Table 4 Ethnic differences in *ABCB1* Block 1 haplotypes

Marker site[a]	This study		Reported data (Takane *et al.* 2004)		
	Subgroup (see Fig. 7)	Japanese (n = 1066)	Group	Japanese (n = 188)	Caucasian (n = 192)
	A	0.712	H1	0.665	0.964
−1789G>A	B	0.147	H4	0.191	nd
−1789G>A, −371A>G	J	0.031	H5	0.027	nd
−1789G>A, −145C>G	L	0.025	H6	0.032	nd
−1847T>C[b]	G	0.054	H2	0.043	nd
−1461delCATCC, −371A>G, −1847T>C[b]	E	0.030	H3	0.037	nd
−1154T>C		nd	H7	0.005	nd
−1753delGA		nd	H8	nd	0.010
−1347T>C, −129T>C		nd	H9	nd	0.016
−1085A>G		nd	H10	nd	0.010

[a]Each reported position was adjusted to the nucleotide numbers used in this study.
[b]This SNP is linked to −1347T>C and −129T>C.
n; 2 × number of subjects.
nd; not detected.

Table 5 Ethnic differences in the *ABCB1* Block 2 haplotypes

Group	This study	Reported data (Kroetz *et al.* 2003)[a]		
	Japanese (n = 1066)	Asian (n = 60)	Caucasian (n = 200)	African (n = 200)
*1	0.216	0.216	0.370	0.721
*2	0.386	0.365	0.410	0.075
*3	nd	nd	0.010	0.010
*4	0.016	0.016	0.005	0.090
*6	0.034	0.016	0.120	0.035
*7	nd	nd	0.015	0.005
*8	0.141	0.216	0.010	0.040
*9	0.020	0.082	0.025	0.010
*10	0.174	0.066	0.025	0.005
*11	0.005	nd	nd	nd
*12	0.002	nd	nd	nd
*13	0.002	nd	nd	nd
*14	0.001	nd	nd	nd
*15	0.001	nd	nd	nd
*16	0.001	nd	nd	nd
*17	0.001	nd	nd	nd
*18	0.001	nd	0.01	nd

[a]Reported haplotypes were re-assigned according to our haplotype nomenclature.
n = 2 × number of subjects.
nd; not detected.

Discussion

Extensive studies of *ABCB1* haplotypes and their functional significance have been conducted, mostly focused on the common SNPs of 1236C>T, 2677G>T/A, and 3435C>T. However, recent association studies on promoter region haplotypes have indicated the importance of haplotypes within this region (Taniguchi *et al.* 2003; Takane *et al.* 2004). The results of functional or P-gp expression analyses based on these polymorphisms/haplotypes have not always been consistent, possibly due to the small number of subjects used, different ethnic backgrounds, or insufficient haplotyping over a limited region. In the present study, we have conducted a re-assignment of Block 1 haplotypes by extending the region sequenced to the distal promoter, and

Table 6 Major tagging SNPs of *ABCB1* for genotype-phenotyhpe association studeis

i) Block 1 haplotypes (subgroups)					
Position	−1847	−1789	−1461_−1457	−371	−145
Nucleotide change	T > C	G > A	delCATCC	A > G	C > G
	a	a	a	a	a
A					
B		A			
J		A		G	
L		A			G
G	C			G	
E	C		del	G	

ii) Block 2 haplotypes				
Position	1236		2677	3435
Nucleotide change	C > T	G > A	G > T	C > T
Amino acid change		A893T	A893S	
		a		
*1				
*2	T		T	T
*4	T			T
*6				T
*8	T			
*9	T		T	
*10		A		
*11	T	A		
*18		A		T

[a]Specific for Asian populatioins.

added novel haplotypes in other blocks after assessing a large number of subjects.

LD analysis revealed that one of the marker SNPs in the promoter region, −1789G>A, was moderately linked to IVS5 + 123A>G, previously classified into Block 2. Therefore, we shifted the border between Block 1 and Block 2 and re-analyzed the Block 1 haplotypes. Two promoter haplotype classes associated with functional changes have been reported previously (Taniguchi *et al.* 2003; Takane *et al.* 2004). One class included the −1789G>A SNP, and the other included the three linked SNPs of −1847T>C, −1347T>C and −129T>C. In our analysis these SNPs were included in our Block 1 region.

The haplotype containing −1789G>A was reported to be associated with reduced P-gp expression levels in the colon and liver, and reduced promoter activity was shown in a reporter gene assay (Taniguchi *et al.* 2003) (see Fig. 7). However, another study found that a haplotype containing −1789G>A without −145C>G (subgroups B and J in our present study) showed no change in the reporter assay, while another haplotype that contained −1789G>A together with −145C>G (subgroup L) showed reduced promoter activity (Takane *et al.* 2004). Data on the functional effects of haplotypes harbouring the three linked SNPs (G and E subgroups) are also contradictory. While one study showed an association with reduced colon and liver P-gp expression levels in patients and reduced promoter activity in a reporter gene assay (Taniguchi *et al.* 2003), another study reported an association with increased P-gp expression levels in the placenta and liver, and with increased promoter activity in a reporter gene assay (Takane *et al.* 2004). By expanding Block 1 into intron 5 we identified additional types within previously reported wild-type sequences (corresponding to subgroup A in this study) and other variant haplotypes (subgroups B, E, G, J, and L) (Fig. 7). In total our data revealed 11 tagging variations in Block 1: −1789G>A, −1461_−1457CATCdel, −371A>G, −145C>G, −129T>C, IVS1 − 78delG, IVS4 − 25G>T, 304G>C (G102R), 325G>A (E109K), IVS + 76T>G and IVS5 + 123A>G. Thus, if some of these markers are of functional importance it is possible that

our subdivisions (types within A and other subgroups) might explain the discrepancies in P-gp expression levels in the previously reported studies. In fact, our preliminary observation has suggested possible influences of some of the tagging variations in Block 1 on pharmacokinetic parameters of paclitaxel (data not shown). However, this hypothesis requires further clarification in large scale clinical studies.

Several novel haplotypes were added to the other 3 blocks (1, 38, and 4 new haplotypes in Blocks −1, 2, and 3, respectively). We identified a new haplotype *1d in Block −1, but this variant haplotype was very rare and the functional significance of uncommon Block −1 haplotypes remains unknown. We added 7 new groups to Block 2 haplotypes (*12 to *18), but their frequencies were also very low (0.002 and less). We also confirmed the previous finding that, in order of frequency, the major groups were *2d, *10a, *1e, and *8a. In our previous study we estimated the relative P-gp activity of the different haplotypes according to the renal clearance of irinotecan and its metabolites in Japanese cancer patients. While we found a significant association between *2, which contained the three common SNPs, and reduced renal clearance levels, associations with the *6, *8, and *10 groups that contained only one of the common markers remained unclear. For the *4, *9, and *11 groups, which harbour two marker SNPs in Block 2, functional evaluation was impossible due to the small number of subjects. Previously we showed that *1f may have been associated with reduced P-gp activity. The current study revealed that *1f in Block 2 was completely linked with the newly defined *1d in Block 1, which contained IVS4 −25G>T. A further association study is needed to clarify the effects of the linked *1d (Block 1) and *1f (Block 2) haplotypes. Regarding Block 3 we added several minor *1 haplotypes and confirmed the previous findings that *1a and *1b were the major haplotypes. We previously observed a trend for an association between *1b and higher P-gp activity. Taking into consideration the haplotype-combinations across the blocks this trend also needs to be confirmed in a larger number of subjects.

It is well recognized that there are large ethnic differences in the frequencies of functionally important haplotypes, including 1236C>T, 2677G>T, and 3435>T (corresponding to the *2 group in Block 2), and promoter region SNPs (corresponding to the variant Block 1 subgroups). Comparison of our data with the results from other ethnic groups indicated the existence of unique haplotype profiles in the Japanese population. As suggested by the previous report on the promoter region (Takane *et al.* 2004), Japanese samples exhibited large variations in Block 1 haplotypes. This suggested that not only *2 in Block 2 but also certain Block 1 haplotypes may be functionally important in the Japanese ethnic group. For Block 2 we confirmed our previous findings that the major groups were *1 and *2, and that *2d was the most frequent haplotype. While both groups were detected as the major types in other Asian and Caucasian populations, *1 was considerably more frequent than *2 in Africans (Kroetz *et al.* 2003). Another recent study found that the two major haplotypes were common to 5 ethnic groups (Tang *et al.* 2004). That study also revealed that the Chinese and Malay haplotype profiles were very similar, and that while some similarities were also observed between Caucasian and Indian populations, Africans differed from all other non-African populations. Furthermore, their study suggested that positive selection for 2677T-3435T had occurred in Chinese and Malays, and for 3435C in Africans. As pointed out previously, frequent occurrence of *10 (2677G>A) was unique to Japanese compared with Caucasians and African populations. Our study revealed higher frequencies of *10 (2677G>A) and *6 (3435C>T) and lower frequencies of *8 (1236C>T) and *9 (1236C>T and 2677G>T) than reported for Asian populations in Kroetz *et al.* (2003) (Table 5). This difference might be due to the mixed Asian population used in the report, as differences in the frequencies of 2677G>A between the Chinese, Malay, and Indian populations have been noted (Tang *et al.* 2004). The finding that the high frequency of 2677G>A is shared among Japanese, Koreans (Yi *et al.* 2004) and Chinese (Tang *et al.* 2004) suggests a close evolutionary relationship between these three populations.

A whole-genome haplotype database for three populations is now available at the Perlegen website (www.perlegen.com), which provides a good tool for investigation of the structures of human genetic variation within and between different populations (Hinds *et al.* 2005). For the *ABCB1* gene, however, we could not directly compare their data with ours because their

SNPs are mostly intronic and did not overlap with our SNP markers (<20%).

For genotype-phenotype association studies on the *ABCB1* gene, genotyping of the major functional key SNPs in Blocks 1 and 2 (Table 6) would be useful. Further studies on the clinical significance of the haplotypes described in the present study and elucidation of the haplotype-combinations across blocks, will be required to achieve the goal of personalized drug therapy.

Conclusions

We re-established *ABCB1* haplotypes in the Japanese population based on novel polymorphisms found in a large number of subjects, expanding the promoter region. Our current data added more detailed information on functionally-important haplotypes in Blocks 1 and 2 in the Japanese population, and identified differences in haplotype profiles between ethnic groups. The information provided in this study will be of use in further studies investigating the relationship between genetic markers and functional changes.

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References

Chowbay, B., Cumaraswamy, S., Cheung, Y. B., Zhou, Q. & Lee, E. J. (2003) Genetic polymorphisms in MDR1 and CYP3A4 genes in Asians and the influence of MDR1 haplotypes on cyclosporin disposition in heart transplant recipients. *Pharmacogenetics* **13**, 89–95.

