Acquired Resistance to Imatinib in Gastrointestinal Stromal Tumor Occurs Through Secondary Gene Mutation

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Abstract Most gastrointestinal stromal tumors (GIST) have an activating mutation in either KIT or PDGFRA. Imatinib is a selective tyrosine kinase inhibitor and achieves a partial response or stable disease in about 80% of patients with metastatic GIST. It is now clear that some patients with GIST develop resistance to imatinib during chronic therapy. To identify the mechanism of resistance, we studied 31 patients with GIST who were treated with imatinib and then underwent surgical resection. There were 13 patients who were nonresistant to imatinib, 3 with primary resistance, and 15 with acquired resistance after initial benefit from the drug. There were no secondary mutations in KIT or PDGFRA in the nonresistant or primary resistance groups. In contrast, secondary mutations were found in 7 of 15 (46%) patients with acquired resistance, each of whom had a primary mutation in KIT exon 11. Most secondary mutations were located in KIT exon 17. KIT phosphorylation was heterogeneous and did not correlate with clinical response to imatinib or mutation status. That acquired resistance to imatinib in GIST commonly occurs via secondary gene mutation in the KIT kinase domain has implications for strategies to delay or prevent imatinib resistance and to employ newer targeted therapies.

Gastrointestinal stromal tumor (GIST) is the most common mesenchymal tumor of the intestinal tract. After surgical removal of primary GIST, tumor recurrence is frequent, and previously, about 50% of patients died within 5 years of initial diagnosis (1). In 1998, Kitamura and colleagues reported that GIST is commonly associated with activating mutations in the KIT receptor tyrosine kinase (2). More recently, we showed that a knock-in KIT activation mutation, KITV558D+/+, is sufficient to induce GIST in mice (3). Imatinib mesylate (STI571, Gleevec, Novartis Pharmaceuticals, Basel, Switzerland) is an oral agent that specifically inhibits the BCR-ABL and ABL tyrosine kinases as well as the KIT and PDGFR receptor tyrosine kinases (4). Initially, imatinib was applied to the treatment of chronic myelogenous leukemia (CML), where it achieves a 90% complete response rate (5, 6). Subsequently, imatinib was tested in metastatic or unresectable GIST and found to induce a partial response or stable disease in >80% of patients (7, 8). Primary resistance to imatinib, in which GIST continues to progress despite the institution of therapy, occurs in about 15% of patients. Remarkably, the 2-year survival of patients with metastatic GIST is now ~70% (9).

In up to 90% of cases, GISTs have activating mutations in either the KIT or PDGFRA receptor tyrosine kinases (10–13). The most common site of KIT mutation is in the 5′ end of the exon (11), which encodes the juxtamembrane domain, and usually deletions or substitutions of codons 550 to 560 occur. KIT exon 9 mutation occurs in 10% to 15% of patients. It defines a distinct subset of GISTs that are often located in the small bowel and have an aggressive clinical behavior (11, 14). Infrequently, a mutation is identified in KIT exon 13 or 17 (15, 16). Another 5% of patients with GIST have a PDGFR A mutation that typically involves exon 12 or 18 (12, 13). About 10% of patients do not have a detectable mutation in either KIT or PDGFR. In particular, GISTs that occur in pediatric patients are nearly always wild-type for both genes (11A). Recent data suggest a possible correlation between imatinib response and the type of mutation, as tumors with an exon 9 mutation or wild-type KIT or PDGFR are less likely to respond to imatinib (17, 18).

Although most patients with advanced GIST benefit from imatinib treatment, it is now clear that many patients subsequently develop resistance to the agent. The median time to progression is about 24 months (9). The mechanism of acquired resistance to imatinib in GIST has not been well defined. In CML, second site mutation in BCR-ABL is the predominant mechanism of imatinib resistance (19, 20). Therefore, we postulated that acquired resistance to imatinib in GIST is due to secondary site mutation in the KIT or PDGFR genes. We did molecular analysis of 65 tumor nodules from 31 patients who were treated with imatinib.
Three patients showed primary resistance to imatinib, whereas 15 patients acquired resistance to imatinib during therapy.

Materials and Methods

Clinicopathologic analysis. Patients with the diagnosis of GIST who were treated with imatinib and underwent surgical resection of their tumor at Memorial Sloan-Kettering Cancer Center were identified from our prospective sarcoma database. There were 31 patients who had adequate tissue for molecular analyses following treatment. Patient, tumor, and treatment information was obtained from the database and by reviewing medical charts. Primary resistance to imatinib was defined as continued growth of any tumor despite the institution of imatinib therapy. Acquired resistance was defined as new tumor growth that occurred subsequent to an initial period during 2 to 3 months on imatinib in which the patient had stable or responding disease. Tumor size was determined by computed tomography scan or magnetic resonance imaging. This study was approved by the Institutional Review Board.

