Identification of Novel Mutations in the Dihydropyrimidine Dehydrogenase Gene in a Japanese Patient with 5-Fluorouracil Toxicity

Masanori Kouwaki, Naoki Hamajima, Satoshi Sumi, Masaru Nonaka, Makoto Sasaki, Kazuyoshi Dobashi, Kiyoshi Kidouchi, Hajime Togari, and Yoshiro Wada

ABSTRACT

5-Fluorouracil (5-FU) is used widely in the treatment of several common neoplasms. Dihydropyrimidine dehydrogenase (DPD) is the initial and rate-limiting enzyme in the catabolism of 5-FU. Several recent studies have described a pharmacogenetic disorder in which cancer patients with decreased DPD activity develop life-threatening toxicity following exposure to 5-FU. We reported recently the first Japanese case of decreased DPD activity accompanied by severe 5-FU toxicity. The present study describes the results of molecular analysis of this patient and her family, in which three novel mutations (Arg21Gln, Val335Leu, and Glu386Ter) of the gene coding for DPD were identified. We also revealed that Arg21Gln and Glu386Ter are on the same allele and that Val335Leu is on the other allele, on the basis of measurement of the family genome. Expression analysis in Escherichia coli showed that Val335Leu and Glu386Ter led to mutant DPD protein with significant loss of enzymatic activity and no activity, respectively. The Arg21Gln mutation, however, resulted in no decrease in enzymatic activity and no activity, respectively. The Arg21Gln mutation, however, resulted in no decrease in enzymatic activity and no activity, respectively.

INTRODUCTION

In humans, catabolism of uracil and thymine takes place through a three-step pathway leading to the generation of β-alanine and β-aminoadipic acid (1). DPD \(^{1}\) (EC 1.3.1.2) is the initial and rate-limiting enzyme of the pathway (2).

DPD is also the key enzyme that degrades the structurally related pyrimidine antimetabolite 5-FU and its analogues. These chemotherapeutic drugs are used widely in the management of several common malignancies, including cancer of the gastrointestinal tract, ovary, and breast (3). In humans, >85% of administered 5-FU is degraded through this catabolic pathway (4).

DPD deficiency (Muskic 274270) was described first in pediatric patients exhibiting thymine-uraciluria associated with a variety of neurological symptoms (5–8). Family studies have shown that the DPD deficiency follows an autosomal recessive pattern of inheritance, based on measurements of catalytic activity in lymphocytes (9, 10). On the other hand, DPD deficiency that demonstrates no clinical symptoms has also been reported (11, 12).

Several recent studies have described a pharmacogenetic disorder in which individuals with decreased DPD activity develop life-threatening toxicity following exposure to 5-FU (9, 13–16).

The recent cloning of cDNA and genomic DNA encoding DPD has allowed detection of the defect at the molecular level (17, 18). These studies have demonstrated exon skipping, deletion, and some missense mutations in Caucasian patients (10–12, 19, 20).

In Japan, until recently there have been no reports of DPD deficiency. We first reported a Japanese female with decreased DPD activity accompanied by severe 5-FU toxicity in 1997 (21). The present study describes the results of molecular analysis of this patient and her family.

MATERIALS AND METHODS

Patient. The proband was a 57-year-old woman who was diagnosed with breast cancer. She presented with leukopenia, thrombocytopenia, and severe mucositis during 5-FU therapy, and the level of DPD activity in her peripheral blood mononuclear cells was decreased significantly (21).

Pyrimidine Metabolite Concentration in Urine. Urinary pyrimidines and their derivatives, such as uracil, dihydrouracil, thymine, and dihydrothymine, were measured as reported previously (22).

1 The abbreviations used are: DPD, dihydropyrimidine dehydrogenase; 5-FU, 5-fluorouracil; RT, reverse transcription; Ter, termination codon.
DPD Catalytic Activity. DPD catalytic activity in the proband and her family members was determined in peripheral blood mononuclear cells using a previously described method (Ref. 23; Kyowa Analytical Research Center, Shizuoka, Japan).

Isolation of Total RNA and RT-PCR. Whole blood was obtained from the proband. Total RNA was extracted from peripheral blood leukocytes using ISOGEN (Nippon Gene, Tokyo), a procedure based on acid guanidine thiocyanate-phenol-chloroform extraction (24). The RNA solutions were dissolved in diethyl pyrocarbonate-treated water and stored at –80°C until use. RT was carried out as described (10), using 5 μg of total RNA. The coding sequence (17) was divided into seven parts, corresponding to each part of the cDNA clone (Fig. 1a). Each sequence was obtained from both strands.