Cordon-Cardo, C., O'Brien, J. P., Casals, D., Rittman-Grauer, L., Biedler, J. L., Melamed, M. R. & Bertino, J. R. (1989) Multidrug-resistance gene (P-glycoprotein) is expressed by endothelial cells at blood-brain barrier sites. *Proc Natl Acad Sci U S A* **86**, 695–698.

Debry, P., Nash, E. A., Neklason, D. W. & Metherall, J. E. (1997) Role of multidrug resistance P-glycoproteins in cholesterol esterification. *J Biol Chem* **272**, 1026–1031.

Drach, J., Gsur, A., Hamilton, G., Zhao, S., Angerler, J., Fiegl, M., Zojer, N., Raderer, M., Haberl, I., Andreeff, M. & Huber, H. (1996) Involvement of P-glycoprotein in the transmembrane transport of interleukin-2 (IL-2), IL-4, and interferon-gamma in normal human T lymphocytes. *Blood* **88**, 1747–1754.

Fojo, A. T., Ueda, K., Slamon, D. J., Poplack, D. G., Gottesman, M. M. & Pastan, I. (1987) Expression of a multidrug-resistance gene in human tumors and tissues. *Proc Natl Acad Sci USA* **84**, 265–269.

Furuno, T., Landi, M. T., Ceroni, M., Caporaso, N., Bernucci, I., Napp, G., Martignoni, E., Schaeffeler, E., Eichelbaum, M., Schwab, M. & Zanger, U. M. (2002) Expression polymorphism of the blood-brain barrier component P-glycoprotein (MDR1) in relation to Parkinson's disease. *Pharmacogenetics* **12**, 529–534.

Geick, A., Eichelbaum, M. & Burk, O. (2001) Nuclear receptor response elements mediate induction of intestinal MDR1 by rifampin. *J Biol Chem* **276**, 14581–14587.

Goto, M., Masuda, S., Saito, H., Uemoto, S., Kiuchi, T., Tanaka, K. & Inui, K. (2002) C3435T polymorphism in the MDR1 gene affects the enterocyte expression level of CYP3A4 rather than Pgp in recipients of living-donor liver transplantation. *Pharmacogenetics* **12**, 451–457.

Hinds, D. A., Stuve, L. L., Nilsen, G. B., Halperin, E., Eskin, E., Ballinger, D. G., Frazer, K. A. & Cox, D. R. (2005) Whole-genome patterns of common DNA variation in three human populations. *Science* **307**, 1072–1079.

Hoffmann, U. & Kroemer, H. K. (2004) The ABC transporters MDR1 and MRP2: multiple functions in disposition of xenobiotics and drug resistance. *Drug Metab Rev* **36**, 669–701.

Hoffmeyer, S., Burk, O., von Richter, O., Arnold, H. P., Brockmoller, J., Johne, A., Cascorbi, I., Gerloff, T., Roots, I., Eichelbaum, M. & Brinkmann, U. (2000) Functional polymorphisms of the human multidrug-resistance gene: multiple sequence variations and correlation of one allele with P-glycoprotein expression and activity in vivo. *Proc Natl Acad Sci USA* **97**, 3473–3478.

Ieiri, I., Takane, H. & Otsubo, K. (2004) The MDR1 (ABCB1) gene polymorphism and its clinical implications. *Clin Pharmacokinet* **43**, 553–576.

Itoda, M., Saito, Y., Komamura, K., Ueno, K., Kamakura, S., Ozawa, S. & Sawada, J. (2002) Twelve Novel Single Nucleotide Polymorphisms in ABCB1/MDR1 among Japanese Patients with Ventricular Tachycardia who were Administered Amiodarone. *Drug Metab Pharmacokinet* **17**, 566–571.

Johne, A., Kopk, K., Gerloff, T., Mai, I., Rietbrock, S., Meisel, C., Hoffmeyer, S., Kerb, R., Fromm, M. F., Brinkmann, U., Eichelbaum, M., Brockmoller, J., Cascorbi, I. & Roots, I. (2002) Modulation of steady-state kinetics of digoxin by haplotypes of the P-glycoprotein MDR1 gene. *Clin Pharmacol Ther* **72**, 584–594.

Kim, R. B., Leake, B. F., Choo, E. F., Dresser, G. K., Kubba, S. V., Schwarz, U. I., Taylor, A., Xie, H. G., McKinsey, J., Zhou, S., Lan, L. B., Schuetz, J. D., Schuetz, E. G. & Wilkinson, G. R.. (2001) Identification of functionally

variant MDR1 alleles among European Americans and African Americans. *Clin Pharmacol Ther* **70**, 189–199.

Kim, R. B. (2002) MDR1 single nucleotide polymorphisms: multiplicity of haplotypes and functional consequences. *Pharmacogenetics* **12**, 425–427.

Kimchi-Sarfaty, C., Gribar, J. J. & Gottesman, M. M. (2002) Functional characterization of coding polymorphisms in the human MDR1 gene using a vaccinia virus expression system. *Mol Pharmacol* **62**, 1–6.

Kitamura, Y., Moriguchi, M., Kaneko, H., Morisaki, H., Morisaki, T., Toyama, K. & Kamatani, N. (2002) Determination of probability distribution of diplotype configuration (diplotype distribution) for each subject from genotypic data using the EM algorithm. *Ann Hum Genet* **66**, 183–193.

Kurata, Y., Ieiri, I., Kimura, M., Morita, T., Irie, S., Urae, A., Ohdo, S., Ohtani, H., Sawada, Y., Higuchi, S. & Otsubo, K. (2002) Role of human MDR1 gene polymorphism in bioavailability and interaction of digoxin, a substrate of P-glycoprotein. *Clin Pharmacol Ther* **72**, 209–219.

Kroetz, D. L., Pauli-Magnus, C., Hodges, L. M., Huang, C. C., Kawamoto, M., Johns, S. J., Stryke, D., Ferrin, T.E., DeYoung, J., Taylor, T., Carlson, E. J., Herskowitz, I., Giacomin, i K. M. & Clark, A. G. (2003) Pharmacogenetics of Membrane Transporters Investigators. Sequence diversity and haplotype structure in the human ABCB1 (MDR1, multidrug resistance transporter) gene. *Pharmacogenetics* **13**, 481–494.

Liu, Y. Y., Han, T. Y., Giuliano, A. E. & Cabot, M. C. (2001) Ceramide glycosylation potentiates cellular multidrug resistance. *FASEB J* **15**, 719–730.

Morita, N., Yasumori, T. & Nakayama, K. (2003) Human MDR1 polymorphism: G2677T/A and C3435T have no effect on MDR1 transport activities. *Biochem Pharmacol* **65**, 1843–1852

Riordan, J. R., Deuchars, K., Kartner, N., Alon, N., Trent, J. & Ling, V. (1985) Amplification of P-glycoprotein genes in multidrug-resistant mammalian cell lines. *Nature* **316**, 817–819.

Sai, K., Kaniwa, N., Itoda, M., Saito, Y., Hasegawa, R., Komamura, K., Ueno, K., Kamakura, S., Kitakaze, M., Shirao, K., Minami, H., Ohtsu, A., Yoshida, T. Saijo, N., Kitamura, Y., Kamatani, N., Ozawa, S. & Sawada, J. (2003) Haplotype analysis of ABCB1/MDR1 blocks in a Japanese population reveals genotype-dependent renal clearance of irinotecan. *Pharmacogenetics* **13**, 741–757.

Schwab, M., Schaeffeler, E., Marx, C., Fromm, M. F., Kaskas, B., Metzler, J., Stange, E., Herfarth, H., Schoelmerich, J., Gregor, M., Walker, S., Cascorbi, I., Roots, I., Brinkmann, U., Zanger, U. M. & Eichelbaum, M. (2003) Association between the C3435T MDR1 gene polymorphism and susceptibility for ulcerative colitis. *Gastroenterology* **124**, 26–33.

Siegsmund, M., Brinkmann, U., Schaffeler, E., Weirich, G., Schwab, M., Eichelbaum, M., Fritz, P., Burk, O., Decker, J., Alken, P., Rothenpieler, U., Kerb, R. & Hoffmeyer, S. (2002) Association of the P-glycoprotein transporter MDR1(C3435T) polymorphism with the susceptibility to renal epithelial tumors. *J Am Soc Nephrol* **13**, 1847–1854.

Takane, H., Kobayashi, D., Hirota, T., Kigawa, J., Terakawa, N., Otsubo, K. & Ieiri, I. (2004) Haplotype-oriented genetic analysis and functional assessment of promoter variants in the MDR1 (ABCB1) gene. *J Pharmacol Exp Ther* **311**, 1179–1187.

Tanabe, M., Ieiri, I., Nagata, N., Inoue, K., Ito, S., Kanamori, Y., Takahashi, M., Kurata, Y., Kigawa, J., Higuchi, S., Terakawa, N. & Otsubo, K. (2001) Expression of P-glycoprotein in human placenta: relation to genetic polymorphism of the multidrug resistance (MDR)-1 gene. *J Pharmacol Exp Ther* **297**, 1137–1143.

Tang, K., Ngoi, S. M., Gwee, P. C., Chua, J. M., Lee, E. J., Chong, S. S. & Lee, C. G. (2002) Distinct haplotype profiles and strong linkage disequilibrium at the MDR1 multidrug transporter gene locus in three ethnic Asian populations. *Pharmacogenetics* **12**, 437–450.

Tang, K., Wong, L. P., Lee, E. J., Chong, S. S. & Lee, C. G. (2004) Genomic evidence for recent positive selection at the human MDR1 gene locus. *Hum Mol Genet* **13**, 783–797.

Taniguchi, S., Mochida, Y., Uchiumi, T., Tahira, T., Hayashi, K., Takagi, K., Shimada, M., Maehara, Y., Kuwano, H., Kono, S., Nakano, H., Kuwano, M. & Wada, M. (2003) Genetic polymorphism at the 5′ regulatory region of multidrug resistance 1 (MDR1) and its association with interindividual variation of expression level in the colon. *Mol Cancer Ther* **2**, 1351–1359.

van Helvoort, A., Smith, A. J., Sprong, H., Fritzsche, I., Schinkel, A. H., Borst, P. & van Meer, G. (1996) MDR1 P-glycoprotein is a lipid translocase of broad specificity, while MDR3 P-glycoprotein specifically translocates phosphatidylcholine. *Cell* **87**, 507–517.

