Molecular Medicine in Practice

Exon 7 Deletion in the bcr-abl Gene Is Frequent in Chronic Myeloid Leukemia Patients and Is Not Correlated with Resistance against Imatinib

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Abstract
Chronic myeloid leukemia (CML) patients treated with imatinib develop frequent resistance generally due to a point mutation. Recently, large rearrangements of abl sequence have also been described. In this study, we focused on the complete deletion of exon 7. We screened for bcr-abldelexon7 in 63 resistant patients by high-resolution melting (HRM) analysis and direct sequencing. Moreover, we analyzed expression of abldelexon7 and bcr-abldelexon7 in 17 CML patients at diagnosis, 32 patients at resistance, and 20 negative controls by quantitative PCR or fragment length analysis. bcr-abldelexon7 was detected on 34 (54%) among 63 resistant patients by HRM, showing an increase in the sensitivity of screening, because only 3.2% could be detected by direct sequencing. This deletion was not associated with a point mutation (P = 0.3362). In addition, abldelexon7 was found in all tested samples with the same pattern of expression, suggesting an alternative splicing mechanism. In the bcr-abl component, there was no statistical difference between CML patients at diagnosis and resistant patients (P = 0.2815) as regarding bcr-abldelexon7 proportion, thus arguing against involvement of deletion in resistance. Moreover, among two patients harboring bcr-abldelexon7 at diagnosis, one experienced a complete disappearance of this transcript, and the other decreased >75% at resistance. In conclusion, bcr-abldelexon7 is frequently observed in CML patients when using sensitive techniques. It seems to be the result of an alternative splicing mechanism and to be independent from the occurrence of resistance. Mol Cancer Ther; 9(11); 3083–9. ©2010 AACR.

Introduction
Chronic myeloid leukemia (CML) is a hematologic malignancy characterized by a chromosomal abnormality, the Philadelphia chromosome, due to a reciprocal translocation involving the long arms of chromosomes 9 and 22, t(9;22)(q34;q11). This rearrangement leads to a fusion gene, bcr-abl, which encodes a chimeric protein, BCR-ABL. This neofomed oncprotein carries a kinase domain in a constitutively active form, which is essential for cell transformation, proliferation, and survival through interaction and dysregulation of intracellular processes involving RAS, phosphatidylinositol 3-kinase/AKT, and signal transducer and activator of transcription 5 pathways (1).

Before the imatinib era, IFN-α was considered as the gold standard therapy, because a major cytogenetic response rate (i.e., at least 35% of cells without Philadelphia chromosome) has been observed in 28% of patients at 24 months and an overall survival rate at 5 years in 68% (2). The IRIS phase II trial highlighted the ability of imatinib to induce complete cytogenetic response and improve overall survival (3). Namely, a 6-year follow-up of patients included in the IRIS study showed a rate of complete cytogenetic response of 82% and an estimated overall survival at 5 years of 95% (4). Imatinib mesylate is a competitive inhibitor of ATP binding to the BCR-ABL tyrosine kinase, inhibiting its phosphorylation capacity (5, 6). Despite this targeted therapy, it is not infrequent, ranging from 15% to 40% (7, 8), that patients develop resistance. Several mechanisms have been described, some of them being independent from BCR-ABL—like inappropriate drug level concentrations due to efflux/influx abnormailities and others being BCR-ABL dependent, like genetic amplification and acquisition of mutations in ABL tyrosine kinase domain (8). For these latter cases, resistance depends on the amino acid involved. To date, up to 100 point mutations have been described, 17 of them accounting for roughly 80% to 90% of cases (9, 10). Recently, new kinds of mutations have been described, which do not correspond to a point mutation but to a large rearrangement-like in-frame deletions in exon 4 (11), insertion of 35 bp between exon 8 and exon 9 (12), insertion of 12 nucleotides...
in exon 5 (13), and complete deletion of exon 7 (14, 15). It is to date generally assumed that these “new mutations” are related to a high-degree resistance level to imatinib.