Pathologic material was examined and the diagnosis was confirmed using standard H&E staining and CD117 immunohistochemistry on formalin-fixed, paraffin-embedded tissue as previously described (11). Histologic response to imatinib was based on gross and microscopic findings of necrosis and fibrosis and was scored for each tumor nodule as: minimal (<10% response), low (10-50% response), moderate (50-90% response), or high (>90% response) degree of response.

KIT/PDGFRA genotyping. Mutation analysis was done as described previously (11). Genomic DNA was isolated from snap-frozen tumor tissue samples stored at −70°C, using a standard phenol-chloroform organic extraction protocol. Adequate DNA for mutational analysis was obtained in 65 tumor nodules from 31 patients. All cases were tested for the known sites of KIT (exons 9, 11, 13, 14, and 17) and PDGFRA (exons 12 and 18) mutations. One microgram of genomic DNA was subjected to PCR using Platinum TaqDNA Polymerase High Fidelity (Life Technologies, Inc., Gaithersburg, MD). Primer sequences and annealing temperatures were as described (11), with the addition of primers for KIT exon 14 (GTCGTGATCTGAGGCGCCATGCTG at 50°C and ACCCCAGATGTCGCGCCTGTC at 51°C), PDGFRA exon 12 (TCCAGT-CACCTGTCCCTGTC and GGAGGGAAAAGGATCGCTT at 54°C), and PDGFRA exon 18 (ACACTGATGCAGCAGCCTGCT and TGAAGGAG-GATGAGGCGCAG at 55°C). Direct sequencing of PCR products was done for all exons tested and each ABI sequence was compared with the National Center for Biotechnology Information human KIT and PDGFRA gene sequences. In four patients, including three with acquired resistance, there was adequate tumor tissue available for mutation analysis from a surgical resection that occurred prior to initiation of imatinib. In each case, including one patient who developed a second site mutation, we confirmed the same primary mutation as in the recurrence.

cDNA sequencing and cloning. For tumors with secondary KIT mutations by genomic DNA analysis, we then amplified and sequenced the KIT cDNA from exons 10 to 18. In this way, we confirmed our initial genotype results and also determined whether the secondary mutation occurred on the same or opposite allele as the primary mutation. Adequate RNA was obtained in 32 tumor nodules from 18 patients by using the RNA Wiz reagent (Ambion, Inc., Austin, TX) and the guanidinium isothiocyanate-phenol chloroform method. Five micrograms of RNA were transcribed using reverse transcriptase superscript II (Invitrogen, Carlsbad, CA). The cDNA was subjected to PCR using primers in KIT exon 10 (GGCGCATCCTGTCATTACGT- AACCCTGAAATG) with an EcoRI linker. Amplification of the KIT insert was done separately with Platinum Taq (Invitrogen) and Pfu ultra high-fidelity DNA polymerase (Stratagene, La Jolla, CA) in order to exclude false-positive mutations due to errors in polymerase proofreading. For cloning, the KIT insert and the chloramphenicol-resistant pBC KS+ vector (Stratagene) were digested with BamHI and EcoRI and then ligated using the rapid DNA ligation kit (Roche Applied Science, Penzburg, Germany). Plasmid transformation of XL-1 blue supercompetent cells (Stratagene) and colony selection on chloramphenicol Luria-Bertani agar plates were done using standard methods. For each sample, 10 distinct clones were picked and expanded overnight in a shaking incubator. Colony PCR was done using Taq polymerase and the same KIT exon 10 and 18 linker primers. Clones containing the insert were selected and DNA was isolated with a DNA Miniprep kit (Qiagen, Inc., Valencia, CA) and then directly sequenced.

Western blotting. Adequate tissue for protein extraction was available in 24 patients (43 tumor nodules). We also included for comparison 8 untreated GISTs with KIT exon 11 mutations, 4 of which were in-frame deletions, and 4 were substitutions. A CD117-negative and desmin-positive high-grade gastric leiomyosarcoma was included as a negative control. For preparation of whole lysates, 1 g of snap-frozen tumor was ground to powder in liquid nitrogen using a PowerGen 700 Homogenizer (Omnitome International, Marietta, GA), and resuspended in radioimmunoprecipitation assay lysis buffer (Upstate, Lake Placid, NY) containing a cocktail of protease and phosphatase inhibitors (Sigma, St. Louis, MO). Protein concentrations were determined with the Bio-Rad Protein Assay (Bio-Rad Laboratories, Hercules, CA). Protein samples were subjected to electrophoresis and immunoblotting using a standard protocol. Antibodies included mouse anti-phospho-Tyr205 and Tyr99 (Santa Cruz Biotechnology, Santa Cruz, CA), rabbit polyclonal anti-phospho-KIT Y721 (Zymed Lab., Inc., San Francisco, CA), rabbit anti-KIT (OncoGene Science, Boston, MA), mouse anti-actin (Santa Cruz), donkey anti-mouse secondary antibody (Santa Cruz), and anti-rabbit secondary antibody (Calbiochem, La Jolla, CA). Blots were incubated with Immum-Star horseradish peroxidase lumino/ enhancer (Bio-Rad) and exposed to Kodak BioMax MR Film (Eastman Kodak Company, Rochester, NY). Results with phospho-KIT were scored as: 1, strong; 2, weak; and 3, negative.

