Relation between mRNA Expression Level of Multidrug Resistance 1/ABCB1 in Blood Cells and Required Level of Tacrolimus in Pediatric Living-Donor Liver Transplantation

Maki Goto, Satohiro Masuda, Tetsuya Kiuchi, Yasuhiro Ogura, Fumitaka Oike, Koichi Tanaka, Shinji Uemoto, and Ken-ichi Inui

Department of Pharmacy, Faculty of Medicine, Kyoto University Hospital (M.G., S.M., K.I.) and Department of Surgery, Graduate School of Medicine (T.K., Y.O., F.O., K.T., S.U.), Kyoto University, Kyoto, Japan

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ABSTRACT

It has been difficult to set an individualized therapeutic window of tacrolimus after organ transplantation, because of wide interindividual variation of responsiveness to immunosuppressive therapy. In this study, we examined the significance of multidrug resistance 1 (MDR1) in the peripheral blood cells by comparing the trough concentration of tacrolimus with the occurrence of acute cellular rejection (ACR) in retrospectively collected pediatric living-donor liver transplant patients, who were enrolled after obtaining written informed consent. No significant difference in the intraindividual variation in MDR1 mRNA expression in the peripheral blood cells was observed between postoperative days 3 and 7. The average trough concentration of tacrolimus during the 15-day postoperative period was significantly higher in the event-free patients than in those who experienced ACR (21 of 44 cases), and they had higher levels of blood MDR1 mRNA. In addition, the average trough concentration of tacrolimus significantly correlated with the logarithmically transformed MDR1 mRNA data from the blood cells in patients of both the event-free ($r = 0.5406; P = 0.0077$) and ACR ($r = 0.4772; P = 0.0284$). The cellular accumulation of $[14C]$tacrolimus in the peripheral blood mononuclear cells was 2-fold higher in mdr1a/1b-knockout mice than in wild-type mice ($P = 0.0182$). These results suggest that MDR1 in blood cells decreases the leukocytic concentration of tacrolimus, and it could be a useful marker to establish an individualized target concentration of tacrolimus to prevent ACR in pediatric patients after liver transplantation.

Tacrolimus, a calcineurin inhibitor, is widely used as an immunosuppressant in patients undergoing organ transplantation. It acts on T lymphocytes and inhibits the nuclear factor of activated T cells-derived production of interleukin 2 and the subsequent proliferation of lymphocytes, thereby contributing to a marked improvement in graft survival (Denton et al., 1999; Scott et al., 2003). The therapeutic range of tacrolimus for liver transplantation is considered to be approximately 5–20 ng/ml, but the blood concentration of tacrolimus during the development of acute cellular rejection (ACR) differs among patients (Yasuhara et al., 1995). Because no sensitive marker of drug effectiveness has yet been identified, the establishment of a dosage regimen based on individual susceptibility is required.

P-glycoprotein is the product of multidrug resistance gene MDR1/ABCB1. It exists in several tissues such as the intestine, liver, and kidney and prevents the intracellular accumulation of numerous drugs (Cordon-Cardo et al., 1990; Hoffmann and Kroemer, 2004). P-glycoprotein in the intestine and kidney is considered to influence the pharmacokinetics of various types of drugs during absorption and tubular excretion, and some drug interactions via the transporter have also been reported (Wakasugi et al., 1998; Greiner et al., 1999). It is also expressed in various types of blood cells; depending on its expression level, it is reported to prevent the uptake of doxorubicin (Klimecki et al., 1994). Furthermore, it has also been reported as a prognostic factor to predict relapse of childhood acute lymphoblastic leukemia (Dhooge et al., 1999). Based on these findings, it is hypothesized that P-glycoprotein in the peripheral blood cells also decreases the leukocytic concentration of tacrolimus, and its expression

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ABBREVIATIONS: ACR, acute cellular rejection; MDR, multidrug resistance; LDLT, living-donor liver transplantation; PBMC, peripheral blood mononuclear cell.
level is related to the frequency of ACR in liver transplant patients.