In the present article, we studied a series of cases of resistance to imatinib with exon 7 deletion to better evaluate its frequency and its involvement in the resistance process by comparison with newly diagnosed CML cases and normal controls.

Materials and Methods

Patients and samples

The data set included 17 CML patients at diagnosis and 63 resistant patients defined according to ELN 2009 criteria (16) as an absence of complete cytogenetic response at 12 months, or an absence of major molecular response at 18 months (i.e., bcr-abl/abl ratio lower than 0.1%), or at any moment a lost of cytogenetic/molecular response, seen in our laboratory between 2001 and 2010. All patients received between 400 and 800 mg/d imatinib from diagnosis (or from the time this drug became available) until resistance.

Twenty patients negative on bcr-abl screening were included as negative control.

Total RNA was isolated from peripheral blood cells using the Trizol/phenol/chloroform method, followed by a linearization step at 70°C during 10 minutes. RNA reverse transcription was done using 1 μg of total RNA, random hexamer primers at 25 μmol/L, 1 mmol/L of each deoxynucleotide triphosphate (dNTP), 10 mmol/L DTT, and 20 units of RNAse inhibitor with 100 units of RTase reverse in manufacturer’s buffer in a total volume of 25 μL for 45 minutes at 42°C and 3 minutes at 99°C. cDNAs were stored at −20°C.

ABL kinase domain mutation analysis by direct sequencing

Mutations within the BCR-ABL kinase domain were detected by direct sequencing in forward and reverse directions as previously described (17) on the 3130xl Genetic Analyzer (Applied Biosystems).

Detection of bcr-abldelexon7 by high-resolution melting analysis

To avoid abldelexon7 detection, a first bcr-abl 35-cycle amplification step was done on cDNA using a forward primer that annealed in bcr exon 13 and a reverse one in abl exon 10. Then, we did high-resolution melting (HRM) analysis on the PCR products.

The PCR and melting analysis for abl mutations were all done on the LightCycler 480 (Roche Diagnostics), a real-time PCR machine with HRM capability and a 96/384-well capacity. All samples were tested in duplicate.

Approximately 1 μL of “preamplified” cDNA was amplified in a total volume of 10 μL containing 2.5 pmol each of the relevant forward and reverse primer (351AF, GTGGTGCTGCTGTACATG; Abl4065R, CAGGTTGAT-

Quantification of bcr-abldelexon7 form

On bcr-abl PCR products, we did a nested PCR lead on the abl component with the same primers as used in HRM analysis. The only difference was the use of a forward 5’ fluorescence-labeled one (Eurofins MWG Operon). Amplified cDNA (1 μL) was mixed with 2.5 μL of 10× Buffer, 5 μL of SolutionQ, 1.5 μL of 25 mmol/L MgCl2, 1 μL of 5 mmol/L dNTP mix, 10 pmol of 10 mmol/L forward primer and 15 pmol of reverse primer, 0.5 μL of HotStarTaq (5 U/μL; Qiagen), and distilled water in a final volume of 25 μL. Thermal cycling conditions were as follows: 94°C for 7 minutes for denaturation, then 95°C for 60 seconds, 59°C for 40 seconds, 72°C for 90 seconds, repeated for 20 cycles, followed by 72°C for 5 minutes. After amplification, 2 μL of PCR product were mixed with 12 μL of deionized formamide and 0.4 μL of GeneScan 500 ROX Size Standard (Applied Biosystems), followed by a quick denaturation step at 95°C during 3 minutes stopped by chilling on ice. Samples were loaded onto the 3130xl Genetic Analyzer with POP7 (Applied Biosystems), a capillary electrophoresis system with fluorescence detection. The size and height of the peak were determined using GeneMapper Software.