Wong, M., Evans, S., Rivory, L. P., Hoskins, J. M., Mann, G. J., Farlow, D., Clarke, C. L., Balleine, R. L. & Gurney, H. (2005) Hepatic technetium Tc 99m-labeled sestamibi elimination rate and ABCB1 (MDR1) genotype as indicators of ABCB1 (P-glycoprotein) activity in patients with cancer. *Clin Pharmacol Ther* **77**, 33–42.

Yi, S. Y., Hong, K. S., Lim, H. S., Chung, J. Y., Oh, D. S., Kim, J. R., Jung, H. R., Cho, J. Y., Yu, K. S., Jang, I. J. & Shin, S. G. (2004) A variant 2677A allele of the MDR1 gene affects fexofenadine disposition. *Clin Pharmacol Ther* **76**, 418–427.

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Regular Article

Genetic Variation and Haplotype Structure of the ABC Transporter Gene ABCG2 in a Japanese Population

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Full text of this paper is available at http://www.jstage.jst.go.jp/browse/dmpk

Summary: The ATP-binding cassette transporter, ABCG2, which is expressed at high levels in the intestine and liver, functions as an efflux transporter for many drugs, including clinically used anticancer agents such as topotecan and the active metabolite of irinotecan (SN-38). In this study, to elucidate the linkage disequilibrium (LD) profiles and haplotype structures of *ABCG2*, we have comprehensively searched for genetic variations in the putative promoter region, all the exons, and their flanking introns of *ABCG2* from 177 Japanese cancer patients treated with irinotecan. Forty-three genetic variations, including 11 novel ones, were found: 5 in the 5′-flanking region, 13 in the coding exons, and 25 in the introns. In addition to 9 previously reported nonsynonymous single nucleotide polymorphisms (SNPs), 2 novel nonsynonymous SNPs, 38C>T (Ser13Leu) and 1060G>A (Gly354Arg), were found with minor allele frequencies of 0.3%. Based on the LD profiles between the SNPs and the estimated past recombination events, the region analyzed was divided into three blocks (Block −1, 1, and 2), each of which spans at least 0.2 kb, 46 kb, and 13 kb and contains 2, 24, and 17 variations, respectively. The two, eight, and five common haplotypes detected in 10 or more patients accounted for most (>90%) of the haplotypes inferred in Block −1, Block 1, and Block 2, respectively. The SNP and haplotype distributions in Japanese were different from those reported previously in Caucasians. This study provides fundamental information for the pharmacogenetic studies investigating the relationship between the genetic variations in *ABCG2* and pharmacokinetic/pharmacodynamic parameters.

Key words: ***ABCG2*; nonsynonymous SNP; haplotype; haplotype-tagging SNP**

On August 8, 2005, the novel variations described in this paper were not found in the Japanese Single Nucleotide Polymorphisms (JSNP) (http://snp.ims.u-tokyo.ac.jp/), dbSNP in the National Center for Biotechnology Information (http://www.ncbi.nlm.nih.gov/SNP/) or PharmGKB (http://www.pharmgkb.org/do/) databases.

Introduction

The ATP-binding cassette transporter G2, ABCG2, also named breast cancer resistance protein (BCRP), placenta-specific ATP-binding cassette transporter

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(ABCP) or mitoxantrone resistance protein (MXP), belongs to a superfamily (*white*) of ABC half transporters. ABCG2 was originally identified as a multi-drug resistance transporter because it was cloned from cancer cell lines selected with high concentrations of mitoxantrone[1] or verapamil and doxorubicin.[2] The *ABCG2* gene spanning over 66 kb, is located at 4q22 and consists of 16 exons, which encode a 72.6 kDa membrane protein of 655 amino acids.[2-4] Unlike many other drug-resistant transporters, such as ABCB1 (multidrug resistance protein 1 or P-glycoprotein) and ABCC1 (multidrug resistance-associated protein 1), ABCG2 has only one ATP binding region and six transmembrane domains, requiring dimerization or oligomerization to transport substrates.[5-6]

In normal human tissues, ABCG2 is expressed at high levels in placental trophoblast cells, the epithelium of the small intestine and colon, liver canalicular membranes, and the venous and capillary endothelium.[7] These distribution patterns suggest that ABCG2 may play a protective role against toxic substances and metabolites by extruding them across the apical membrane. *In vitro* studies have also indicated that a number of anticancer drugs are good substrates for ABCG2: e.g. topotecan, an irinotecan metabolite, 7-ethyl-10-hydroxycamptothecin (SN-38), and its glucuronide conjugate, SN-38G.[8-10] Indeed, inhibition of the murine ABCG2 homologue, Bcrp 1, increases the bioavailability of topotecan when orally administered to *mdr1a/1b*-deficient mice.[11] In a clinical study, coadministration of topotecan with GF120918, a dual inhibitor for ABCG2 and P-glycoprotein, was shown to markedly increase the bioavailability and systemic exposure of topotecan.[12]

The cloning of ABCG2 from drug-selected cell lines revealed that acquired amino acid substitutions at residue 482 (Arg482Gly and Arg482Thr) of ABCG2 resulted in marked alterations in substrate recognition and transport ability.[13] Thereafter, naturally occurring genetic variations in *ABCG2* have been extensively examined in various ethnic populations[14-21] because they were expected to explain interindividual differences in oral bioavailability and clearance of ABCG2 substrate drugs.[22] Two nonsynonymous polymorphisms, 34G>A (Val12Met) and 421C>A (Gln141Lys), were detected at relatively high frequencies in most ethnic groups including Caucasians, Asians, and Africans.[14-16,18-21,23] Both polymorphisms were reported to be associated with reduced protein expression *in vitro* and/or the increased sensitivity of the expressed cells toward several anticancer drugs although conflicting data were also reported.[16,24-26] The expression of ABCG2 protein in placenta was significantly lower in homozygotes with the 421A alleles than in those with the 421C alleles, while 34G>A (Val12Met) did not affect ABCG2 protein expression.[23] However, in intestinal samples, no association was found between the ABCG2 protein levels and the 421C>A (Gln141Lys) genotype.[18] A pharmacokinetic study showed that 421A (Gln141Lys) was unlikely to influence the *in vivo* disposition of irinotecan in European Caucasian cancer patients.[27] On the other hand, diflomotecan pharmacokinetics were significantly affected by the 421A genotype.[28] To explain these inconsistencies, the elucidation of the haplotype structure of *ABCG2* would be helpful; however, only limited information is available for the linkage disequilibrium (LD) profile and haplotype structure of this gene.[20,21] Also, to facilitate future pharmacogenetic studies on *ABCG2* genetic variations, haplotype analysis using its high-density SNPs found in a large number of samples is warranted.

In this study, we searched for genetic variations in *ABCG2* by sequencing 5′ regulatory regions and all the exons with their surrounding introns from 177 Japanese cancer patients administered irinotecan. Then, LD and haplotype analysis was performed using the detected variations, and haplotype-tagging single nucleotide polymorphisms (htSNPs) were identified to discriminate the common haplotypes in Japanese.

Materials and Methods

Human genomic DNA samples: All of the 177 patients participating in this study were administered irinotecan for the treatment of various cancers (mainly lung, stomach and colon cancers) at the National Cancer Center. Previously, we examined genetic variations in all *ABCG2* exons with their surrounding introns for 60 Japanese subjects treated with irinotecan.[17] In this study, we sequenced the additional 5′ regulatory regions in *ABCG2* for these patients and incorporated all the polymorphism data obtained from them into the haplotype analysis. Other 117 Japanese cancer patients were newly recruited. Genomic DNA was extracted from blood leukocytes from all the subjects and used as template in the polymerase chain reaction (PCR). The ethical review boards of the National Cancer Center and National Institute of Health Sciences approved this study. Written informed consent was obtained from all subjects.

PCR conditions for DNA sequencing: First, multiplex PCR was performed to amplify all 16 exons of *ABCG2* from 600 ng of genomic DNA utilizing 1.25 units of Ex-Taq (Takara Bio Inc., Shiga, Japan) with 0.30 μM each of the 32 primers designed in the intronic regions (listed in **Table 1**). The first round of PCR conditions were 94°C for 5 min, followed by 30 cycles of 94°C for 30 sec, 55°C for 1 min, and 72°C for 2 min, and then a final extension for 7 min at 72°C. Next, each PCR fragment was separately amplified in a second PCR using the first round PCR product as a template by