In the present study, we examined the relationship among the MDR1 mRNA expression level in the peripheral blood cells, tacrolimus trough concentration, and occurrence of ACR in pediatric patients undergoing living-donor liver transplantation (LDLT). Furthermore, we compared the intracellular concentration of tacrolimus in the peripheral blood mononuclear cells (PBMCs) between mdr1a/1b null mice and wild-type mice.

**Materials and Methods**

**Patients, Dosage Regimen of Tacrolimus, Analysis of Blood Samples, and Criteria for ACR.** Between October 2001 and September 2003, 44 pediatric patients who underwent LDLT in Kyoto University Hospital were enrolled in this study after written informed consent was obtained from them and/or their parents. The patients were aged between 0.25 and 14 years. The primary diseases were biliary atresia (33 patients, including one patient with a liver tumor and one patient with Alagille syndrome), Alagille syndrome (two patients), propionic acidemia (two patients), Wilson disease (one patient), primary sclerosing cholangitis (one patient), Byler disease (one patient), and re-LDLT (four patients). The blood type matches between the donors and recipients were identical in 34 cases and compatible in 10 cases. The demographics of the control event-free group and the ACR group are shown in Table 1. This study was conducted in accordance with the Declaration of Helsinki and its amendments, and it was approved by the Ethics Committee of Kyoto University.

After transplantation, immunosuppression by oral administration of tacrolimus (0.04 mg/kg) every 12 h was initiated at 12 h after reperfusion (Asonuma et al., 1998). The target trough blood concentration of tacrolimus was 10 to 12 ng/ml during the first 2 weeks after transplantation. The daily oral dose was modulated based on the whole blood tacrolimus concentration that was measured approximately 12 h after the evening administration by using a semiautomated microparticle enzyme immunoassay (IMx; Abbott, Tokyo, Japan) (Yasuhara et al., 1995).

ACR was defined by the biochemical abnormalities that were mainly evaluated by the re-elevation of transaminases and by the histological evaluation of liver biopsy specimens. The patients who were diagnosed with ACR were treated with a high-dose i.v. administration of methylprednisolone or corticosterone.

**Evaluation of MDR1 mRNA Expression Level in Blood.** The blood samples for the examination of mRNA expression were collected in a PAXgene Blood RNA tube (QIAGEN Gmbh, Hilden, Germany) on postoperative days 3 and 7. The total RNA was extracted using the PAXgene Blood RNA kit (QIAGEN), and they were reverse transcribed by SuperScript II transcriptase (Invitrogen, Carlsbad, CA) after the digestion of contaminated genomic DNA by RQ1 DNase (Promega, Tokyo, Japan), as described previously (Masuda et al., 2000). The mRNA expression level of MDR1 was quantitated by real-time PCR using the Prism 7700 sequence detection system (Applied Biosystems, Foster City, CA). The primer and TaqMan probe sets used have been described previously (Uwai et al., 2004).

**Distribution of [14C]Tacrolimus in PBMCs in mdr1a/1b Null Mice.** FVB control wild-type mice and mdr1a/1b double-knockout mice, weighing 30 to 40 g (Taconic Farms, Albany, NY), were used. Before the experiments, the mice were housed in a temperature- and humidity-controlled room, and they were allowed free access to water and standard chow. The animal experiments were performed in accordance with the Guidelines for Animal Experiments of Kyoto University. The experimental protocol was approved by the Animal Research Committee (Graduate School of Medicine, Kyoto University, Kyoto, Japan).

After diethyl ether anesthesia, whole blood sample was collected from the aorta, and biochemical parameters were confirmed using the I-STAT analyzer (Abbott). The mean hematocrit values of the FVB control mice (n = 7) and mdr1a/1b null mice (n = 8) were 32.9% and 30.9%, respectively (P = 0.3315 by Student’s t test). The blood levels of Na+, K+, Cl−, blood urea nitrogen, and glucose (data not shown) did not exhibit abnormal values. The [14C]tacrolimus (683 kBq/mg; kindly provided by Astellas Pharma Co., Tokyo, Japan) was spiked in the whole blood (6.4 kBq/ml; 10.4 μg/ml), and then it was incubated at 37°C for 30 min with gentle shaking. At the end of the incubation, the whole blood was diluted with the same volume of phosphate-buffered saline, pH 7.4, to isolate PBMCs by using Picoll-Paque Plus (GE Healthcare Biosciences, Tokyo, Japan) (Fukudo et al., 2005a,b). The contaminating red blood cells were removed with red blood cell lysis buffer (Roche Diagnostics KK, Tokyo, Japan). The PBMC samples were dissolved with 0.5 ml of NCS tissue solubilizer (GE Healthcare Biosciences), and liquid scintillation counting was performed with 3 ml of the ACSII scintillation cocktail (GE Healthcare Biosciences).