The wild-type transcript, bcr-abldelexon7, was sized to 352 bp, and the bcr-abldelexon7 was sized to 167 bp (exon 7 size, 185 bp). bcr-abldelexon7/bcr-abl proportion was assigned, making the ratio of the height of the peak of bcr-abldelexon7 sum of the height of the peak.

Sequencing analysis of fragment analysis products

After migration of amplicons on agarose gel, PCR products were purified with Wizard SV Gel and PCR Clean-Up System (Promega) according to the manufacturer’s protocol and directly sequenced in forward and reverse directions with the same primers used for the nested PCR onto the 3130xl Genetic Analyzer after purification with the BigDye XTerminator (Applied Biosystems).

Quantification of abldelexon7

Plasmid construct. A PCR with a forward primer overlapping abl exons 6 and 8, in excess of Taq polymerase to add additional A at the 5’ and 3’ extremities, was used to produce an amplicon carrying the abldelexon7 with a 309-bp size. After checking PCR specificity, this amplicon was inserted in a vector and then in a chemically competent Escherichia coli (Invitrogen). After 2 days of culture on isopropyl-l-thio-B-d-galactopyranoside/
5-bromo-4-chloro-3-indolyl-β-D-galactopyranoside/ampicillin medium, white colonies were isolated; after overnight culture in Luria-Bertani medium, plasmids were extracted and then sequenced with the same protocol as previously described. In parallel, DNA dosage was done using a NanoDrop and concentration (X) was converted into plasmid copy number/μL using the following formula: \[ X \text{g.μL}^{-1} \text{DNA/}[\text{plasmid length in base pairs} \times 660] \times 6,022.1023 = Y \text{molecules.μL}^{-1}. \] In this case, the plasmid length was 4,177 bp.

**Quantitative PCR analysis.** Quantitative PCR was done on a LightCycler 480. For that, 2 μL of cDNA were mixed with 10 μL of SYBR Green Master Mix (Roche Diagnostics), 1 μL of relevant primers (10 μmol/L), and 8 μL of H2O. All samples for each gene (i.e., abl as reference gene and abl\text{delexon7} as target gene) were made in duplicate. Standard curves were obtained for abl using three known dilutions of abl plasmid (Ipsogen) and for abl\text{delexon7} with six dilutions of our plasmid, concentrations spreading between 10^8 and 10^3 copies/μL.

The abl\text{delexon7}/abl ratio was calculated using the software provided with the LightCycler 480.

**Statistical analysis**

To estimate whether the difference in the ratio bcr-\text{abldelexon7}/bcr-\text{abl} and abl\text{delexon7}/abl was statistically significant between different groups (patients and healthy donor), we did a nonparametric test (Wilcoxon), and a P value of <0.05 was considered statistically significant. χ² or McNemar χ² test (for matched samples) was used for comparisons of frequencies.

**Results**

bcr-\text{abldelexon7} rate increases with the sensitivity of techniques used for screening

Sequences were analyzed with sequencing analysis in the two reading directions. Deletion of exon 7 leads to a frameshift. On a cohort of 63 resistant patients, 15 patients

![Figure 1. Amplicon melting analysis for screening of bcr-\text{abldelexon7} in nondeleted and deleted samples showing the normalized melting curve (A) and derivative melting curve (B). The sample without the alternative variant harbors just one peak. The samples with the alternative variant have two peaks: one for the normal transcript and one for the deleted one. The curve with the highest peak on the left corresponds to a patient confirmed by direct sequencing. Other curves were negative by direct sequencing but confirmed on post-HRM product sequencing.](#)
(23.8%) harbored a point mutation and only 2 patients (3.2%) harbored the bcr-abldelexon7 mutation.