Table 1. Primer sequences used for the analysis of the *ABCG2* gene

Amplified and sequenced region		Forward primer		Reverse primer		PCR product (bp)
		Sequence (5′ to 3′)	Position[a]	Sequences (5′ to 3′)	Position[a]	
PCR	5′-flanking	TTAAGGGTCTTGAAACTGAC	13575766	CACTCTCAGCGAAACTGGTT	13574208	1559
	Exon 1	CTGTGCCCACTCAAAAGGTT	13574540	GAAACTGCGAAAGGCTAAAA	13574110	431
	Exon 2	GGATGTTCTTATCACAATGG	13556027	CAAATGAAAGCATGTGTCTG	13555509	519
	Exon 3	TGGTTTGTGCTTGTGTTCTA	13548617	GCTCAATAAATACCTGCTCG	13548337	281
	Exon 4	GGATTCAAAGTAGCCATGAGAT	13547885	GTCACATAATCAACTGGAAGCA	13547563	323
	Exon 5	GGCTTTGCAGACATCTATGGAG	13547246	CAGGTTAATTTCCACGTTCA	13546776	471
	Exon 6	ACCAGGTATCCACTTATTTG	13537791	TGACTTTCACTCCAACAGAA	13537366	426
	Exon 7	AAGACTGTCCTAGAATCTGC	13534384	TAGCACCAAATGGAACAAAC	13533817	568
	Exon 8	ATTACATGGGAAGAAGAGAG	13531063	TTGACTGGTATCAGAAGACTG	13530689	375
	Exon 9	TAGAATGAAGGTGTTAGGGA	13529516	AGGTGGAGTGAAGATAACAA	13529040	477
	Exon 10	GCCAAGCCATTGAGTGTTTA	13523258	CTGACTCATCCTACCCTCAA	13522908	351
	Exon 11	ACCAGAACAGTTTCCCTTTT	13517307	AAAAGTACTGGTAATCCTCCG	13516972	336
	Exon 12	TCATGGGATGCTTTCTCAGG	13515499	GTGTTTCCTTATCTCATGGT	13515056	444
	Exon 13	CATGGACAGACACAACATTG	13513633	GGCAAAGAGGAAAGTTAGTA	13513133	501
	Exon 14	ACCGTAAATGACTTCAGCTA	13511673	ATTCTCATTCCTTGCTCCTA	13511235	439
	Exon 15	TTGGTGAGACAAAGACTGTG	13510655	GCAGCAGAATACTGAGGGGT	13510242	414
	Exon 16	AGGCTTGGTTCAATTTTAGG	13508342	CATGATGTCTTGGGTTCTTT	13507897	446
Sequencing	5′-flanking[b]	GGTCTTGAAACTGACAGAAA	13575761	AATGGGTGGTTTCTGGTGAA	13575176	
		ATTCAGTAAGTTTCTCCCCT	13575291	CTGACACGAACTTCCTAAGC	13574712	
		TTAGGAAGTTCGTGTCAGCG	13574729	TAACCAAAGGCTCAGGATCT	13574265	
	Exon 1	GTGCCCACTCAAAAGGTTCC	13574538	CTAAAAAACTCAGTCGTCTCGT	13574124	
	Exon 2	GGATGTTCTTATCACAATGG	13556027	CAAATGAAAGCATGTGTCTG	13555509	
	Exon 3	GGTTTGTGCTTGTGTTCTAT	13548616	GCTCAATAAATACCTGCTCG	13548337	
	Exon 4	GGATTCAAAGTAGCCATGAGAT	13547885	GTCACATAATCAACTGGAAGCA	13547563	
	Exon 5	CTTTGCAGACATCTATGGAGT	13547244	GACCATACACATTACAGGAAAC	13546816	
	Exon 6	TGTCTCTTACAGGACTGGCA	13537738	TGACTTTCACTCCAACAGAA	13537366	
	Exon 7	GACAAAGTCAGGCTGAACTA	13534231	CTACCCAAAGACCAAACAGC	13533869	
	Exon 8	TCTGTCTTCTCTAGCCTTACC	13531015	ACAGAAATTCACAAAGCCAC	13530715	
	Exon 9	CATCCAAGAAAGGGTTCACA	13529494	AAGGGTGGGTAGAAGATAAA	13529068	
	Exon 10	CAAGCCATTGAGTGTTTATC	13523256	GAATGACATTTACACTATACTTG	13522933	
	Exon 11	CCCTTTTTTTCCTGCTTAAC	13517294	AACCCCAGATGTAATCAGTC	13517011	
	Exon 12	CTGTCAGCAGAGGTCTGTAAC	13515397	TTCCTTATCTCATGGTTTGG	13515060	
	Exon 13	GGACAGACACAACATTGGAG	13513630	AAGTAAAGCAGAGCCCCATT	13513189	
	Exon 14	TGCAGAGGAGAAGAGTTTAG	13511637	TTCTGGATGGGAGACTTTCA	13511264	
	Exon 15	AGACAAAGACTGTGAATATGTT	13510649	AGCAGAATACTGAGGGGTTG	13510244	
	Exon 16	GCTTGGTTCAATTTTAGGCT	13508340	GATGGCAAGGGAACAGAAAA	13507989	

[a]The nucleotide position of the 5′ end of each primer on NT_016354.17.
[b]Three sets of overlapping primers were used for sequencing of 5′-flanking region.

Table 2. Summary of *ABCG2* SNPs detected in a Japanese population

SNP ID				Location	Position		Nucleotide change and flanking sequences (5′ to 3′)	Amino acid change	Number of subjects			Allele Frequency
This Study	JSNP	dbSNP (NCBI)	Reference		NT_016354.17 (or AC084732.1)	From the translational initiation site or from the end of nearest exon			Wild-type	Heterozygote	Homozygote	
MPJ6_AG2027[a]				5′-Flanking	19496[b]	−1412[b,c]	TCTTTTTAAAAAA/GTTATGTATAGTC		176	1	0	0.003
MPJ6_AG2028	ssj0001952	rs3219191		5′-Flanking	19705_19708[b]	−1203_−1200[b,c]	TGGCTACACTCACTCA/-CAAAGCCTGATG		103	64	10	0.237
MPJ6_AG2029[a]				5′-Flanking	20155[b]	−753[b,c]	GGCGGGAGTGTTT/CGGCTTGTCCCTG		176	1	0	0.003
MPJ6_AG2030[a]				5′-Flanking	20246[b]	−662[b,c]	CGCGGCAGGACAC/TGTGTGCGCTTTC		175	2	0	0.006
MPJ6_AG2001		rs2231136		5′-Flanking	20646[b]	−262[b,c]	CAGTGCCCGCCAC/TTCCCACTGAGAT		173	4	0	0.011
MPJ6_AG2031[a]				Intron 1	13574206	IVS1+37	CGCTGAGAGTGTG/TTGTCTGGAAAGG		176	1	0	0.003
MPJ6_AG2032[a]				Intron 1	13555999	IVS1−128	ATGGTATGGGCCA/GTTCATTGGAAAT		176	1	0	0.003
MPJ6_AG2033[a]				Intron 1	13555999	IVS1−128	ATGGTATGGGCCA/TTTCATTGGAAAT		176	1	0	0.003
MPJ6_AG2002	IMS-JST131649, ssj0001922	rs1564481		Intron 1	13555970	IVS1−99	CTGCTCATTGCCG/ACACATTTAAAAA		70	87	20	0.359
MPJ6_AG2003	ssj0001924	rs2231137		Exon 2	13555819	34	GTTTTTATCCCAG/ATGTCACAAGGAA	Val12Met	111	64	2	0.192
MPJ6_AG2034[a]				Exon 2	13555815	38	TTATCCCAGTGTC/TACAAGGAAACAC	Ser13Leu	176	1	0	0.003
MPJ6_AG2004	ssj0001925	rs4148152		Intron 2	13555614	IVS2+36	GACAGCTTTTTAA/GTTTACCTACAGT		111	64	2	0.192
MPJ6_AG2005			17)	Intron 2	13548585	IVS2−93	TTTGTAATTTCAT/CCAACCTTCATTG		167	10	0	0.028
MPJ6_AG2006	ssj0001929	rs2231138		Intron 3	13548423	IVS3+10	TTCGTGAGTATAA/GGAGAGTATAAGT		153	24	0	0.068
MPJ6_AG2007		rs5860119	17,23)	Intron 3	13548361_13548362	IVS3+71_+72	CCACTTTTTTTT-/TGTGTGCGAGCAG		174	3	0	0.008
MPJ6_AG2008		rs2231139		Exon 4	13547669	369	TAATTCAGGTTAC/TGTGGTACAAGTA	Tyr123Tyr	176	1	0	0.003
MPJ6_AG2009			16,23)	Exon 4	13547662	376	GGTTACGTGGTAC/TAAGTAAGTATTA	Gln126X	167	10	0	0.028
MPJ6_AG2010	IMS-JST080116, ssj0001930	rs2231142		Exon 5	13547028	421	AGAGAAAACTTAC/AAGTTCTCAGCAG	Gln141Lys	79	83	15	0.319
MPJ6_AG2035			21)	Exon 5	13546970	479	AAAAAAACGAACG/AGATTAACAGGGT	Arg160Gln	176	1	0	0.003
MPJ6_AG2036		rs2231144		Intron 5	13537665	IVS5−16	ATTGACAATTATA/GATATTTGTGATT		176	1	0	0.003
MPJ6_AG2011	ssj0001931	rs1871744		Intron 6	13534334	IVS6−217	AGTTGATTCTAGA/GTTGTCAATACAA		102	63	12	0.246
MPJ6_AG2012			17)	Intron 6	13534321	IVS6−204	TTGTCAATACAAC/TACACTGAAAATT		166	11	0	0.031
MPJ6_AG2013	ssj0001932	rs2231145		Intron 6	13534289	IVS6−172	TGTTTTAATAAAA/GGCATTGAATTTA		133	43	1	0.127
MPJ6_AG2014	ssj0001933	rs2231146		Intron 6	13534205	IVS6−88	GAACTAGAGCAAA/GCAATCTAAAGGC		133	43	1	0.127
MPJ6_AG2037[a]				Exon 9	13529294	1060	CATCAACTTTCCG/AGGGGTGAGAAGA	Gly354Arg	176	1	0	0.003
MPJ6_AG2015			17,23)	Exon 9	13529256	1098	AGTCTTCAAGGAG/AATCAGCTACACC	Glu366Glu	172	5	0	0.014
MPJ6_AG2016	ssj0001936	rs2231148		Intron 9	13523183	IVS9−60	TAAATGGTGTGTA/TTAAGTTTTTATC		124	46	7	0.169
MPJ6_AG2038[a]				intron10	13522946	IVS10+95	AGACAAGTATAGT/AGTAAATGTCATT		175	2	0	0.006
MPJ6_AG2017			17)	Exon 11	13517163	1291	GCTGGGGTTCTCT/CTCTTCCTGACGA	Phe431Leu	176	1	0	0.003
MPJ6_AG2039			23,24)	Exon 11	13517132	1322	AGTGTTTCAGCAG/ATGTTTCAGCCGT	Ser441Asn	176	1	0	0.003
MPJ6_AG2018	ssj0001939	rs2231153		Intron 11	13517067	IVS11+20	GGTCTTTGTTCTA/GGGAACGGGGCTG		124	49	4	0.161
MPJ6_AG2019			17)	Intron 11	13515440	IVS11−135	CATGCATAGTGGG/ATCTAGCCCTGAG		171	6	0	0.017
MPJ6_AG2020			17,23)	Exon 12	13515208	1465	CCAAGTATTATAT/CTTACCTGTATAG	Phe489Leu	174	3	0	0.008
MPJ6_AG2021	ssj0001941	rs2231156		Intron 12	13515132	IVS12+49	AGTCTTGCCTATG/TGGTGAAGTCAGT		95	71	11	0.263
MPJ6_AG2040			23)	Exon 13	13513442	1515	AAAGGCAGATGCC/-TTCTTCGTTATG	Phe506SerfsX4	176	1	0	0.003
MPJ6_AG2022	IMS-JST064085, ssj0001943	rs2231157		Intron 13	13513270	IVS13+40	AAGGAATTGTTTC/TTTTCCTTCATTT		28	85	64	0.602
MPJ6_AG2023			17)	Intron 13	13513245	IVS13+65	CTTCCTGCACATT/GCACTTGTCATGT		175	2	0	0.006
MPJ6_AG2041[a]				Intron 13	13511651	IVS13−185	ACTTCAGCTATAT/CAGAGATGTGCAC		176	1	0	0.003
MPJ6_AG2024	IMS-JST064086, ssj0001944	rs2231162		Intron 13	13511487	IVS13−21	GCAGGCCTGACTC/TTTAGTATTTGCT		124	49	4	0.161
MPJ6_AG2042			21)	Exon 14	13511391	1723	TTCAGCATTCCAC/TGATATGGATTTA	Arg575X	176	1	0	0.003
MPJ6_AG2025	ssj0001946	rs2231164		Intron 14	13510562	IVS14−46	TGGAAACTTCTTA/GAAATTTAAAACT		58	86	33	0.429
MPJ6_AG2026	IMS-JST064087, ssj0001947	rs2231165		Intron 15	13510324	IVS15+110	ACTGAATTTTTCC/TGAGCCTACGTTT		136	39	2	0.121
MPJ6_AG2043a				Intron 15	13510292	IVS15+142	CATAAAGTGAGTT/GGTGCGCGAATGC		175	2	0	0.006

[a]Novel variations detected in this study.