**Statistics.** Statistical analysis was performed using Prism version 4.0 software (GraphPad Software Inc., San Diego, CA). Logarithmic transformation of the mRNA levels of MDR1 was performed to improve normality before performing statistical analyses such as distribution examination and correlation analysis. Statistical differences between the two groups were analyzed by Student’s t test and the Mann-Whitney U test after performing analysis of normality and the F test.

**Results**

**MDR1 mRNA Expression Level in the Peripheral Blood Cells.** Figure 1A shows a histogram of logarithmically transformed data representing the expression levels of MDR1 mRNA in the peripheral blood cells at postoperative day 3. The median values of MDR1 mRNA in the all patients at postoperative days 3 and 7 were 0.05 and 0.09 amol/μg total RNA, respectively. The MDR1 mRNA level in the peripheral blood cells was compared between postoperative days 7 and 3 in each of the 32 patients (Fig. 1B). Because the high-dose steroid pulse therapy was administered between
postoperative days 3 and 7 to seven patients, their MDR1 mRNA expression data were excluded. The blood samples of five patients could not be obtained due to patient refusal. The distribution of the MDR1 mRNA level exhibited a similar unimodal pattern in both control cases (event-free, empty columns) as well as in the ACR cases (filled columns) (Fig. 1, A and C); furthermore, there was no statistically significant difference with regard to the MDR1 mRNA level in the peripheral blood cells between the event-free patients and those who experienced acute cellular rejection. Statistical analysis was performed using the Mann-Whitney U test (B and C). However, the P values were greater than 0.05.

Blood Concentration Profiles of Tacrolimus, MDR1 mRNA Level in Blood Cells, and ACR. The blood concentration profiles of tacrolimus during the 15-day postoperative period are shown in Fig. 2. The patients were categorized into the following four groups based on the mRNA expression level of MDR1 at postoperative day 3: below 0.02, between 0.02 and 0.05, between 0.05 and 0.1, and higher than 0.1 amol/μg total RNA. The open circles represent the trough concentrations of tacrolimus a day before the initiation of transaminase levels. The tacrolimus concentrations in 10 patients who experienced ACR were below 5 ng/ml immediately before the increase in transaminase levels. The patients who experienced ACR after postoperative day 10 exhibited a blood tacrolimus concentration profile that increased rapidly a few days after the operation and decreased by nearly 5 ng/ml preceding the occurrence of ACR. Although the trough concentrations of tacrolimus were higher than 10 ng/ml, episodes of ACR occurred in three patients.

Fig. 1. Expression levels of MDR1 mRNA in the peripheral blood cells in pediatric patients after living-donor liver transplantation. A, histogram of the MDR1 mRNA expression level in the event-free patients (empty columns) and in those who experienced acute cellular rejection (filled columns) (n = 44). B, comparison of the MDR1 mRNA levels between postoperative days 3 and 7 (n = 32). The data are expressed as the fold change at postoperative day 7 compared with postoperative day 3. Seven patients were excluded because of high-dose steroid therapy administered between postoperative days 3 and 7. The blood samples at postoperative day 7 could not be obtained from five patients due to patient refusal. C, there was no statistical difference with regard to the MDR1 mRNA level in the peripheral blood cells between the event-free patients and those who experienced acute cellular rejection. Statistical analysis was performed using the Mann-Whitney U test (B and C). However, the P values were greater than 0.05.

