypothesised in case nos. 7 and 8. The precise IVS1(CA) allele could not be determined, as the father’s DNA was not available.

**The linked haplotype was hypothesised, considering the most frequent haplotype IVS8(CA)/IVS17b(ATA)/33/IVS17b(CA)/13 linked to GS42X.**

Table 3

<table>
<thead>
<tr>
<th>Patient no.</th>
<th>Rearrangement</th>
<th>Simplified name</th>
<th>Exon(s) involved</th>
<th>Linked haplotype</th>
<th>Motif sequence at the breakpoints</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>c.136_c.185</td>
<td>136del119ins299</td>
<td>Part of 1 (codons 2–18)</td>
<td>23–16–29–13</td>
<td>Inverted CCATG</td>
</tr>
<tr>
<td>2</td>
<td>c.186–7_c.296–7delT</td>
<td>CFTR dele2</td>
<td>2</td>
<td></td>
<td>ND</td>
</tr>
<tr>
<td>3</td>
<td>c.3413_c.3499</td>
<td>3413del353ins6</td>
<td>Part of 17b (codons 1094–1122)</td>
<td>14b–17b</td>
<td>Direct CTGT and AT rich</td>
</tr>
<tr>
<td>4</td>
<td>c.2752–674_c.3499</td>
<td>CFTR dele14b–17b</td>
<td>14b–17b</td>
<td>23–16–13–13t</td>
<td>Direct TCGG and AT rich</td>
</tr>
<tr>
<td>5–8</td>
<td>c.3121–977_c.3499</td>
<td>CFTR dele17a–17b</td>
<td>17a–17b</td>
<td>23–16–7–13t;1</td>
<td>Symmetric ATG and AT rich</td>
</tr>
<tr>
<td>10</td>
<td>CFTR dele1–24</td>
<td>CFTR dele1–24</td>
<td>1–24</td>
<td></td>
<td>ND</td>
</tr>
<tr>
<td>11</td>
<td>c.406–7_c.1341–7del</td>
<td>CFTR dup4–8</td>
<td>4–8</td>
<td></td>
<td>ND</td>
</tr>
</tbody>
</table>

The nomenclature recommendations were followed (www.hgvs.org) but the A of the ATG translation start codon was numbered as +133, according to the current CFTR gene numbering (GenBank NM_000492.2) and the CF mutation database. The new rearrangements are indicated in bold.

*The same indel was described in a CF patient with paternal isodisomy20 and further found in a French CF patient.14

tHe same CFTR dele3 as that described by Mekus and Tümmler (www.genet.sickkids.on.ca/cftr) was identified using specific primers provided by T Đork.

**/C192/C244/(TA) repeats, indicated in italics, has thus been determined by sequencing.

The same indel was described in a CF patient with paternal isodisomy20 and further found in a French CF patient.14

The linked haplotype was demonstrated in case nos. 5 and 6 and hypothesised in case nos. 7 and 8.

*The precise IVS1(CA) allele could not be determined, as the father’s DNA was not available.

**The linked haplotype was hypothesised, considering the most frequent haplotype IVS8(CA)/IVS17b(ATA)/33/IVS17b(CA)/13 linked to GS42X.**

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Considering the CFTR deletions already described and those we report here, it clearly appears that some CFTR sequences may be prone to rearrangements. Strikingly, the small intron 17b (2.8 kb) is involved in the 3' breakpoint of five deletions (CFTRdele14b–17b, CFTRdele16–17b, CFTRdele17a–17b, 3413del355ins6, and the deletion removing the entire exon 17b described by Magnani et al.15), the IVS17b(TA) site appearing as a critical hotspot involved in the three described here. The CFTR introns 1, 3, and 18 are involved in the breakpoints of four, six, and five other deletions, respectively. However, these introns are large and it is not documented whether identical sequences are involved in the rearrangements.

**Implications for genetic counselling**

Identification of a CF rearrangement definitely confirmed the CF diagnosis in all cases but that of the CBAVD patient, although, at present, a moderate form of CF cannot be ruled out. Some of the patients were referred to our laboratory several years ago and, even if the diagnosis had been clearly established on the basis of clinical and biological findings,15 the presence of only one CF mutation after exhaustive screening of the CFTR gene coding regions could have thrown doubt upon the diagnosis. Moreover, in the context of a hereditary disease, identification of each parental CF anomaly allows the psychological burden to be shared in the family. Indeed, family studies showed that all the rearrangements were inherited from a parent (father in six cases, mother in the five others including that of the duplication). In other respects, it greatly facilitates genetic counselling and cascade screening in relatives and makes feasible prenatal diagnosis by direct analysis of the causative mutations. Precise identification of the breakpoints enables the design of primers for conventional PCR which may be easier and cheaper to use in these situations (in particular, the PCR primers and conditions for the detection of the common CFTRdele17a–17b are available upon request). The search for CFTR gene rearrangements should also be considered in patients presenting with a CFTR related disease and who carry a mild mutation, since they may have a severe CF mutation in trans.