[b]For the 5′-flanking variations, the genomic sequence, AC084732.1, was used as the reference sequence.

[c]Intron 1 was skipped for numbering.

Table 3. Haplotypes of Block -1 in a Japanese population

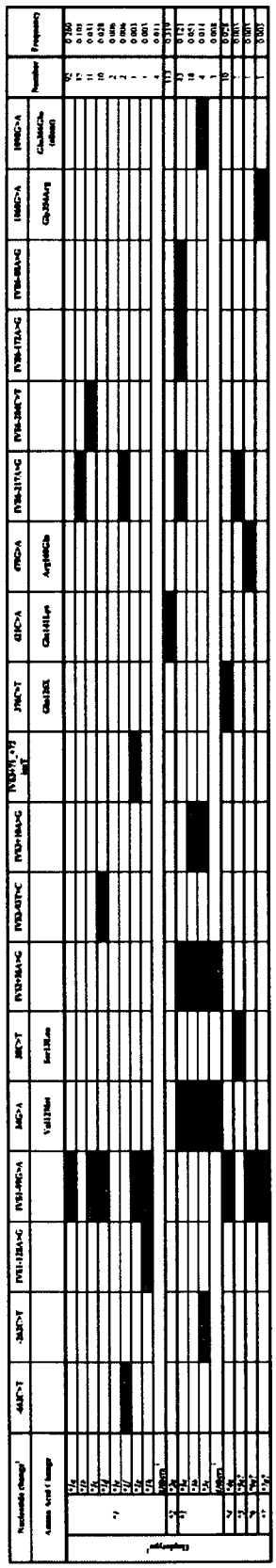
Nucleotide change[1]		-1412A>G	-1203_-1200 delCTCA	Number	Frequency
Amino Acid Change					
Haplotype[2]	*1 *1a			270	0.763
	*1b			83	0.234
	*1c?			1	0.003

[1]The position on the cDNA sequence (A of the translational start codon is 1, based on AC084732.1. Intron 1 was skipped for numbering the nucleotide positions.)
[2]The haplotype, *1c, ambiguously inferred in only one patient is described with a question mark.
White cell, wild-type; gray cell, nucleotide alteration.

Ex-Taq (0.625 units) with the same primers and conditions used in the first round PCR. Because of the high GC content in the 5′-flanking region of *ABCG2*, this region was separately amplified by a single PCR reaction from 50 ng of genomic DNA using 0.625 units of Ex-Taq and GC buffer I (Takara Bio Inc.) with 0.2 μM primers (listed in **Table 1**). The PCR conditions for amplifying the 5′-flanking region were the same as described above. The PCR products were then treated with a PCR Product Pre-Sequencing Kit (USB Co., Cleveland, OH, USA) and were directly sequenced on both strands using an ABI BigDye Terminator Cycle Sequencing Kit (Applied Biosystems, Foster City, CA, USA) with the sequencing primers listed in **Table 1** (Sequencing column). The excess dye was removed by a DyeEx96 kit (Qiagen, Hilden, Germany). The eluates were analyzed on an ABI Prism 3700 DNA Analyzer (Applied Biosystems). All the novel SNPs were confirmed by repeat sequencing of PCR products that were newly generated by amplification of genomic DNA. The genomic and cDNA sequences of *ABCG2* obtained from GenBank (NT_016354.17 and NM_004827.1, respectively) were used as the reference sequences for all the analyzed regions except for the 5′-flanking region. Unless otherwise indicated, the description of the nucleotide position was based on cDNA sequence, and adenine of the translational initiation site in exon 2 was numbered as +1. For the 5′-flanking variations (upstream of exon 1), the genomic sequence, AC084732.1, was used as the reference sequence, and intron 1 was skipped for numbering the nucleotide positions. For intronic polymorphisms, the position was numbered from the nearest exon.

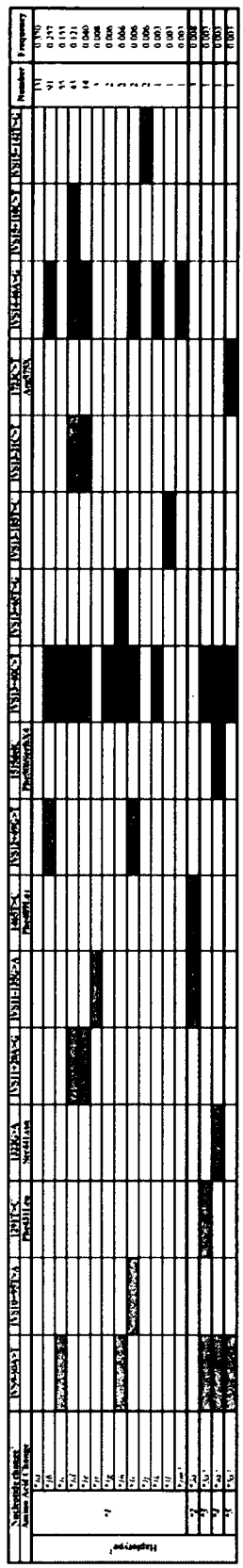
Linkage disequilibrium (LD) and haplotype analyses: Hardy-Weinberg equilibrium and LD analysis were performed by SNPAlyze software (Dynacom Co., Yokohama, Japan) and a pairwise LD between variations was obtained for the |D′| and rho square (r^2) values. Some of the haplotypes were unambiguous from subjects with homozygous variations at all sites or a heterozygous variation at only one site. The diplotype

Table 4. Haplotypes of Block 1 in a Japanese population



[1]The position on the cDNA sequence (A of the translational start codon is 1, based on NT_016354.17) or position from the nearest exon.
For the 5′-flanking variations, the genomic sequence, AC084732.1, was used as the reference sequence, and intron 1 was skipped for numbering the nucleotide positions.
[2]The haplotypes inferred in only one patient are classified into "Others" (in the *1 and *3 groups) or indicated with a question mark (*5a, *6a and *7a).
[3]"Others" include haplotypes harboring −753T>C, IVS1+37G>T, IVS1-128A>T, IVS3+71_+72insT, 369C>T (Tyr123Tyr), IVS5-16A>G or 1098G>A (Glu366Glu).
White cell, wild-type; gray cell, nucleotide alteration.

Table 5. Haplotypes of Block 2 in a Japanese population



[1]The position on the cDNA sequence (A of the translational start codon is 1, based on NT_016354.17) or position from the nearest exon.
[2]The haplotypes inferred in only one patient are indicated with a question mark (**1m*, **3a*, **4a* and **5a*).
White cell, wild-type; gray cell, nucleotide alteration.

configurations were inferred by LDSUPPORT software, which determines the posterior probability distribution of the diplotype for each subject based on the estimated haplotype frequencies.[29] The haplotypes without any amino acid change were designated as **1*, and the nonsynonymous SNP-bearing haplotypes were numerically numbered. The subtypes were named by use of alphabetical small letters in the order of their frequencies. The haplotypes ambiguously inferred in only one patient were placed into an "Others" category within each group, or are shown as a haplotype name plus a question mark in **Tables 3-5**.

Network analysis of the inferred haplotypes was performed with Network 4.1.0.9 (http://www.fluxus-engineering.com.) based on the algorithms of the reduced median network.

Results

ABCG2 variations found in a Japanese population: We found 43 variations, including 11 novel ones, from 177 Japanese cancer patients treated with irinotecan (**Table 2**). Five variations were located in the 5′-flanking region, 13 (2 synonymous and 11 nonsynonymous) in the coding exons, and 25 in the introns. The observed allele frequencies were all in Hardy-Weinberg equilibrium ($p > 0.05$) except for 34G>A (Val12Met) and IVS2 +36A>G ($p = 0.028$ for both variations). The deviation from Hardy-Weinberg equilibrium for both variations resulted from a slightly smaller number of homozygotes than expected. Currently, the reason for this deviation is not clear.

Two novel nonsynonymous SNPs, 38C>T (Ser13Leu) and 1060G>A (Gly354Arg), were heterozygous in different patients at an allele frequency of 0.003. Both Ser13 and Gln354 are in the intracellular loop of the N-terminus. Of the other novel variations, three (−1412A>G, −753T>C, and −662C>T) were found in the 5′ flanking region and six (IVS1+37G>T, IVS1-128A>G, IVS1-128A>T, IVS10+95T>A, IVS13-185T>C, and IVS15+142T>G) in the introns.

Thirty-two variations detected were already reported or publicized in the dbSNP database and/or the JSNP database. Their database ID numbers are also listed in **Table 2**. For these known polymorphisms, similar allele frequencies were obtained as described in previous reports[16,23] and the JSNPs database for Japanese populations. However, marked ethnic differences in the allele frequencies were observed with −1203_−1200delCTCA, 34G>A (Val12Met), 421C>A (Gln141Lys), and some intronic variations. The deletion of four nucleotides, −1203_−1200delCTCA, is located upstream of the basal promoter and identified at a much lower frequency in our population (0.237) than in 60 Swedish individuals (0.540).[19] This deletion is within the region characterized as a positive regulatory element