Fig. 2. The tacrolimus trough concentrations in the living-donor liver transplant patients who experienced ACR (E–H) and the event-free patients (A–D) during the 15-day postoperative period. The patients were categorized into the following four groups by their MDR1 mRNA level in blood cells at postoperative day 3: below 0.02 amol/μg total RNA (A and E), between 0.02 and 0.05 amol/μg total RNA (B and F), between 0.05 and 0.10 amol/μg total RNA (C and G), and higher than 0.10 (D and H) amol/μg total RNA. The circles in E to H represent the tacrolimus trough concentrations on the day before the initiation of ACR.
To obtain additional information on the association of the MDR1 mRNA expression level in the peripheral blood cells with the tacrolimus blood concentration required to avoid ACR, a $\chi^2$ test was carried out, and the odds ratio was calculated. After step-by-step examinations, we determined the cut-off value of 9 ng/ml of the average tacrolimus blood concentration during 15 postoperative days for subsequent statistical analyses. As shown in Table 2, the significance of a minimum tacrolimus blood concentration of 9 ng/ml during the 15-day postoperative period was found in 44 patients in this study ($P = 0.0004$). Next, we examined the effect of the MDR1 mRNA expression level on the frequency of ACR after classifying the patients based on the median expression level (0.05 amol/$\mu$g total RNA). The importance of tacrolimus blood concentration was observed in patients with a higher as well as lower MDR1 mRNA expression level in blood cells (higher MDR1, $n = 22$, $P = 0.0112$; lower MDR1, $n = 22$, $P = 0.01543$). The odds ratio revealed that the average trough level of tacrolimus of $<$9 ng/ml was a significant risk factor for ACR, particularly in patients with a high level of MDR1 mRNA expression in the blood cells (Table 2).

**Correlation between the MDR1 mRNA Expression Level in Blood Cells and the Average Trough Levels of Tacrolimus during the 15-Day Postoperative Period.** To examine whether the MDR1 mRNA expression level at postoperative day 3 was associated with the individual target trough concentration of tacrolimus during the early phase after liver transplantation, the relationship between the molecular data and the average trough concentration of tacrolimus during the 15-day postoperative period was investigated in the event-free and ACR patients. Because high-dose steroid injection treatment (pulse therapy) is a strong immunosuppressive treatment against ACR, the data of trough concentration of tacrolimus with regard to this treatment were excluded in the patients who experienced ACR. Although the data were logarithmically transformed, the observed blood MDR1 mRNA expression level was weak, but it significantly correlated with the average trough concentration of tacrolimus in both event-free patients ($r = 0.5406$, $P = 0.0077$; Fig. 3A) and ACR patients ($r = 0.4772$, $P = 0.0284$; Fig. 3B). The average trough level of tacrolimus was higher in the event-free patients than in the ACR patients ($P = 0.0008$; Fig. 3C).

**Comparison of $^{14}$C Tacrolimus Accumulation in the PBMCs of mdr1a/1b Knockout Mice and Wild-Type Mice.** The pharmacological significance of blood MDR1 on the cellular accumulation of tacrolimus was investigated using the PBMCs derived from wild-type or mdr1a/1b knockout mice. After the incubation of whole blood samples with $^{14}$C tacrolimus, its accumulation in the PBMCs was examined. As shown in Fig. 4, the $^{14}$C tacrolimus concentration in the PBMCs of the mdr1a/1b knockout mouse was 2-fold higher than that in the PBMCs of the wild-type mouse ($P = 0.0182$).

**Discussion**

MDR1 is expressed in various types of PBMCs, and it plays a role in the extrusion of substrates in these cells; therefore, MDR1 has been considered a factor that determines the intracellular concentration of drugs, including immunosuppressants, targeting blood cells. A possible correlation between MDR1 expression in peripheral blood and an ACR episode was determined by immunocytochemical analyses of patients who had undergone a heart and lung transplantation (Kemnitz et al., 1991; Yousem et al., 1993). However, in the case of kidney transplantation, it was reported that MDR1 expression could not predict the occurrence of rejection (Mek et al., 1999). In these studies, cyclosporine was used as the primary immunosuppressant. Grude et al. (2002) reported that in liver transplant recipients who were administered tacrolimus and cyclosporine, the MDR1 expression level in the total peripheral blood was higher before ACR ($P = 0.054$); furthermore, this value was significantly lower in patients with severe infection ($P = 0.030$) (Grude et al., 2002). These reports did not provide detailed information regarding the blood concentration of immunosuppressants; therefore, it was difficult to establish a direct relationship between these events and the expression level of MDR1 in blood cells. However, these reports suggested a possible relationship between MDR1 expression in blood cells and the susceptibility to calcineurin inhibitors.