All patients harboring bcr-abldelexon7 show in fact a mixture with wild-type kinase domain and the deleted one. To improve the detection of bcr-abldelexon7, we developed an HRM assay for its screening. The normalized melting curves of each genotype are shown in Fig. 1. The slope of the melting curve of patients harboring bcr-abldelexon7 was markedly reduced, and so, the deleted allele could be easily distinguished from the wild-type one. Analysis was actually done on second derivative melt curve plots, which plot the rate of change in fluorescence against the temperature because it is easier to visualize the different melting domains. The presence of bcr-abldelexon7 leads to a shift in the Tm from 87.5°C to 84.3°C (P < 0.0001). Method specificity was confirmed by sequencing HRM products in the two reading directions with the same primers used for HRM analysis. After agarose migration, patients with two peaks in HRM analysis show two bands. The upper one corresponds to bcr-abldelexon7 and the lower one to bcr-ablwt.

Using HRM analysis, among the 63 patients tested, 34 (54%) show a shift in Tm, interpreted as the presence of bcr-abldelexon7. The two patients found to be deleted in sequencing analysis were indeed confirmed by HRM analysis. As in sequencing method, all patients harboring bcr-abldelexon7 show in fact a mixture of bcr-abldelexon7 and bcr-ablwt. Moreover, the height of the peak of bcr-abldelexon7 is not constant, suggesting variations in bcr-abl delexon7 amount.

On the other hand, 12 patients with bcr-abldelexon7 associated a point mutation (35.3%), as well as 7 of 29 patients with bcr-ablwt. No significant difference in the number of detected mutations between patients harboring bcr-abldelexon7 or bcr-ablwt was detected (P = 0.3362; Table 1).

Abldelexon7 is a splice variant of native abl
Specificity of our abldelexon7 cDNA was proved using a plasmid harboring no abldelexon7, which showed no amplification, allowing us to quantify only abldelexon7 transcripts without interferences. The plasmid abldelexon7 standard curve is characterized by a slope of −3.361 and a Y intercept of 37.81. Ratio was normalized to abl gene, showing a curve with a slope of −3.475 and a Y intercept of 38.93. First, all samples, including negative control CML.

Table 1. Frequencies of bcr-abldelexon7 by direct sequencing and HRM analysis and its association with point mutation

<table>
<thead>
<tr>
<th>Technique for screening</th>
<th>Genotype</th>
<th></th>
<th>P</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>bcr-abl+</td>
<td>bcr-abldelexon7</td>
<td></td>
</tr>
<tr>
<td>Sequencing analysis</td>
<td>61 (96.8)</td>
<td>2 (3.2)</td>
<td>&lt;0.05$</td>
</tr>
<tr>
<td>HRM analysis</td>
<td>29 (46)</td>
<td>34 (54)</td>
<td></td>
</tr>
<tr>
<td>Point mutation associated</td>
<td>7</td>
<td>12</td>
<td></td>
</tr>
<tr>
<td>No point mutation associated</td>
<td>22</td>
<td>22</td>
<td></td>
</tr>
</tbody>
</table>

*P-values are by McNemar χ² test.

Table 2. Expression of abldelexon7 and bcr-abldelexon7 compared with diagnosis and resistance status

<table>
<thead>
<tr>
<th>Type of transcript</th>
<th>Status</th>
<th>n</th>
<th>Normalized ratio (%)</th>
<th>P*</th>
</tr>
</thead>
<tbody>
<tr>
<td>abldelexon7/abl</td>
<td>CML at diagnosis</td>
<td>17</td>
<td>1.81</td>
<td>0.0743</td>
</tr>
<tr>
<td></td>
<td>CML at resistance</td>
<td>32</td>
<td>1.37</td>
<td>0.1286</td>
</tr>
<tr>
<td></td>
<td>Negative control</td>
<td>20</td>
<td>1.63</td>
<td></td>
</tr>
<tr>
<td>bcr-abldelexon7/bcr-abl</td>
<td>CML at diagnosis</td>
<td>11‡</td>
<td>21.3</td>
<td>0.2815</td>
</tr>
<tr>
<td></td>
<td>CML at resistance</td>
<td>12‡</td>
<td>29.11</td>
<td></td>
</tr>
</tbody>
</table>