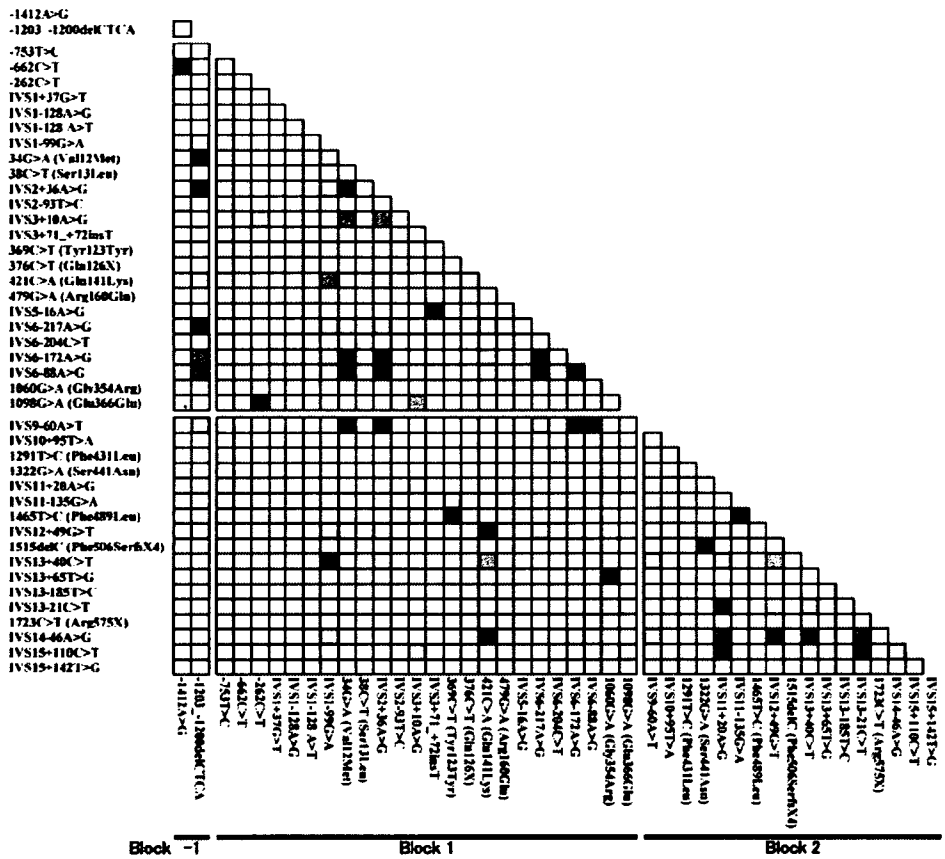


Fig. 1. Linkage disequilibrium (LD) analysis of *ABCG2* by r^2 statistics. Pairwise LD between all the detected SNPs is depicted as r^2 (from 0 to 1) by a 10-graded gray color. The denser color represents a higher linkage.

(from −1836 to −1175 bp upstream of the translational start site) of the basal promoter,[30] and was suggested to influence irinotecan pharmacokinetics.[31]

The frequencies of two well-known nonsynonymous SNPs, 34G>A (Val12Met) and 421C>A (Gln141Lys), were 0.192 and 0.319 in our study, which were comparable to those in Chinese (0.204 and 0.222–0.350, respectively).[20,27] However, the frequencies were much higher than those in Caucasians (0.02–0.065 and 0.08–0.15), African-Americans (0–0.09 and 0–0.05), and a Swedish population (0.02 and 0.1).[18,19,21,23,27] Of other relatively rare nonsynonymous SNPs, 376C>T (Gln126X), 1291T>C (Phe431Leu), 1322G>A (Ser441Asn), 1465T>C (Phe489Leu), and 1515delC (Phe506SerfsX4) were already detected in a Japanese population by Itoda *et al.*[17] and/or Kobayashi *et al.*,[23] but not found in other ethnic groups. Recently, the two nonsynonymous SNPs, 479G>A (Arg160Gln) and 1723C>T (Arg575X), have been reported by Bosch *et al.*[21] Arg160Gln and Arg575X were found as heterozygotes in single Asian and Caucasian subjects, respectively. Therefore, the distribution of 479G>A (Arg160Gln) might be restricted in Asians, while 1723C>T (Arg575X) is likely to be detected both in Caucasians and Japanese at low frequencies. Arg575X results in a truncated protein that terminates at the extracellular loop between transmembrane domains 5 and 6 and lacks transmembrane domain 6.

On the other hand, several nonsynonymous SNPs reported in other ethnic groups were not detected: 805C>T (Pro269Ser) found in Chinese at a 0.037 frequency,[20] 1858G>A (Asp620Asn) in undefined (combined) ethnicities[14] (0.011) and in a Dutch population[21] (0.005), 616A>C (Ile206Leu) in Hispanics (0.100), and 1768A>T (Asn590Tyr) in Caucasians (0.010).[18] Thus, these SNPs are either ethnic-specific or rare.

The ethnic differences in the allele frequencies were also observed with intronic variations. Bosch *et al.* searched for variation in *ABCG2* in 100 healthy Dutch volunteers that consisted mainly of Caucasians.[21] The reported allele frequencies of IVS11+20A>G (0.045), IVS12+49G>T (0.095), IVS13-21C>T (0.035), and IVS14-46A>G (0.160) in Caucasians were lower than those in Japanese (0.161, 0.263, 0.161, and 0.429, respectively). On the other hand, IVS9-60A>T was detected at a higher frequency in Caucasians (0.360)

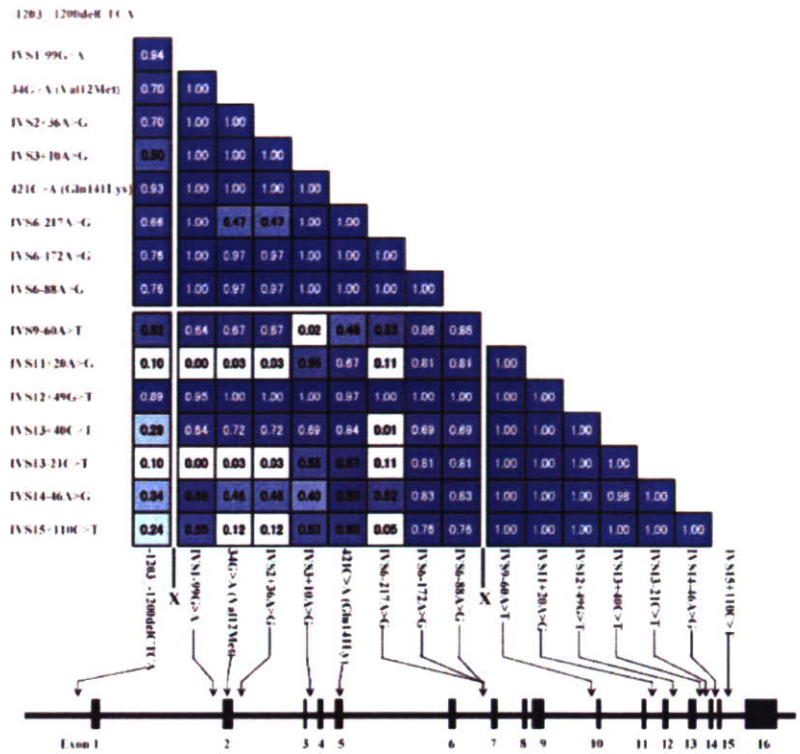


Fig. 2. Linkage disequilibrium (LD) analysis of *ABCG2* by |D'| statistics. The values of |D'| between 16 common SNPs (≥0.05 in their allele frequencies) are shown. The positions of the estimated minimum recombination events are indicated by a "X", and the location of the variations is indicated in the schematic diagram of the *ABCG2* gene.

than in Japanese (0.169), while IVS13+40C>T had a comparable frequency between Caucasians (0.535) and Japanese (0.602).

Linkage disequilibrium (LD) analysis and haplotype block partition: Using the 43 detected genetic variations, LD analysis was performed by |D'| and r^2 statistics, and the pairwise values of r^2 are depicted with 10-graded blue color in **Fig. 1**. As previously reported in various ethnic groups,[14,18] perfect LD ($r^2=1.0$) was observed between 34G>A (Val12Met) and IVS2+36A>G. In addition, two pairs of SNPs, between IVS6-172A>G and IVS6-88A>G and between IVS11+20A>G and IVS13-21C>T, were perfectly linked ($r^2=1.0$). Because the two rare nonsynonymous variations, 1515delC (F506SfsX4) and 1322G>A (Ser441Asn), were found in the same patient, they were statistically estimated to be linked with each other. Strong LDs ($r^2>0.7$) were observed between −262C>T and 1098G>A (Glu366Glu) ($r^2=0.798$), between 421C>A (Gln141Lys) and IVS12+49G>T ($r^2=0.709$), and among IVS11+20A>G, IVS13-21C>T, and IVS15+110C>T ($r^2>0.720$).

As for |D'| values, when considering 16 common SNPs (≥0.05 in their allele frequencies), only 48 pairs (40%) out of 120 pairs gave |D'|=1.0 (**Fig. 2**), indicating that recombination had occurred within this gene. To further estimate the past recombination events, the absence or presence of all four gametes between these 120 site pairs was assessed (data not shown).[32] The results obtained implied that recombination had happened in at least two sites: between −1203_−1200delCTCA and IVS1-99G>A, and between IVS6-88A>G and IVS9-60A>T (**Fig. 2**). Therefore, the *ABCG2* gene was divided into three blocks (Block −1, Block 1, and Block 2) as indicated in **Fig. 1**. Block −1 included two variations, −1412A>G and −1203_−1200delCTCA, in the 5′ regulatory region and might have its 5′ boundary upstream of the analyzed region. Block 1, spanning 46 kb, included 24 variations from −753T>C in the 5′ regulatory region to 1098G>A (Glu366Glu) in exon 9. The 5′ boundary of Block 1 was tentatively assigned because of the very low frequencies of −753T>C and −662C>T. The 3′ boundary of Block 1 was assigned by considering the strong association between −262C>T and 1098G>A (Glu366Glu) described above. Block 2, which included the remaining 17 variations, ranged from intron 9 to intron 15 (13 kb). No close associations were observed ($r^2<0.70$) between the variations across the blocks except for one pair of SNPs, 421C>A (Gln141Lys) and IVS12+49G>T,