Genomic DNA Analysis. To identify the family genotype and confirm the sequence alterations, we performed genomic DNA analysis by PCR amplification, using peripheral blood leukocyte genomic DNA from the proband as well as other available members of the family (her mother, sister 1, and sister 2). Genomic DNA was prepared from whole blood by the standard methods (25). Each exon (exons 2, 10, and 11) of the gene coding for DPD was amplified using exon-specific primer pairs (Fig. 1c) (18). In exons 2 and 11, RFLP analysis was performed to demonstrate the predicted site alterations in their amplified fragments. The PCR product was digested to completion with the appropriate restriction enzymes and analyzed by electrophoresis on a 3.0% agarose gel. In exon 10, the PCR product was subcloned and sequenced to screen for mutations.

Construction of Expression Plasmids. Expression plasmids were constructed in the vector pSE420 (Invitrogen) using the human DPD cDNA. First, part of the polylinker sequence in pSE420 between the SalI and HindIII sites was deleted by cleavage with these enzymes and religation. The resulting vector pSE420ΔSH was cut with NcoI and EcoRI, and the DPD NcoI-EcoRI fragment, spanning the entire coding region and part of the 3’ untranslated region up to the BspHI site, was ligated, resulting in the plasmid pSE420-DPD. [The vector pSE420ΔSH and the plasmid pSE420-DPD were kindly supplied by Dr. P. Vreken (26).] PCR-based mutagenesis by a two-stage method (27), using the pSE420-DPD as template, was used to create mutations Arg21Gln, Val33Ser, and Glu386Ter. At least eight independent clones were sequenced for each part of the cDNA clone (Fig. 1a). Each sequence was determined from both strands.

Mutation Detection. To identify mutations, RT-PCR products were subcloned into the pCR 2.1 vector (Invitrogen Corp., San Diego, CA) and subjected to cDNA sequence analysis. The cDNA clones were sequenced on a 373A automated DNA sequencer (Applied Biosystems, Foster City, CA), using the PRISM dye-terminator cycle sequence kit (Applied Biosystems).
binant mutant clone was sequenced to verify the presence of the mutation and the absence of any other alterations. The resulting clones were designated pSE420-DPD-Arg21Gln, pSE420-DPD-Val335Leu and pSE420-DPD-Glu386Ter, respectively. The 893-bp NeoI-EcoNI-digested fragment from the pSE420-DPD-Arg21Gln was ligated into NeoI-EcoNI-digested pSE420-DPD-Glu386Ter plasmid, resulting in pSE420-DPD-Arg21Gln/Glu386Ter.

Expression Analysis of Missense Mutation in Escherichia coli. Expression plasmids were introduced into E. coli strain BL21(F-ompT, hsdSb(rhmh), gal, dcm). A 20-ml Luria-Bertani broth culture, supplemented with 100 µg/ml ampicillin, 100 µM uracil, 100 µM each of flavin adenine dinucleotide and flavin mononucleotide, and 10 mM each of Na2S and Fe(NH4)2(SO4) was inoculated with 100 µl of an overnight preculture grown in Luria-Bertani broth. Cells were grown in the culture medium to an absorbance at 550 nm of 0.5-0.6 at 30°C, and induction was performed by the addition of 1 mM isopropyl-1-thio-galactopyranoside. Cells were precipitated by centrifugation at a 2-h time point, washed with isolation buffer [35 mM potassium phosphate (pH 7.3), 10 mM EDTA, 1 mM DTT, 0.1 mM phenylmethylsulfonyl fluoride, 2 µM leupeptin, and 2 µM pepstatin], and resuspended in the same buffer. The cell suspension was frozen at -20°C for at least 16 h, thawed on ice, and lysed by sonication. The crude lysate was centrifuged at 20,000 × g for 15 min. The resulting supernatant was used for the DPD activity assay (26). The assay was performed by the same method described previously (Ref. 23; Otsuka Assay Laboratory, Tokushima, Japan).

The level of exogenous DPD enzymatic activity was determined by subtracting the DPD enzymatic activity of pSE420ΔSH from that of each expression plasmid.

RESULTS

Pyrimidine Metabolite Concentration in Urine. As shown in Table 1, urinary thymine and uracil concentrations were increased in the proband.

DPD Catalytic Activity. DPD catalytic activity of the proband and her family ranged from an undetectable level to 55 pmol/min/mg protein. The DPD catalytic activity of the normal control in this study was 258.2 ± 144.8 pmol/min/mg protein (adult, n = 10). All of the family members presented with relatively low DPD catalytic activity, <25% of the mean in the normal control (Table 2).

cDNA Sequence Analysis. We analyzed the cDNA sequences containing the whole coding region of the proband and found three nucleotide changes (Table 2, Fig. 2). First, there was a G→A transition in exon 2 (position 62 on the cDNA, 62G-A), which caused a missense mutation (Arg21Gln). Second, in exon 10, there was a G→T transversion in exons 10 (1003G→T, Val335Leu). Third, there was a G→T transversion in exon 11, which caused premature termination at codon 386. This leads to a truncated peptide of 385 amino acids (stop codon; 1156G→T, Glu386Ter). These three mutations were detected based on four of eight, five of eight, and three of eight clones analyzed, respectively, indicating a heterozygotic state.