*CML at diagnosis or at resistance versus negative control.
†CML at diagnosis versus CML resistant.
‡Eleven and 12 among 17 and 18 patients, respectively, for whom bcr-abldelexon7 was detectable.
patients at diagnosis or at occurrence of resistance tested, showed an amplification for $abl_{delexon7}$ with a Cp mean:

- negative control, 27.944 (27.133–28.755);
- CML at diagnosis, 28.393 (27.453–29.333);
- resistant CML, 28.053 (27.659–28.447), compared with $abl$ with respective Cp mean:
  - negative control, 22.559;
  - CML at diagnosis, 22.996;
  - resistant CML, 22.350.

CML patients at diagnosis show a median ratio at 1.81%, resistant CML at 1.37%, compared with negative controls with a ratio of 1.63%. No statistically significant difference was found neither between CML at diagnosis and negative control ($P = 0.0743$) nor between resistant CML and negative control ($P = 0.1286$). However, the difference was found between CML at diagnosis and resistant CML ($P = 0.0130$) due to a higher mean for CML at diagnosis and a lower mean for resistant CML compared with negative control (Table 2).

$bcr-abl_{delexon7}$ is not related to occurrence of resistance

Quantification of $bcr-abl_{delexon7}$ after a nested PCR (long-range PCR for selection of $bcr-abl$ transcript) with the same technique as the one used for quantification of $abl_{delexon7}$, namely, use of SYBR Green, which incorporates in any double-strand DNA, risked to quantify not desired amplicons. That is why we chose a fragment analysis method.

The presence of $bcr-abl_{delexon7}$ was not more common in resistant patients than in patients at diagnosis ($P = 0.8149$). Indeed, among the 17 patients at diagnosis, 11 (64.7%) show a peak corresponding to $bcr-abl_{delexon7}$ in mixture with $bcr-abl_{wt}$ (Fig. 2) and, for resistant patients, we detected a $bcr-abl_{delexon7}$ in 12 patients (18 patients could be tested because, for others patients, the quantity amount of $bcr-abl$ was too low to do fragment analysis).

This technique allowed us to know if there was a correlation between expression level of $bcr-abl_{delexon7}$ and resistance (Table 2). When the deleted form was present, with a mean expression for patients at diagnosis of 21.3%, there was no difference in expression for resistant patients (29.11%, $P = 0.2815$). Moreover, for six resistant patients, samples at diagnosis were available. Two patients showed no $bcr-abl_{delexon7}$ neither at diagnosis nor at resistance, and one showed appearance of the deleted form at time of resistance. On the contrary, in two patients harboring $bcr-abl_{delexon7}$ at diagnosis, one experienced a complete disappearance of this transcript, and the other decreased of >75% at resistance. So, $bcr-abl_{delexon7}$ and its expression did not seem to be involved in development of resistance against tyrosine kinase inhibitors.

Discussion

Occurrence of point mutations is the main mechanism of acquired resistance in CML (18–20), and bypassing them is the major challenge for the next years. In addition, different deleted or inserted forms have been described recently and several studies focused on their incidence and putative deleterious potential. $bcr-abl_{delexon7}$ was first described by Curvo et al. (14) who found it in five resistant patients and hypothesized that it could be related to imatinib resistance. In a large cohort of resistant patients, Sherbenou et al. reported 2 cases of this deletion among 101 samples. Using more sensitive techniques, such as HRM (21) or PCR fluorescent fragment analysis, we show in the present study that $bcr-abl_{delexon7}$ is not so rare. Indeed, its incidence is ∼54% in our cohort, whereas by direct sequencing we could detect only 3.2% cases, a result very similar to what was previously published (1.98%). This is not surprising because sensitivity of direct sequencing is roughly 20% (22), and we found a median expression of 27.4% of $bcr-abl_{delexon7}$, ranging from 6.4% to 55.2%. So, by direct sequencing, a minor mutated population cannot be separated from

![Figure 2. bcr-abl_{delexon7} detection using fragment length analysis. Patient showing a mixture of bcr-abl_{delexon7} (major peak on the left) with bcr-abl_{wt} (major peak on the right).](image-url)
background signal, hence a clear underestimation of deletion frequency.