Fluorescence in situ hybridization analysis. Touch preps of frozen tissue were done in nine nodules from eight patients. The slides were fixed in 3:1 methanol/acetic acid then stored at −20°C. Fluorescence in situ hybridization (FISH) was done according to standard procedures. Briefly, the slides were pretreated with pepsin-HCl (0.007 mol/L HCl, 8 µg/mL pepsin) at 37°C for 3 to 5 minutes, rinsed in PBS, fixed in 1% formaldehyde for 10 minutes, then rinsed, dehydrated, and air-dried. The slides were then denatured in 70% formamide at 68°C for 2 to 4 minutes, quenched, dehydrated, and air-dried. The KIT probes used were two overlapping BAC clones: CTD-3180G20 and RP11-722F21 (Invitrogen), labeled by nick-translation with Spectrum Green (Vysis, Abbott Laboratories, IL). A chromosome 4 centromeric probe labeled with Spectrum Orange (CEP 4, Vysis) was used as reference. The probe mix, 50 to 80 ng of each KIT BAC and 2 µL Cot-1 DNA (Invitrogen), was ethanol-prefucinated, and resuspended in hybridization buffer. The KIT probe mix was denatured at 70°C for 10 minutes, followed by pre-annealing at 37°C for 30 minutes. The KIT probe was then combined with the denatured CEP 4 probe on the slide, coverslipped and incubated overnight at 37°C. After standard posthybridization washes, the slides were stained with 4',6-diamidino-2-phenylindole and mounted in antifade (Vectorshield, Vector Laboratories). Analysis was done using a Nikon E800 epifluorescence microscope with MetaSystems Isis 3 imaging software. A minimum of 100 cells was scanned over separate regions for each slide.

Results

Imatinib resistance may develop during chronic imatinib therapy. We identified 31 patients with GIST who were treated with imatinib and subsequently underwent surgical resection. There were 8 females and 23 males, and the median...
age at initial diagnosis was 56 (range 31-84) years. The extent of
disease at the original diagnosis of GIST was localized in 19
patients and metastatic in 12. Disease at the start of imatinib
therapy consisted of a primary tumor alone in 6 patients, a
primary GIST with liver and/or peritoneal metastasis in 7
patients, and recurrent liver and/or peritoneal disease in the
remaining 18 patients. Imatinib was administered at a starting
dose of 400 to 600 mg per day.

Based on the responsiveness of their disease to imatinib at the
time of surgery, we categorized patients into “nonresistant,”
“primary resistance,” or “acquired resistance.” Elective removal
of residual GIST following either a partial response or stable
disease on imatinib was done in the 14 nonresistant patients
(Table 1). Their median duration of imatinib therapy was
8 (1-22) months. Surgery was done in 3 patients with primary
resistance to imatinib. Each had progression of disease detected
8 (1-22) months. Surgery was done in 3 patients with primary
resistance to imatinib. Each had progression of disease detected
on computed tomography within 3 months of starting therapy
(Table 2). There were 15 patients who developed acquired
resistance. Each had either a partial response (n = 10) or stable
disease (n = 5) in response to imatinib and then subsequently
acquired resistance and radiologic progression of disease. The
median length of imatinib treatment in patients with acquired
resistance was 18 (8-32) months (Table 2). One of these patients
(#14) first had an operation to remove stable disease and later
underwent another resection to remove resistant disease. Two
patients required surgery because of a complication during
imatinib therapy, involving either bleeding or perforation.

**Histologic response correlates with clinical response to
imatinib.** The primary tumor was located in the stomach in 8
patients, small bowel in 17, rectum in 5, and intra-abdominal in
1 patient. The median size of the primary GIST was 9.5 (2.6-24)
cm. There were 13 tumors larger than 10 cm. The morphology of
the primary tumor was spindle-shaped in 25 cases, epithelioid in
4, and mixed in 2 tumors. Histologic response was graded based
on the combined extent of tumor necrosis and fibrosis, because
both are usually absent in untreated GIST, although central
necrosis may be present in large tumors. Patients with primary
resistance uniformly lacked any histologic evidence of response
to imatinib (patients 29-31, Table 2). Six of 14 patients in the
nonresistant group had a histologic response of >90%. Moderate
histologic responses (50-90%) occurred in four others. Only
three nonresistant patients had a minimal histologic response
despite a clinical partial response or stable disease. In contrast, in
the acquired resistant group, all but two patients had had at least
one nodule lacking any response (Table 2).

**Secondary KIT mutation occurs in acquired imatinib resistance.**
In the nonresistant group, there were 11 patients with a KIT
mutation (3 in exon 9, 7 in exon 11, and 1 in exon 13), 1
patient with a PDGFRA mutation (exon 18), and 2 were wild-
type. There were no identifiable secondary mutations in the
nonresistant group. However, there was one patient (#2) who
had a homozygous exon 11 deletion in 6 of 15 nodules tested.
The significance of this finding is unclear as the patient had
stable disease and currently has no evaluable tumor. As
expected, the 3 patients with primary resistance to imatinib
also had only a single mutation, which involved KIT exon 9 or
11 or PDGFRA exon 18.