Mutation Analysis of Genomic DNA. Two point mutations (62G→A and 1156G→T) were expected to disrupt restriction endonuclease sites in the corresponding exons, permitting the confirmation of their presence and segregation analysis by RFLP (Fig. 3). With regard to the mutation in exon 10 (1003G→T), the PCR product was subcloned and sequenced to screen for mutations.

Family screening revealed that sister 2 had the same DPD genotype as the proband. The mother and sister 1 did not demonstrate the two mutations in exons 2 and 11 (Arg21Gln and Glu386Ter). These three mutations were detected based on four of eight, five of eight, and three of eight clones analyzed, respectively, indicating a heterozygotic state.

Table 1  Pyrimidine metabolite concentrations in urine samples of patient and controls

<table>
<thead>
<tr>
<th>Family member</th>
<th>DPD activity in lymphocyte</th>
<th>Mutation</th>
<th>Effect of mutation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Proband</td>
<td>11</td>
<td>(allele 1)</td>
<td>1003G→T</td>
</tr>
<tr>
<td>Control</td>
<td>55</td>
<td>(allele 1)</td>
<td>1003G→T</td>
</tr>
<tr>
<td></td>
<td></td>
<td>(allele 2)</td>
<td>62G→A</td>
</tr>
<tr>
<td></td>
<td></td>
<td>(allele 2)</td>
<td>1156G→T</td>
</tr>
<tr>
<td></td>
<td></td>
<td>wt</td>
<td>Val335Leu</td>
</tr>
<tr>
<td>Mother</td>
<td>41</td>
<td>(allele 1)</td>
<td>1003G→T</td>
</tr>
<tr>
<td></td>
<td></td>
<td>(allele 2)</td>
<td>62G→A</td>
</tr>
<tr>
<td>Sister 1</td>
<td>ND</td>
<td>(allele 1)</td>
<td>1003G→T</td>
</tr>
<tr>
<td></td>
<td></td>
<td>(allele 2)</td>
<td>1156G→T</td>
</tr>
<tr>
<td>Sister 2</td>
<td>ND</td>
<td>(allele 1)</td>
<td>1003G→T</td>
</tr>
<tr>
<td></td>
<td></td>
<td>(allele 2)</td>
<td>62G→A</td>
</tr>
</tbody>
</table>

| Table 2  Characteristic mutations detected in the gene coding for DPD |
|-------------------|-----------------|-----------------|
| Family member     | DPD activity in lymphocyte | Mutation | Effect of mutation |
| Proband           | 11               | (allele 1)      | 1003G→T           |
|                   |                 | (allele 2)      | 62G→A             |
|                   |                 | (allele 2)      | 1156G→T           |
|                   |                 | wt              | Val335Leu         |
| Mother            | 55               | (allele 1)      | 1003G→T           |
|                   |                 | (allele 2)      | 62G→A             |
| Sister 1          | 41               | (allele 1)      | 1003G→T           |
|                   |                 | (allele 2)      | 1156G→T           |
|                   |                 | wt              | Val335Leu         |
| Sister 2          | ND               | (allele 1)      | 1003G→T           |
|                   |                 | (allele 2)      | 62G→A             |
|                   |                 | 1156G→T         | Glu386Ter         |

a  DPD activity is expressed as pmol/min/mg protein. DPD activity in normal control was 258.2 ± 144.8 pmol/min/mg protein (adult, n = 10).
b  Ter, termination codon leading to a truncated peptide of 385 amino acids.
c  wt, wild type; ND, not detectable (<2 pmol/min/mg protein).
We identified three novel mutations of the gene that codes for DPD in a Japanese family with decreased DPD activity. The proband was a compound heterozygote who presented with a 62G→A mutation in exon 2 (Arg21Gln) and a 1156G→T mutation in exon 11 (Glu386Ter) on one allele, and another mutation on the other allele.

Expression of Mutant Proteins. To examine the functional defects of mutant proteins, three mutant genes were introduced into the pSE420-DPD (wild-type) expression vector. The endogenous DPD enzymatic activity in the E. coli strain used for expression of the constructs was below the limit of detection of the assay (26). The construct containing wild-type DPD cDNA expressed DPD activity approximately 13-fold above the background activity of pSE420ΔSH vector. The exogenous DPD enzymatic activity, from which the background activity was subtracted, is summarized in Table 3. The pSE420-DPD-Val335Leu construct shows significant loss of the activity, and the constructs of pSE420-DPD-Glu386Ter and pSE420-DPD-Arg21Gln/Glu386Ter constructs show no activity; the construct of pSE420-DPD-Arg21Gln shows no decrease in enzymatic activity (Table 3).