Different studies hypothesized that bcr-ablΔexon7 could be correlated with a high degree of resistance against tyrosine kinase inhibitor, only based on its presence in a resistant patient cohort, without comparison with a normal control population. Our results lead to a quite different interpretation. First, studying abl transcript, we found this exon 7 deletion in all samples tested, among bcr-abl negative as well as positive donors, suggesting that ablΔexon7 probably results from an alternative splicing of the abl gene. Roughly 90% of human protein-coding genes have alternative splicing form, this mechanism being a key regulator of gene expression (23, 24). For the abl gene, one alternative variant has already been described and studied (25), and four others have been annotated in different databases such as Havana or Ensembl genebuild, but none of them includes an exon 7 deletion while retaining normal exons 6 and 8. This exon skipping is not random, some exons being more sensitive to alternative splicing, first due to the presence of elements in DNA sequences enhancing splicing as ESE (exonic splicing enhancer), ISE (intronic splicing enhancer), or Alu elements but also to the localization of the exon in tertiary structure of the protein. Indeed, exons out of the membrane or in a loop are more sensitive to alternative splicing. Exon 7 of abl is located in the activation loop, surrounded by four different Alu elements in intron 7 (http://transpogene.tau.ac.il; ref. 26), and seems to contain various ESE (http://genes.mit.edu/burgelab/rescue-ese/; ref. 27) that could explain why this exon is preferentially spliced. Whereas some authors showed that alternative splicing patterns are changed in cancer (28, 29), this mechanism does not seem to exist in the abl component for insertion or deletion. Indeed, as we showed for ablΔexon7, the insertion of 35 bp between exon 8 and exon 9, another big rearrangement of abl, first described in CML-resistant patients, has been reported in normal population (30), whereas its bcr-abl component has been related to resistance (31).

To know whether bcr-ablΔexon7 is related to resistance, we decided to focus on its expression. bcr-ablΔexon7 is found not only in resistant but also in newly diagnosed patients with an equivalent frequency. Moreover, the level of its expression does not seem to be correlated with occurrence of resistance because some patients, for example, show this transcript at diagnosis but lost it at resistance occurrence. bcr-ablΔexon7 leads to a codon stop in exon 8 at position 382, resulting in a truncated protein with no activation loop, this loop being phosphorylated that is necessary for a full activation of the kinase, stabilizing an active conformation for substrate binding and catalysis (32). A truncated protein would probably be inactive and undergo degradation or, alternatively, its RNA would disappear through nonsense RNA decay mechanisms. Using a quantitative microarray technique, it has been evaluated that 35% of alternative splicing events lead to a premature termination codon, and these splice variants are targeted by the process of nonsense RNA decay (33). Sherbenou et al. focus in another deletion in kinase domain, the exon 4 deletion. As for bcr-ablΔexon7, they found it in a large number of patients under imatinib therapy (80%), with no correlation between the presence of this deletion and outcome, and showed that this deletion mutant does not exhibit a dominant-negative effect with respect to bcr-abl activation (34).

Our result confirmed that bcr-abl deletions of exon 7 are quite frequent in patients under imatinib therapy, probably resulting from an alternative splicing mechanism. The use of sensitive techniques allows to easily detect this variant, frequently passed over by direct sequencing. There is no correlation between the detection of this peculiar form and resistance to tyrosine kinase inhibitor. Additional studies are required to know, first, if the resulting truncated protein is indeed synthesized in the cell or if its RNA goes to RNA decay mechanism and, second, to explain why only some patients at diagnosis exhibit this rearrangement, whereas all patients carry ablΔexon7.

Disclosure of Potential Conflicts of Interest

No potential conflicts of interest were disclosed.

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References

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