Of the 15 patients with acquired resistance to imatinib, 14
had a common primary KIT mutation (11 in exon 11 and 3
in exon 9) and 1 patient was wild-type. Secondary mutations

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### Table 1. Patients with nonresistant GIST

<table>
<thead>
<tr>
<th>Primary tumor location</th>
<th>Histology</th>
<th>Disease at imatinib start</th>
<th>Time on imatinib* (months)</th>
<th>Best clinical response</th>
<th>Histologic response</th>
<th>Primary mutation</th>
<th>Phospho-KIT Y721</th>
<th>Secondary mutation</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 SB S, P, L</td>
<td>22</td>
<td>PR 2, 3</td>
<td>Ex11 VYIDPTQL569-576del</td>
<td>abs 0 (0 of 2)</td>
<td>2, 3</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2A SB S, P, PE, L</td>
<td>15</td>
<td>PR 2, 3</td>
<td>Ex11 P551H MY552-554del</td>
<td>abs 0 (0 of 6)</td>
<td>1</td>
<td></td>
<td></td>
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</tr>
<tr>
<td>2B L</td>
<td>20</td>
<td>PR 1, 2</td>
<td>Ex11 P551H MY552-554del</td>
<td>abs 0 (0 of 3)</td>
<td>3</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>3A SB S, PE</td>
<td>12</td>
<td>SD 1</td>
<td>Ex9 INS502AY</td>
<td>abs 0 of 1</td>
<td>NA</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>3B S, PE</td>
<td>18</td>
<td>SD 1</td>
<td>Ex9 INS502AY</td>
<td>abs 0 of 3</td>
<td>1, 3</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>4 SB S, P, L</td>
<td>3</td>
<td>SD 1</td>
<td>Ex9 INS502AY</td>
<td>abs 0 of 3</td>
<td>1</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>5 rectum S, P</td>
<td>9</td>
<td>PR 4</td>
<td>WT</td>
<td>abs 0 of 1</td>
<td>NA</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>6 SB S, P</td>
<td>4</td>
<td>SD 2</td>
<td>Ex9 INS502AY</td>
<td>abs 0 of 1</td>
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<td></td>
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<tr>
<td>7 rectum S, P</td>
<td>6</td>
<td>PR 4</td>
<td>Ex11 VQWKV555-559del</td>
<td>abs 0 of 1</td>
<td>3</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>8 SB S, P</td>
<td>2</td>
<td>PR 1</td>
<td>Ex11 K558N, INS559Q</td>
<td>abs 0 of 1</td>
<td>NA</td>
<td></td>
<td></td>
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</tr>
<tr>
<td>9 SB S, PE, L</td>
<td>1</td>
<td>PR 3, 4</td>
<td>WT</td>
<td>abs 0 of 1</td>
<td>NA</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>10 stomach S, P</td>
<td>8</td>
<td>PR 4</td>
<td>Ex11 WK557-558del</td>
<td>abs 0 of 1</td>
<td>NA</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>11 stomach E, PE</td>
<td>5</td>
<td>SD 2, 3</td>
<td>PDGFRA D842V</td>
<td>abs 0 of 2</td>
<td>1</td>
<td></td>
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<tr>
<td>12 SB S, P, PE, L</td>
<td>9</td>
<td>PR 4</td>
<td>Ex11 INGNNYVYIDPTQL563-576del</td>
<td>abs 0 of 2</td>
<td>3</td>
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<tr>
<td>13 rectum S, P</td>
<td>8</td>
<td>PR 3</td>
<td>Ex13 K642E</td>
<td>abs 0 of 1</td>
<td>2</td>
<td></td>
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</tr>
<tr>
<td>14A SB S, PE</td>
<td>3</td>
<td>PR 4</td>
<td>Ex11 VYIDPTQL569-576del</td>
<td>abs 0 of 1</td>
<td>2</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Abbreviations: SB, small bowel; S, spindle; E, epithelioid; P, primary tumor; PE, peritoneal; L, liver; PR, partial response; SD, stable disease; del, deletion; LOH, loss of heterozygosity; INS, insertion; NA, not available.

*Time from the start of imatinib to surgical resection.

+Tested for KIT amplification by FISH.
were detected in 10 tumor nodules samples from seven (46%) patients and involved five different residues. The majority were KIT exon 17 mutations and occurred in six of seven patients with secondary mutations. All involved substitutions and three were N822K, two were D820Y, and one was Y823D (Table 2; Fig. 1). The other two secondary mutations included substitutions in exon 13 (V654A) and exon 14 (T670I). We again identified loss of the wild-type allele (loss of heterozygosity), WK557-8del in one patient (#28, one of three nodules tested) as we had in one nonresistant patient (#2).