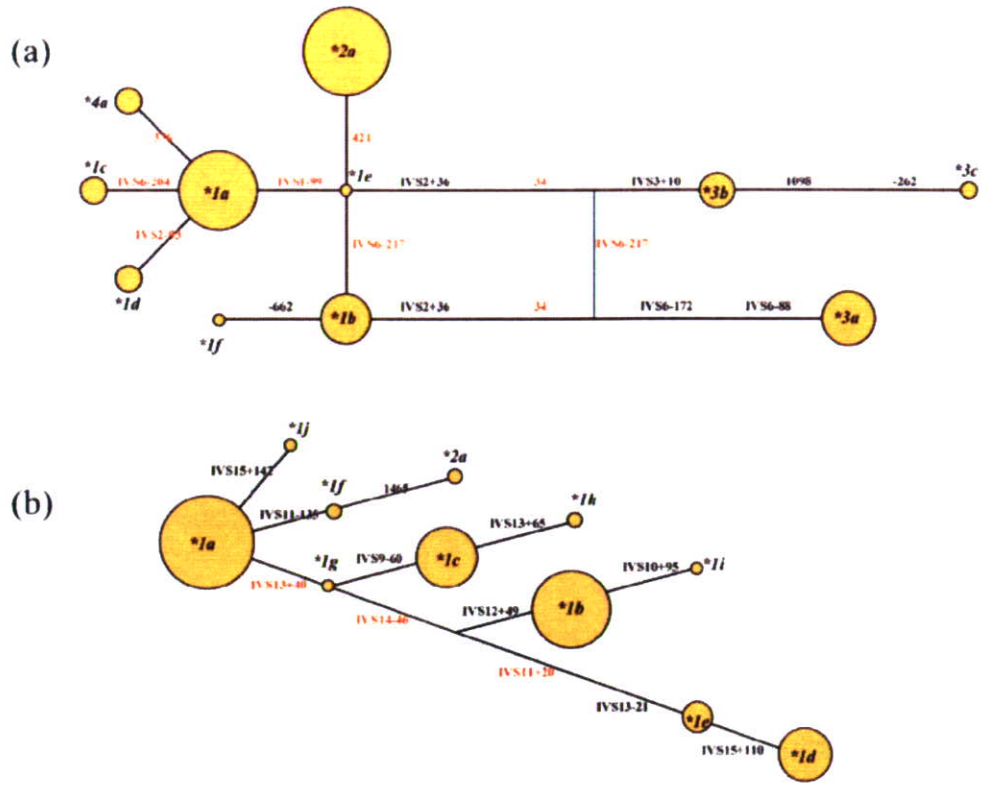


Fig. 3. Network analysis of *ABCG2* haplotypes of Block 1 (a) and Block 2 (b). Haplotypes found in at least two patients are shown. The areas in the circles represent the approximate frequencies of each haplotype. The variations connecting adjacent haplotypes are indicated using their positions. The htSNPs are indicated in red.

which were in strong LD ($r^2 = 0.709$) as described above. Our block partitioning was compatible with the definition of the LD block:[33] 254 pairs (92%) out of all 276 pairs in Block 1 and 127 pairs (93%) out of all 136 pairs in Block 2 gave pair-wise |D'| values greater than 0.9.

Haplotype estimation, selection of htSNPs and network analysis: First, diplotypes/haplotypes within each *ABCG2* block were inferred. Using all 2, 24, and 17 variations in Block −1, Block 1, and Block 2, respectively, 3 (Block −1), 23 (Block 1), and 17 (Block 2) haplotypes were inferred (**Tables 3-5**). The probabilities of diplotype configurations in Block −1, Block 1, and Block 2 were over 0.95 for 100%, 97.7%, and 97.2% of the subjects, respectively. Of all the estimated haplotypes (except for the unambiguously identified haplotypes), 1 in Block −1, 10 in Block 1, and 4 in Block 2 were inferred in only one patient. Since the estimation of rare haplotypes is often ambiguous, they were classified into "Others" within each group (the **1* and **3* groups in Block 1) or indicated with a "?".

In Block −1, three haplotype (**1a*, **1b*, and **1c*) were inferred. The frequencies of the common haplotypes, **1a* and **1b*, were 0.763 and 0.234, respectively.

In Block 1, seven haplotype groups (**1* to **7*) were inferred, and the groups of **2* to **7* harbored nonsynonymous SNPs, 421C>A (Gln141Lys) (**2*), 34G>A (Val12Met) (**3*), 376C>T (Gln126X) (**4*), 38C>T (Ser13Leu) (**5*), 479G>A (Arg160Gln) (**6*), and 1060G>A (Gly354Arg) (**7*). The most dominant haplotype was **2a* (0.319 frequency), followed by **1a* (0.260), **3a* (0.121), **1b* (0.105), **3b* (0.051), **1c* (0.031), **1d* (0.028), and **4a* (0.028). These 8 common haplotypes, found in 10 or more patients, accounted for 94% of all the inferred haplotypes. The nonsynonymous **5* to **7* groups were rare and found at frequencies less than 0.003. The haplotype-tagging SNPs (htSNPs) that were able to resolve the 8 common haplotypes were the following 7 variations: IVS1-99G>A, 34G>A (Val12Met), IVS2-93T>C, 376C>T (Gln126X), 421C>A (Gln141Lys), IVS6-217A>G, and IVS6-204C>T. The result of Network analysis in Block 1 is shown in **Fig. 3a**. The cladogram shows that **1a* and its closely connected haplotypes (**1c*, **1d*, and **4a*) are distant from the **3* group.

In Block 2, five haplotype groups (**1* to **5*) were inferred. The groups of **2* to **5* were defined as the

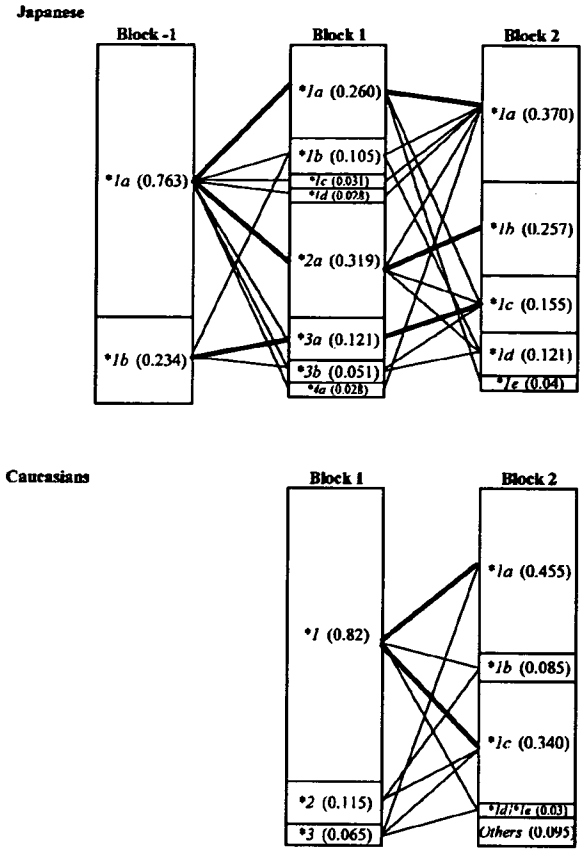


Fig. 4. The combination profiles of block haplotypes in Japanese (upper panel) and in Caucasians (lower panel) are shown. The haplotypes in Caucasians were classified based on our criteria from the previous report by Bosch *et al.*[21] The haplotypes in Block −1 were not available in Caucasians. The thick lines represent the combinations with frequencies over 10%, and the thin lines represent the combinations with frequencies of 1.0 to 9.9%.

haplotype harboring nonsynonymous SNPs, 1465T>C (Phe489Leu) (**2*), 1291T>C (Phe431Leu) (**3*), 1322G>A (Ser441Asn)/1515delC (Phe506SerfsX) (**4*), and 1723C>T (Arg575X) (**5*), respectively. Of them, **3a*, **4a*, and **5a* were inferred in only one patient, and the assignment of concurring SNPs was ambiguous. Five common haplotypes found in 10 or more patients (**1a*-**1e*) account for 94% of all the observed haplotypes. We found that 3 htSNPs, IVS11+20A>G, IVS13+40C>T, and IVS14-46A>G, are sufficient to distinguish four major haplotypes (**1a*-**1d*), which account for 90% of all the inferred haplotypes. The cladogram of network analysis suggests that the most common haplotype, **1a*, is the root of the tree (**Fig. 3b**).

Next, the combinations of block haplotypes were analyzed (inter-block haplotypes, **Fig. 4**). Between Blocks −1 and 1, both **1a* and **2a* in Block 1 were completely linked with Block −1 **1a*. In contrast, **3a* in Block 1 was mostly linked with Block −1 **1b*. As for combinations between Blocks 1 and 2, **1a*, **2a*, and **3a* in Block 1 were mostly linked with Block 2 **1a*, **1b*, and **1c*, respectively. Among the three blocks, the following combinations were major: Block −1 **1a*-Block 1 **2a*-Block 2 **1b* (0.246 frequency), Block −1 **1a*-Block 1 **1a*-Block 2 **1a* (0.192), and Block −1 **1b*-Block 1 **3a*-Block 2 **1c* (0.088).

Discussion

The present study provides comprehensive data on genetic variation in *ABCG2*, a gene encoding a multidrug transporter that is involved in the efficacy of cancer chemotherapy. Eleven nonsynonymous variations, including two novel ones (Ser13Leu and Gly354Arg), were found.

As for three of the reported nonsynonymous SNPs, *in vitro* functional analysis has already been performed to identify their effects on the localization, expression levels, and transport activity. Mizuarai *et al.* showed that 34G>A (Val12Met) was associated with reduced drug resistance in polarized LLC-PK1 cells, which might be caused by its impaired apical membrane localization.[25] In contrast, several groups did not find any significant effects of Val12Met on the protein expression levels as well as drug resistance using stable and transient mammalian expression systems.[16,24,26] According to Imai *et al.* and Kondo *et al.*,[16,24] the Gln141Lys substitution resulted in decreased protein expression and reduced drug resistance. These results are inconsistent with those obtained by Mizuarai *et al.* and Morisaki *et al.*, in which the reduced drug resistance was not caused by the decreased protein expression.[25,26] Kondo *et al.* have shown that the Ser441Asn variant was not localized to apical membranes, but remains intracellular in the transfected LLC-PK1 cells,[24] suggesting its reduced activity. Three variations, Gln126X, Phe506SerfsX4, and Arg575X, result in truncated proteins. Although there is limited information about the structural elements of ABCG2 responsible for its substrate recognition and transporting activity,[34] they are likely to lead to functional defects.

The functional effects of the other five nonsynonymous SNPs (Ser13Leu, Arg160Gln, Gly354Arg, Phe431Leu, and Phe489Leu) have not yet been characterized. Using the PolyPhen program (http://www.bork.embl-heidelberg.de/PolyPhen/) to predict the functional effect of these amino acid substitutions, three substitutions, Ser13Leu, Arg160Gln, and Gly354Arg, were estimated to cause possible alterations in protein function based on the PSIC (position specific independent count) profile score. Notably, Arg160Gln is located in the functionally important ATP-binding region between the Waker A (amino acids 80-89) and Walker B (amino acids 206-210) motifs. Thus, func-

tional analysis of these variants is warranted. Except for Val12Met, Gln126X, and Gln141Lys, the allele frequencies of eight nonsynonymous SNPs were less than 0.01, and these low frequency variations do not largely contribute to the overall heterozygosity of *ABCG2*; however, they might have clinical importance.

Bailey-Dell *et al.* characterized the basal promoter of *ABCG2*, which was mapped in the region from −859 to −187 relative to the translational initiation site and contained a CCAAT box and multiple Sp1 sites.[30] Two novel SNPs in the 5′ flanking region, −753T>C and −662C>T, are located near the putative SP1 binding site in the basal promoter. However, the functional significance of these SNPs is currently unknown.