DISCUSSION

We identified three novel mutations of the gene that codes for DPD in a Japanese family with decreased DPD activity. The proband was a compound heterozygote who presented with a 62G→A mutation in exon 2 (Arg21Gln) and a 1156G→T mutation in exon 11 (Glu386Ter) on one allele,
and a 1003G→T mutation in exon 10 (Val335Leu) on the other allele. Sister 2 had the same DPD genotype as the proband, whereas the mother and sister 1 had only the missense mutation in exon 10.

The mutation in exon 11 causes a premature termination (1156G→T, Glu386Ter). Because the premature stop codon is located before the putative uracil-binding site encoded by nucleotides 1960–1993 (17), this Glu386Ter mutant protein has no residual activity. In fact, using expression analysis, we revealed that this mutant DPD protein did not express any residual activity (Table 3).

On the other hand, the mutation in exon 10 (1003G→T, Val335Leu) was located at the putative NADPH binding-site encoded by nucleotides 1001–1053 (17). Using expression analysis, we revealed that this mutant protein showed about 15% residual DPD activity (Table 3). Moreover, the DPD catalytic activity in the peripheral mononuclear cells of the mother and sister 1 was <25% of the activity of a normal control (Table 2). Therefore, we concluded that Val335Leu is responsible for the reduction of DPD catalytic activity. Although the mother and sister 1 were heterozygotes, they presented with extremely low DPD catalytic activity in the peripheral blood mononuclear cells (Table 2). This apparent discrepancy between the genotype and DPD catalytic activity may be explained by the fact that DPD exists as a homodimer in humans (17, 28). If two intact subunits are required for DPD enzymatic activity, a heterozygous individual would be expected to express only 25% of the activity of a normal control.

With regard to the mutation in exon 2 (62G→A, Arg21Gln), expression analysis of the pSE420-DPD-Arg21Gln construct showed no decrease in enzymatic activity compared with the pSE420-DPD. This result indicates that Arg21Gln is unlikely to be responsible for the catalytic activity of DPD (Table 3).

Until now several mutations of the gene that codes for DPD have been described, including exon skipping and some missense mutations (10–12, 19–20). Skipping of exon 14 (165 bp), which is caused by a G→A point mutation in an invariant GT splice donor sequence, appears to be a common mutation. A study of Caucasian populations revealed an incidence of 3–5% in the heterozygous state of this mutation. On the basis of these results, up to 1 in every 1000 births in the general population might be homozygous for DPD mutation (20). However, this G→A mutation had not been identified previously in the Japanese population (70 alleles).

Severe 5-FU toxicity was reported recently in members of a Caucasian population with heterozygous DPD deficiency (20). In the present study, we identified three novel mutations in a Japanese patient with severe 5-FU toxicity. 5-FU and its analogues are the most commonly prescribed chemotherapeutic drugs for cancer treatment in Japan. This suggests that 5-FU toxicity in DPD deficiency is a serious problem not only among Caucasians but also among Japanese.

Additional studies, such as population study to determine the frequency of these genetic defects, are presently under investigation in our laboratory. We believe that this study is the first step toward preventing 5-FU toxicity in DPD deficiency in Japan.

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**Table 3** Enzymatic activity of mutant DPD proteins

<table>
<thead>
<tr>
<th>Construct</th>
<th>DPD enzymatic activity* (mean ± 1 SD, n = 4)</th>
</tr>
</thead>
<tbody>
<tr>
<td>pSE420-DPD (wild type)</td>
<td>209.0 ± 127.2</td>
</tr>
<tr>
<td>pSE420-DPD-Arg21Gln</td>
<td>202.5 ± 60.2</td>
</tr>
<tr>
<td>pSE420-DPD-Val335Leu</td>
<td>35.7 ± 35.0</td>
</tr>
<tr>
<td>pSE420-DPD-Glu386Ter</td>
<td>ND*</td>
</tr>
<tr>
<td>pSE420-DPD-Arg21Gln/Glu386Ter</td>
<td>ND</td>
</tr>
</tbody>
</table>

* DPD enzymatic activity represents the relative exogenous DPD activity measured in E. coli lysates (pmol/min/mg protein).

* ND, not detectable.
ACKNOWLEDGMENTS

We thank Dr. P. Vreken (University of Amsterdam, Amsterdam, the Netherlands) for providing the human DPD cDNA construct.

REFERENCES

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