In 10 of 15 patients with acquired resistance, more than one nodule was available for molecular analysis. In two of them an identical secondary mutation was identified in both nodules tested. In three patients, the secondary mutation was present on one but not all nodules. Interestingly, in one other patient (#24) a nodule showed an exon 13 V654A mutation, whereas a subsequent nodule removed 7 months later showed an exon 17

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**Table 2. Patients with either acquired or primary resistance to imatinib**

<table>
<thead>
<tr>
<th>Primary tumor location</th>
<th>Histology</th>
<th>Disease at imatinib start</th>
<th>Time on imatinib (months)</th>
<th>Best clinical response</th>
<th>Histologic response</th>
<th>Primary mutation</th>
<th>Secondary mutation</th>
<th>Phospho-KIT Y721</th>
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<tr>
<td>14B SB</td>
<td>PE</td>
<td>S</td>
<td>29 PR</td>
<td>1</td>
<td>Ex11 VYIDPTQL569-576del</td>
<td>D820Y (2 of 2)</td>
<td>2</td>
<td></td>
</tr>
<tr>
<td>15 rectum SB + E</td>
<td>CW</td>
<td>28 SD</td>
<td>1</td>
<td>Ex11 KVVEE558-562del-LOH</td>
<td>Y823D (1 of 1)</td>
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<td>16 SB rectum E</td>
<td>PE</td>
<td>13 PR</td>
<td>1</td>
<td>Ex11 L576P</td>
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<td>PE, L</td>
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<td>1</td>
<td>Ex9 INS502AY</td>
<td>1</td>
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<tr>
<td>18 SB stomach E</td>
<td>PE</td>
<td>26 SD</td>
<td>1,2</td>
<td>Ex9 INS502AY</td>
<td>1, 2</td>
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<td>19 stomach SB PE, L</td>
<td>L</td>
<td>13 PR</td>
<td>1</td>
<td>Ex11 WK557-8del</td>
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<td></td>
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<tr>
<td>20 stomach E</td>
<td>PE</td>
<td>8 SD</td>
<td>1,2</td>
<td>WT</td>
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<td>21 stomach E</td>
<td>PE</td>
<td>25 PR</td>
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<td>22 SB stomach S + E</td>
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<td>Ex11 V560del</td>
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<tr>
<td>24A SB PE</td>
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<tr>
<td>25 SB S</td>
<td>L</td>
<td>32 SD</td>
<td>Ex11 V559D</td>
<td>D820Y (1 of 2)</td>
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<td>20 PR</td>
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<tr>
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<td>28 stomach S PE, L</td>
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<tr>
<td>29 stomach E</td>
<td>L</td>
<td>12 PrimR</td>
<td>PDGFRAD842V</td>
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<td>P, L</td>
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</table>

Abbreviations: SB, small bowel; S, spindle; E, epithelioid; P, primary tumor; PE, peritoneal; L, liver; PR, partial response; SD, stable disease; del, deletion; LOH, loss of heterozygosity; INS, insertion; NA, not available; I-abd, intra-abdominal; PrimR, primary resistance; CW, chest wall.

1 Time from the start of imatinib to surgical resection.
2 Tested for KIT amplification by FISH.
N822K substitution. The remaining four patients had only a primary mutation identified.

To confirm the secondary mutations found at the genomic level and to exclude the possibility of polyclonal resistance and/or the presence of additional KIT mutations that were missed, amplification of the KIT cDNA from exons 10 to 18 was done followed by subcloning and direct sequencing. A total number of 32 samples from 18 patients were analyzed, including 2 pre-imatinib samples, 13 nonresistant nodules from 6 patients, 14 samples from 9 patients with acquired resistance and 3 nodules from 2 primary resistance patients. This analysis included 10 nodules from 5 patients with acquired resistance and second site mutations. Secondary mutations were confirmed in 7 of 7 nodules and the absence of mutation in the 3 other nodules. No additional KIT mutations were detected. Notably, the primary and secondary mutations were all located on the same allele.

**KIT activation is variable regardless of response to imatinib.** KIT activation as measured by phosphorylation was heterogeneous and did not consistently correlate with histologic response or response to imatinib (Table 1; Fig. 2A). Surprisingly, from the 11 operations in 10 nonresistant patients tested, only three specimens lacked evidence of KIT activation. Meanwhile, five nonresistant patients had strong KIT activation (Fig. 2A) and three had moderate expression. From 14 operations in 13 patients in the acquired resistance group, 6 patients had strong KIT activation, 5 had moderate expression, and 2 had none. Notably, KIT activation was also variable in the subset of patients with a second mutation, as there was strong activation in three, moderate expression in three, and no detectable phospho-KIT in two instances. In fact, the three patients (#22, 24, 27) with an identical N822K secondary mutation had either weak (n = 1) or strong (n = 2) phospho-KIT expression. There was also intraindividual variability, because in patient #19, carrying an identical T670I secondary mutation in the two nodules tested, the phospho-KIT was strong and weak (Fig. 2B). Furthermore, the patient (#24) with distinct secondary KIT mutations in two metachronous nodules had strong KIT activation in one and weak activation in the other (Fig. 2B). KIT activation variability was also noted within the resistant nodules without secondary mutations (Fig. 2C). Both patients with primary resistance did have strong phospho-KIT staining (Fig. 2C; Table 2). Inconsistent KIT activation was also observed in the untreated control group. Although, phospho-KIT was detected in all eight tumors tested, it had a weak pattern in five, including all four GISTs with KIT exon 11 in-frame deletions, and was strong in three (Fig. 2D). All three untreated GISTs with identical 557-8 WK deletion showed a weak expression only of the mature isoform.