We have reported that intestinal MDR1 prevented the intracellular accumulation of orally administered tacrolimus (Goto et al., 2003; Masuda et al., 2003, 2005; Omae et al., 2005). In addition, the intestinal MDR1 mRNA level showed a distinct inverse correlation with the concentration/dose ratio of tacrolimus immediately after liver transplantation (Hashida et al., 2001; Masuda et al., 2006). MDR1 is also expressed in the plasma membrane of peripheral leukocytes,

**Table 2**

<p>| Effect of tacrolimus trough level and MDR1 expression on the occurrence of acute cellular rejection |
|-------------------------------------------------|---------------------------------|------------------|-----------------|-----------------|</p>
<table>
<thead>
<tr>
<th>Control (Event-Free) No.</th>
<th>Acute Cellular Rejection No.</th>
<th>$\chi^2$ Test P Value</th>
<th>Odds Ratio (95% confidence interval)</th>
</tr>
</thead>
<tbody>
<tr>
<td>All patients</td>
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<td></td>
</tr>
<tr>
<td>$&gt;$9 ng/ml</td>
<td>14</td>
<td>2</td>
<td>0.0004</td>
</tr>
<tr>
<td>$&lt;$9 ng/ml</td>
<td>9</td>
<td>19</td>
<td></td>
</tr>
<tr>
<td>Patients with blood MDR1 mRNA levels below 0.05 amol/$\mu$g total RNA</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$&gt;$9 ng/ml</td>
<td>4</td>
<td>0</td>
<td>0.0154</td>
</tr>
<tr>
<td>$&lt;$9 ng/ml</td>
<td>6</td>
<td>12</td>
<td></td>
</tr>
<tr>
<td>Patients with blood MDR1 mRNA levels higher than 0.05 amol/$\mu$g total RNA</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$&gt;$9 ng/ml</td>
<td>10</td>
<td>2</td>
<td>0.0112</td>
</tr>
<tr>
<td>$&lt;$9 ng/ml</td>
<td>3</td>
<td>7</td>
<td></td>
</tr>
</tbody>
</table>

N.A., not available.

a The patients were categorized by the average trough concentration of tacrolimus during the 15-day postoperative period. The trough concentrations of tacrolimus during high-dose steroid pulse therapy were excluded.

b The patients were categorized by the median value of the MDR1 mRNA expression level in blood cells on postoperative day 3.
mediating the cellular efflux of numerous drugs, including immunosuppressants and anticancer agents (Chaudhary et al., 1992; Klimecki et al., 1994; Ford et al., 2003). Oselin et al. (2003) quantified the MDR1 mRNA levels in several types of peripheral blood cells, but the expression levels were not affected by single nucleotide polymorphisms (G2677T and C3435T) of the MDR1 gene. Based on this information, we hypothesized that if the MDR1 expression level is low in the peripheral blood cells, the leukocytic tacrolimus concentration is sufficient for immunosuppression (large arrow) when the intracellular concentration of tacrolimus is low in the whole blood. However, with the same concentration of tacrolimus in the whole blood, the leukocytic level of tacrolimus is decreased to a level that is insufficient for immunosuppression (small arrow) when the MDR1 expression levels are high (B). Therefore, in the case of high expression levels of MDR1, a higher concentration of tacrolimus in the whole blood is required to increase its leukocytic level and enable subsequent sufficient immunosuppression (C).