Determination of CFTR copy number allows discrimination between true homozygotes for identified CF mutations and compound heterozygotes for a CF mutation and a deletion removing at least the relevant exon. In cases of apparent homozygosity for a CFTR mutation, ruling out a sequence variation at the primer binding sites can be performed first by sequencing the corresponding exon using a set of external primers. Then, determination of copy number, particularly useful when segregation analysis is difficult or not possible in the family, can be rapidly performed. Such a discrimination is crucial when cascade screening and prenatal diagnosis are requested. Geneticists must also be aware of correlations between genotype and phenotype. In the particular case of patient no. 10, we considered that a R117H–T1 homoygous genotype could not explain the CBAVD phenotype and suggested rather the presence of a severe CF anomaly in trans of R117H. Identification of a gene rearrangement in this patient had notable implications for genetic counselling for himself and his partner, as the couple had been referred for advice about assisted reproduction, and for his family. Indeed, once studied, the patient and his parents forwarded the genetic information to other family members. In other respects, the proven homozygous genotype for mild CFTR mutations found in CBAVD or DB patients of the third group, such as R74W–D1270N or L997F, is not considered as deleterious enough to account for their disease. Other CFTR mutations may have escaped detection or, alternatively, mutations in other disease causing genes may account for the phenotype, possibly acting in concert with CFTR mutations.

Farrar screening for rare mutations or rearrangements should also be considered when patients carry missense mutations whose deleterious effect is questionable with regard to the biochemical properties of the amino acids and the conservation of the CFTR protein sequence among species, and in comparison to other ABC proteins. We considered a possible complex allele in patient no. 9 on a V754M background, as the corresponding part of the R domain is not well conserved among species, residue V754 being a valine in primates but a methionine in rabbit and mouse species. In addition, residue V754 is not located in the refined functional R domain.15 V754M was described as a CF mutation, as it was found in a patient having classical CF (www.genet.sickkids.on.ca/cftr). The identification of the complex CFTRdele3–10,14b–16 in cis with V754M thus leads to the reconsideration of V754M as probably not disease causing, which will reassure individuals studied for carrier screening who are V754M heterozygotes but do not carry any other mutation/deletion. This observation highlights the need to achieve a complete CFTR gene analysis, including screening for rearrangements, when novel or rare missense mutations are found, since their deleterious effect cannot be easily proven.

**A revised strategy for CFTR molecular studies**

Among the gene quantification methods used to identify unknown gene deletions and duplications in hereditary genetic diseases, real-time PCR is the most commonly used.42 However, this method suffers from the inherent limitation of amplification efficiency,43 which can be as low as 95% for some gene fragments.44 For such reasons, we developed a novel strategy for CFTR molecular studies. Since it is based on the combination of gene rearrangements and in cis mutations in the family, it is expected to achieve a complete CFTR gene analysis. It is also expected to be easily proven.
disorders, the QFM-PCR approach is attractive because of the simplicity of its implementation in the clinical setting, its capacity to simultaneously analyse multiple gene loci, and its cost effectiveness as compared to the real time quantitative approach. It has been successfully applied in an increasing number of diseases following various protocols and, very recently, to the diagnosis of CF. The protocol described in the present study enables the rapid detection within a few hours of unknown CFTR gene deletions and duplications. Choosing intronic primers, except for the large exon 13, allowed us to design only three multiplexes comprising amplicons of a broader size range (138–440 bp). A great advantage of the protocol lies in the choice of reference genes amplified in each multiplex: (i) *DSGRI* serves as a double-copy control, as described elsewhere, a control DNA for trisomy 21 was used as a triple-copy control to compare with the CFTR exons 4–8 duplicated pattern observed in patient no. 11; in other respects, combining information on trisomy 21 could be advantageous in prenatal diagnosis of CF; (ii) *F9* serves as a single- or double-copy control depending on patient gender, thus allowing a further check of samples. Moreover, the use of genes located outside the CFTR locus validated the complete CFTR gene deletion pattern observed in patient no. 10.

Besides rearrangements detected by gene dosage, the technique described here is sensitive enough to detect length variations as small as 1 bp insertions/deletions, such as FS506delE1, 1078delT, and 2184insA, as well as STR variants such as those at the IVS8(TG)mt allele. Micro-deletions/insertions and large rearrangements thus account for 24% of the reported CF mutations (www.genet. sickkids.on.ca/cftr), while their cumulative frequency is above 70% of CF alleles in most Caucasian populations. After screening using a commercial kit for approximately 30 frequent mutations which account for 82% of French CF alleles, the use of our QFM-PCR system could contribute to identifying a further 4.5% of CF alleles, and possibly more in other populations. The simplicity and rapidity of such a system, which can be routinely applied in the clinical laboratory, makes it the method of choice for second line screening when frequent mutations are not found. Finally, the procedure can be readily adapted to the molecular diagnosis of many other hereditary diseases.

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**ELECTRONIC-DATABASE INFORMATION**

The URLs mentioned in this study are: www.genet. sickkids.on.ca/cftr, www.hgvs.org, and http://www.repeatmasker.org/.

Authors’ affiliations

F Nielsen, J Martin, F Daster-Le Moal, B Costes, B Boissier, V Delattre, M Goossens, E Girardon, Service de Biochimie et Génétique, AP-HP and INSERM U648, Hôpital Henri-Mondor, 94010 Créteil, France; Emmanuelle.Girardon@m3.insERM.fr

Correspondence to: Emmanuelle Girardon, Service de Biochimie et Génétique, AP-HP and INSERM U648, Hôpital Henri-Mondor, 94010 Créteil, France; Emmanuelle.Girardon@m3.insERM.fr

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