**KIT amplification is not a frequent event in imatinib resistance.** Tissue for FISH analysis was available in nine nodules from eight patients: three nonresistant (#2, 3, 4), four with acquired resistance (three with no secondary mutations #16, 17, 22, and one carrying a D820Y, #14B) and one patient with primary resistance (two nodules, #31). Copy number ratio for KIT: CEP 4 in the nine nodules tested did not differ from the normal control liver sample and no evidence of KIT amplification was identified in any of the tumors tested (Fig. 3).

**Discussion**

We attempted to determine the mechanism of acquired resistance to imatinib in patients with GIST in order to identify strategies to prevent or delay its development. We did a molecular analysis of KIT and PDGFRα mutations in a cohort of patients who were treated with imatinib and then underwent surgical resection. We found second site KIT mutations to be
Acquired Imatinib Resistance in GIST

common in acquired resistance to imatinib. Of the 15 patients with responsive or stable disease who then experienced disease progression, 7 had an identifiable second mutation. In each case, both the first and the second mutation were located in the KIT gene. In fact, they were located on the same allele. In contrast, we have not identified two simultaneous KIT or PDGFRα mutations in >300 untreated GIST tumors that we have analyzed.

All resistant tumors that had a second mutation had a primary KIT exon 11 mutation. These primary mutations were mainly in-frame deletions but there was one insertion and one substitution mutation (Fig. 1). The eight second site mutations were all substitutions that involved five different residues. By comparison, the incidence of point mutations in nontreated GIST is at most 15%. The five residues derived from either the first (exons 13 or 14) or second (exon 17) KIT kinase domain. In contrast, the incidence of exons 13, 14, or 17 mutations in untreated GIST is about 1% (11, 15). Six of the secondary mutations were located in exon 17 between amino acids 820 and 823, the most common being N822K, which was seen in three cases. Although N822K and D820Y have been previously reported as a primary sporadic mutation (10) and germ line mutation in a familial GIST syndrome (21), respectively, we believe that in these resistant nodules, N822K and D820Y substitutions represent a secondary mutation because they were associated with an exon 11 mutation and only one of the multiple nodules analyzed from the same patient carried this mutation. Similar KIT kinase mutations, N822K and Y823D, have been described recently in a subset of seminomas (22). To date, all primary mutations reported in KIT exon 13 have been a K642E substitution (10, 15–17). However, we identified a V654A mutation in exon 13. Interestingly, a recent study by Chen et al. (23) reported a V654A mutation in all six resistant nodules taken from five GIST patients. Similarly, this second mutation in their study was also found on the same allele as the primary mutation. However, there are several differences between our findings and those of Chen et al. (23) including: (a) the incidence of second mutations in acquired resistance (100% versus 46%), (b) the location of second mutations (exon 13 versus different areas of the KIT kinase domain), and (c) the type of primary mutation of tumors developing second mutation (exon 9 and 11 versus only exon 11 mutations).

Some of these discrepancies might be due to a limited number of cases in both series. Although no primary mutations have been previously described in KIT exon 14, a recent report has shown a T670I substitution in a patient with acquired resistance (24). One of our seven patients with a second mutation had a similar T670I mutation. New activating kinase mutations were also reported in seven of nine (78%) GIST patients with a unique pattern of resistance, defined radiologically as a “nodule within a mass”, and thought to represent the progression of a clone resistant to imatinib (25).