In the present study, we retrospectively examined the effect of MDR1 in the peripheral blood cells on the individualized target concentration of tacrolimus by analyzing the event of ACR as an endpoint in the pediatric LDLT patients. There was a widely interindividual variation in the MDR1 expression level in the peripheral blood cells (Fig. 1A); however, the intraindividual variation was low and not statistically significant (Fig. 1B). Although a low concentration of tacrolimus was considered related to the occurrence of ACR, some patients who were administered a relatively high level of tacrolimus also experienced ACR (Fig. 2). Using in vitro sampled whole blood, tacrolimus was found to be mainly distributed in the erythrocytes (95–98%) in dog, monkey, and human (Nagase et al., 1994). In addition, the percentage of [3H]dihydro-tacrolimus associated with the lymphocytes of stable liver transplant patients (0.8% of whole blood) was significantly higher than that of patients experiencing rejec-
tion (0.3%; *P* = 0.012) (Zahir et al., 2004). Based on these findings, the leukocytic concentration rather than the whole blood concentration of tacrolimus is suggested to be a potent factor affecting the immunosuppressive activity of the drug, and leukocytic MDR1 can be a candidate molecule to decrease the cellular accumulation of tacrolimus (Fig. 5). Comparison of the MDR1 mRNA expression level with the trough concentration of tacrolimus suggested that the target concentration of tacrolimus was higher in patients with a high level of MDR1 mRNA expression in the peripheral blood cells (Fig. 3). Using the mdr1a/1b knockout mice, it was revealed that the blood MDR1 acted as a barrier for the cellular accumulation of tacrolimus (Fig. 4). Because of the radioactivity of [14C]tacrolimus, there was a limited decrease in the concentration of tacrolimus, and saturation probably occurred. Therefore, the decrease in the concentration of tacrolimus, which is comparable with the clinical situation, may be more affected by the MDR1 expression in the blood cells. These findings suggest that the MDR1 expression level in the peripheral blood cells is a potential pharmacological marker of tacrolimus concentration and that it can be used to establish the individualized target concentration of this drug.

Therapeutic drug monitoring contributes to the development of individualized pharmacotherapy in patients administered toxic agents, including calcineurin inhibitors. The general therapeutic window of tacrolimus ranges between 5 and 20 ng/ml in transplant patients (Venkataraman et al., 1995; Masuda and Inui, 2006; Oellerich and Armstrong, 2006). However, the target range always varies with the duration of the postoperative period and the patient status. In patients undergoing liver transplantation, the target tacrolimus concentration is between 10 and 20 ng/ml during the 15-day postoperative period. However, the actual level of tacrolimus is relatively low because of its severe adverse effects. We previously reported that at least 7 ng/ml of the average trough concentration of tacrolimus is required immediately after transplantation to prevent ACR (Masuda et al., 2006). However, the ACR episode occurred in 22% of patients in whom the blood tacrolimus concentration was maintained at more than 7 ng/ml. Because tacrolimus targets the leukocytes, the information regarding the concentration of tacrolimus in the whole blood is thought to be insufficient to control the ACR episode in some patients. Therefore, an additional biological marker reflecting the leukocytic concentration of tacrolimus should be identified to establish an individualized target concentration of the drug. In the present study, we have found that a higher target concentration of tacrolimus is required in patients with a high expression level of MDR1 mRNA (>0.05 amol/μg total RNA) than in those with a low expression level (Table 2; Fig. 3). If the expression level of MDR1 mRNA in the peripheral blood is examined immediately after surgery, we can focus on patients with a high risk of ACR and maintain them on a high level (at least 9 ng/ml) of tacrolimus during the 15-day postoperative period.

In conclusion, the MDR1 mRNA expression level in the peripheral blood is a possible predictor of the susceptibility to tacrolimus; a high expression level of MDR1 might cause ACR, necessitating a higher blood concentration of tacrolimus (Fig. 5). Although further analyses with or without intervention should be investigated to establish the clinical significance of blood MDR1 as a pharmacological marker, molecular information about MDR1 expression in peripheral blood cells may be useful in the establishment of an individualized target concentration of tacrolimus in children after liver transplantation.

References


Address correspondence to: Dr. Ken-ichi Inui, Department of Pharmacy, Kyoto University Hospital, Sakyo-ku, Kyoto 606-8507, Japan. E-mail: inui@kuhp.kyoto-u.ac.jp