Recently, the crystal structures of the autoinhibited inactive and active conformations of the KIT kinase have been determined, as well as the structure of the KIT kinase in complex with imatinib (26). These structures provide insight into the mechanism of the normal regulation of KIT kinase function but moreover they provide explanations for the basis of constitutive activation of mutations found in neoplasms such as GIST. A critical feature in KIT kinase function is the role of the juxtamembrane domain of the KIT receptor in regulating kinase activity. In the inactive autoinhibited state, the juxtamembrane domain of KIT inserts into the kinase active site and thus disrupts the formation of the active conformation. Critical residues in these interactions are WK557-558 and VV559-560. Mutation of these residues disrupts these inhibitory interactions and destabilizes the inactive autoinhibited conformation of the KIT kinase. Thus, a diversity of juxtamembrane domain mutations represents the majority of primary oncogenic mutations found in GIST. The activation loop (A-loop) of the KIT kinase, which includes Y823, a pseudosubstrate of the KIT kinase, is another major site of oncogenic mutation. During KIT kinase activation, Y823 becomes phosphorylated and this seems to stabilize the open active conformation of the A-loop presumably by strong negative electrostatic interactions of the phosphate residue. Oncogenic activation loop mutations such as Y823D, which mimic Y823 phosphorylation, thus stabilizing the active conformation of the A-loop. The structure of the KIT-imatinib complex revealed that, similar to BCR-ABL, imatinib binds the inactive conformation of the kinase although the KIT-imatinib complex deviates somewhat from the autoinhibited inactive KIT kinase conformation. It is therefore not surprising that A-loop mutations are generally not inhibited by imatinib, although there seem to be exceptions. Therefore, there are two possible mechanisms of how resistance to imatinib therapy may develop. First, second site mutations may stabilize the active conformation of the KIT kinase which prevents imatinib binding. Alternatively, second site mutations may specifically interfere with imatinib binding without affecting the overall KIT kinase conformation. Our findings are in agreement with these predictions. First, five of the second site mutations in this study are located in the A-loop (26). Tyr625 was found to be substituted by aspartic acid in one of the resistant tumors and other mutations included D820Y and N822K. Although the Y823D mutation introduces a tyrosine-phosphate mimic (Fig. 4), the others may destabilize the inactive conformation by introduction of a positively charged side chain into a positively charged pocket formed on the COOH-terminal lobe of the kinase. Second, one mutation seems to block imatinib binding to KIT. In T670I, the gatekeeper residue Thr670 is replaced by an isoleucine residue. This mutation disrupts an important H-bond between imatinib and the kinase and the
isoleucine methyl group protrudes into the imatinib binding site precluding proper imatinib binding to the KIT kinase (Fig. 4). Investigation of CML revealed that the predominant mechanism of acquired resistance to imatinib is second site mutation in BCR-ABL (19, 20). The BCR-ABL mutations described to date in resistant CML either alter the imatinib binding site or the residues responsible for the unique conformational change that permits imatinib binding and prevents the inactive conformation necessary for imatinib binding (20). BCR-ABL kinase domain substitutions occurred in 29 of 32 (90%) resistant tumors, whereas genomic amplification of BCR-ABL transcript was infrequent. Similarly, we found secondary KIT mutation in patients with acquired resistance. However, there are several distinct features between acquired resistance in CML and GIST (Table 3). First, preexisting BCR-ABL kinase mutations have been found in 2 of 4 patients (20) and in 5 of 24 patients (27) who did not respond to imatinib. Furthermore, BCR-ABL kinase mutations were also found in 4 of 13 patients with chronic phase CML who had stable disease on imatinib and this predicted subsequent clinical relapse (20). We did not find secondary mutations in any of the 14 GIST patients with nonresistant disease. Shah et al. (20) found polyclonal resistance, in which two to four clones harbored distinct mutant BCR-ABL kinase domains mutations in 12 of 32 CML patients. We did not detect polyclonal resistance in 10 samples from five patients with acquired resistance, because all cDNA subclones from one tumor nodule revealed only a single type of secondary mutation. Although we did not find coexisting multiple second mutations from patients with acquired resistance, one patient had two different secondary mutations in resistant nodules at two different time points. This, tumor nodules within a patient may develop independent means of imatinib resistance.

The mechanism for the development of a second mutation in GIST is unclear. The long duration of imatinib therapy (median of 27 months) in patients with acquired resistance who developed a second mutation makes it less likely that a preexisting clone is responsible for acquired resistance (Fig. 5). In CML, the presence of BCR-ABL kinase domain mutations in pre-imatinib samples of patients with primary resistance, the relapse of patients in the blast phase is within 1 to 3 months, and the finding of multiple mutations in resistant patients suggest clonal selection of preexisting mutations that confer imatinib resistance. In GIST, the possibility of preexisting mutations remains to be evaluated carefully.

Our inability to find secondary mutations in eight resistant GIST patients suggests that other gene mutations, or altogether

### Table 3. Comparison of imatinib resistance in CML and GIST

<table>
<thead>
<tr>
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<th>CML*</th>
<th>GIST†</th>
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<tbody>
<tr>
<td><strong>Acquired resistance</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Kinase domain mutations</td>
<td>29 of 32</td>
<td>7 of 15</td>
</tr>
<tr>
<td>Median duration of imatinib therapy</td>
<td>20 months</td>
<td>27 months</td>
</tr>
<tr>
<td>Gene amplification in acquired resistance</td>
<td>3 of 11</td>
<td>0 of 4</td>
</tr>
<tr>
<td>Activation of transcribed protein</td>
<td>11 of 11</td>
<td>heterogeneous</td>
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<tr>
<td><strong>Primary resistance</strong></td>
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<td></td>
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<tr>
<td>Kinase domain mutations pre-imatinib</td>
<td>7 of 28</td>
<td>0 of 4</td>
</tr>
<tr>
<td><strong>Nonresistant disease</strong></td>
<td></td>
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</tr>
<tr>
<td>Kinase domain mutations</td>
<td>4 of 13</td>
<td>0 of 14</td>
</tr>
</tbody>
</table>

NOTE: Results are listed as number of patients with feature over number tested.
*Based on refs. (19, 20, 27).
†Current report
‡Chronic phase CML.

![Fig. 4. Interaction of imatinib and the KIT kinase.](image)

**A**

Thr670
ADP
Auto-inhibitory loop
Tyr823
A-loop

**B**

Thr670
Imatinib
Auto-inhibitory loop
Tyr823
A-loop
different mechanisms, may be involved. Fletcher et al. (28) suggested additional mechanisms of resistance besides secondary KIT mutations in GIST, including KIT genomic amplification and activation of an alternative receptor tyrosine kinase protein in the absence of KIT expression. We have found no evidence for KIT genomic amplification in our five resistant patients. Based on experimental data, other possibilities are increased serum acid glycoprotein levels and increased multidrug resistance gene expression (29, 30). More recently, Van Oosterom and colleagues (17, 31) found preliminary evidence that bioavailability of imatinib may decrease during chronic therapy, possibly due to up-regulation of hepatic enzymes responsible for drug clearance. It is now well documented that cessation of imatinib during stable measurable disease results in tumor proliferation (32) and therefore subtherapeutic imatinib levels may also result in tumor progression.

Our analysis of phosphorylated KIT protein yielded heterogeneous results, signifying the complexity of KIT activation in treated GIST. Strikingly, the majority of nonresistant patients still had activated KIT. Most of the patients in the acquired resistance group also had phospho-KIT and almost half had strong expression. This finding suggests that GIST progression may still depend on KIT and alternative inhibitors of KIT, or its downstream pathway, may be of therapeutic benefit. Nevertheless, there were three patients with acquired resistance whose tumors lacked detectable KIT activation. There was no discernible pattern of KIT activation based on histologic response, the type of detectable KIT activation. There was no discernible pattern of KIT activation based on histologic response, the type of detectable KIT activation.

There was not even a correlation between phosphorylated KIT and total KIT. Our findings are consistent with those of Duensing et al. (33) who found that both phosphorylated and total KIT varied substantially among tumors, even within identical KIT genotype. Our data with KIT phosphorylation may be confounded by the fact that we stopped imatinib generally 2 to 5 days prior to surgery. Currently, there are no established guidelines for the perioperative use of imatinib but our approach seems to be safe.

Secondary mutations during chronic imatinib use has several implications for the clinical management of patients with advanced GIST. Our recommendations are based on the supposition that the risk of developing resistance is proportional to the amount of residual viable tumor in patients on imatinib. Therefore, we consider extirpation of all gross disease whenever possible. Indeed, that was the rationale for operating on most of the patients in this report who were nonresistant. The fact that several nonresistant patients had only minor histologic responses along with activated KIT underscores the potential for viable tumor to progress. An argument may even be made for debulking (removing as much gross disease as possible) in patients with extensive residual disease during imatinib therapy. Alternatively, optimal management may include the combined use of imatinib with other newer molecular agents. Although we did not detect any second mutations in nonresistant patients, Shah et al. (20) found second mutations in 4 of 13 patients with stable CML and that predicted subsequent relapse. Patients with stable GIST who may be found to have a second mutation (such as by biopsy) should certainly be considered for additional surgery or other molecular agents due to the likelihood of impending progression. Of course, serial tumor assessment is not practical in GIST as it is in CML. A variety of other molecular inhibitors are currently under investigation for advanced GIST that is refractory to imatinib. The furthest along is SU11248 (Pfizer Inc., New York, NY), an inhibitor of multiple tyrosine kinases. It seems to be effective in imatinib-resistant GIST, especially in patients with exon 9 mutations (34).

In summary, we report a clinical and molecular study of acquired resistance to imatinib in GIST. We found that secondary mutations are common in imatinib resistance. The mutations tend to be single amino acid substitutions in the KIT kinase domains and occur particularly in exon 17. Secondary mutations were not seen in the pre-imatinib, nonresistant, or primary resistant tumors. There was considerable heterogeneity between KIT activation and responsiveness of GIST to imatinib. Our findings have implications for strategies to treat or avert imatinib resistance and might be useful in the design of second-generation kinase inhibitors.

Acknowledgments

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Fig. 5. Relationship of duration of therapy to the presence of a second KIT mutation in patients with acquired resistance to imatinib. Resistant patients who developed a second KIT mutation had a median duration of imatinib treatment of 27 months, whereas those who did not had a median treatment duration of 14.5 months. Patient 24 developed acquired resistance at 9 and 16 months of imatinib therapy and had a secondary mutation in each instance, which are both plotted.
Acquired Resistance to Imatinib in Gastrointestinal Stromal Tumor Occurs Through Secondary Gene Mutation

Cristina R. Antonescu, Peter Besmer, Tianhua Guo, et al.


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