It has been well recognized that partitioning of haplotype blocks and selection of their htSNPs are useful for association studies.[35] The resulting limited haplotype diversity would offer statistically sufficient power to detect phenotypic differences. In fact, due to the intragenic recombinations in *ABCG2*, too many whole-gene haplotypes (57 haplotypes), each having low frequencies, were inferred with low probabilities when all the 43 detected variations were used (data not shown). Since the LD analysis of *ABCG2* in the Japanese revealed at least two recombination sites, three LD blocks were assigned, which led to the identification of several htSNPs that could discriminate common haplotypes. Our analysis was focused on cancer patients in this study, but the allele frequencies obtained for the common polymorphisms were comparable to those in previous reports[16,23] and the JSNPs database. Thus, the population in this study is likely to represent the general Japanese population. Therefore, we compared our results on the LD patterns and haplotype distribution in Japanese with those in a closely related population (Chinese) and in a distant population (Caucasian).

The LD profile and haplotype structure of *ABCG2* in Chinese was reported recently by Wang *et al.*[20] The LD profile was similar between Japanese and Chinese. Because they did not use the eight common variations detected in our study (−1203_−1200delCTCA, IVS1-99G>A, IVS6-217A>G, IVS6-204C>T, IVS6-172A>G, IVS6-88A>G, IVS9-60A>T, and IVS15+110C>T), their haplotypes do not exactly correspond to ours. Nevertheless, the frequency (31.9%) of the haplotype **2a* in Block 1 harboring 421C>A (Gln141Lys) was comparable to their counterpart (20.4%). In both their (Chinese) and our (Japanese) studies, neither *cis*-acting regulatory polymorphisms nor other common nonsynonymous SNPs in the haplotype **2a* have been detected. Therefore, the substitution itself of Gln141 to Lys is likely to be responsible for the reduced expression of ABCG2 protein in placenta as demonstrated by Kobayashi *et al.*[23] Furthermore, Chinese and Japanese share several common Block 2 haplotypes, **1a*, **1b*, **1c*, and **1d*/**1e*. The frequencies of these haplotypes in Japanese were comparable to those in Chinese (0.222, 0.204, 0.259, and 0.222, respectively).[20]

Recently, the *ABCG2* haplotypes in Caucasians have been reported by Bosch *et al.*[21] by using 19 SNPs detected in a Dutch population. Since their haplotype analysis was conducted using the whole *ABCG2* gene (from exons 2 to 16) as one block, we compared our results with theirs in terms of our Block 1 and Block 2 haplotypes. The haplotype distribution in Caucasians is different from that in Japanese (**Fig. 4**). In Block 1, the frequencies of **2a* (0.115), **3a* (0.05), and **3b* (0.015) in Caucasians are much lower than those in Japanese (0.319, 0.121, and 0.051, respectively). In contrast, the **1* group in Caucasians is much more frequent (0.82) than those in Japanese (0.45). We could not compare the frequencies of the **1* subtypes because the 5 common SNPs detected in our study (IVS1-99G>A, IVS6-217A>G, IVS6-204C>T, IVS6-172A>G, and IVS6-88A>G) were not genotyped in these subjects. In Block 2, the frequencies of **1a* were comparable between Japanese (0.370) and Caucasians (0.455). However, **1b* and **1c* in Caucasians was observed with much lower (0.085) and higher (0.34) frequencies, respectively, than those in Japanese (0.257 and 0.155). Our results suggest that the optimal sets of the htSNPs for *ABCG2* differ to some extent between ethnic groups although the common SNPs are shared between them.

Despite the past recombinations within *ABCG2*, three major inter-block haplotypes were relatively well conserved in Japanese: Block −1 **1a*-Block 1 **2a*-Block 2 **1b* (0.246 frequency), Block −1 **1a*-Block 1 **1a*-Block 2 **1a* (0.192), and Block −1 **1b*-Block 1 **3a*-Block 2 **1c* (0.088). Because the variation, −1203_−1200delCTCA in Block −1 was not screened in both Chinese[20] and Dutch populations[21], we could not assess the associations between Block −1 and Block 1 SNPs in these ethnic groups. In a Swedish population, −1203_−1200delCTCA was reported to be linked with 34G>A (Val12Met), the representative SNP in the Block1 **3* group.[19] Due to the high (0.54) and low (0.02) allele frequencies of −1203_−1200delCTCA and 34G>A (Val12Met), respectively, the Block −1 **1b*-Block 1 **3* combination is not predominant in the Swedish population. Zhou *et al.* suggested that −1203_−1200delCTCA might influence pharmacokinetic parameters of irinotecan.[31] On the other hand, the functional significance of 34G>A (Val12Met) is not fully elucidated as described above.[16,24,26] In this context, the major combination in Japanese, Block −1 **1b*-Block 1 **3a*, should be carefully considered in pharmacogenetic studies in Japanese. As for the combinations of haplotypes between Blocks 1 and 2, Block 1 **2a*-Block 2 **1b*, was observed in Chinese[20] and

Caucasians[21] with frequencies of 0.204 and 0.05, respectively, as well as in Japanese (0.246 frequency). In contrast, Block 1 **3a*-Block 2 **1c* is characteristic of the Japanese. Because Block 2 **1c* was mostly connected to the **1* group in Block 1 in Caucasians,[21] the frequency of Block1 **1*-Block 2 **1c* was higher in Caucasians (0.29) than in Japanese (0.02), while the frequency of Block 1 **3a*-Block 2 **1c* was lower in Caucasians (0.02) than in Japanese (0.102). The profiles of recombinations in *ABCG2* seem to vary among ethnic groups, although the direct comparisons of LD patterns using the same SNPs between Japanese and other major ethnicities are needed to address this issue.

In conclusion, 43 variations were identified in *ABCG2*, including 11 novel ones, in a Japanese population. Two novel SNPs resulted in amino acid substitutions. Based on the LD profile and haplotypes of *ABCG2*, several htSNPs were found that are sufficient to distinguish the major *ABCG2* haplotypes in Japanese. This is the first report on *ABCG2* haplotypes with high-density SNPs in Japanese. This information will be useful in pharmacogenetic studies that investigate the relationship between interindividual differences of drug disposition and *ABCG2* haplotypes.

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References

1) Miyake, K., Mickley, L., Litman, T., Zhan, Z., Robey, R., Cristensen, B., Brangi, M., Greenberger, L., Dean, M., Fojo, T. and Bates, S. E.: Molecular cloning of cDNAs which are highly overexpressed in mitoxantrone-resistant cells: demonstration of homology to ABC transport genes. *Cancer Res.*, **59**: 8-13 (1999).
2) Doyle, L. A., Yang, W., Abruzzo, L. V., Krogmann, T., Gao, Y., Rishi, A. K. and Ross, D. D.: A multidrug resistance transporter from human MCF-7 breast cancer cells. *Proc. Natl. Acad. Sci. U S A*, **95**: 15665-15670 (1998).
3) Allikmets, R., Schriml, L. M., Hutchinson, A., Romano-Spica, V. and Dean, M.: A human placenta-specific ATP-binding cassette gene (ABCP) on chromosome 4q22 that is involved in multidrug resistance. *Cancer Res.*, **58**: 5337-5339 (1998).
4) Allen, J. D., Brinkhuis, R. F., Wijnholds, J. and Schinkel, A. H.: The mouse Bcrp1/Mxr/Abcp gene: amplification and overexpression in cell lines selected for resistance to topotecan, mitoxantrone, or doxorubicin. *Cancer Res.*, **59**: 4237-4241 (1999).
5) Kage, K., Tsukahara, S., Sugiyama, T., Asada, S., Ishikawa, E., Tsuruo, T. and Sugimoto, Y.: Dominant-negative inhibition of breast cancer resistance protein as drug efflux pump through the inhibition of S-S dependent homodimerization. *Int. J. Cancer*, **97**: 626-630 (2002).
6) Xu, J., Liu, Y., Yang, Y., Bates, S. and Zhang, J. T.: Characterization of oligomeric human half-ABC transporter ATP-binding cassette G2. *J. Biol. Chem.*, **279**: 19781-19789 (2004).
7) Maliepaard, M., Scheffer, G. L., Faneyte, I. F., van Gastelen, M. A., Pijnenborg, A. C., Schinkel, A. H., van De Vijver, M. J., Scheper, R. J. and Schellens, J. H.: Subcellular localization and distribution of the breast cancer resistance protein transporter in normal human tissues. *Cancer Res.*, **61**: 3458-3464 (2001).
8) Maliepaard, M., van Gastelen, M. A., de Jong, L. A., Pluim, D., van Waardenburg, R. C., Ruevekamp-Helmers, M. C., Floot, B. G. and Schellens, J. H.: Overexpression of the BCRP/MXR/ABCP gene in a topotecan-selected ovarian tumor cell line. *Cancer Res.*, **59**: 4559-4563 (1999).
9) Kawabata, S., Oka, M., Shiozawa, K., Tsukamoto, K., Nakatomi, K., Soda, H., Fukuda, M., Ikegami, Y., Sugahara, K., Yamada, Y., Kamihira, S., Doyle, L. A., Ross, D. D. and Kohno, S.: Breast cancer resistance protein directly confers SN-38 resistance of lung cancer cells. *Biochem. Biophys. Res. Commun.*, **280**: 1216-1223 (2001).
10) Nakatomi, K., Yoshikawa, M., Oka, M., Ikegami, Y., Hayasaka, S., Sano, K., Shiozawa, K., Kawabata, S., Soda, H., Ishikawa, T., Tanabe, S. and Kohno, S.: Transport of 7-ethyl-10-hydroxycamptothecin (SN-38) by breast cancer resistance protein ABCG2 in human lung cancer cells. *Biochem. Biophys. Res. Commun.*, **288**: 827-832 (2001).
11) Jonker, J. W., Smit, J. W., Brinkhuis, R. F., Maliepaard, M., Beijnen, J. H., Schellens, J. H. and Schinkel, A. H.: Role of breast cancer resistance protein in the bioavailability and fetal penetration of topotecan. *J. Natl. Cancer Inst.*, **92**: 1651-1656 (2000).
12) Kruijtzer, C. M., Beijnen, J. H., Rosing, H., ten Bokkel Huinink, W. W., Schot, M., Jewell, R. C., Paul, E. M. and Schellens, J. H.: Increased oral bioavailability of topotecan in combination with the breast cancer resistance protein and P-glycoprotein inhibitor GF120918. *J. Clin. Oncol.*, **20**: 2943-2950 (2002).
13) Honjo, Y., Hrycyna, C. A., Yan, Q. W., Medina-Perez, W. Y., Robey, R. W., van de Laar, A., Litman, T., Dean, M. and Bates, S. E.: Acquired mutations in the MXR/BCRP/ABCP gene alter substrate specificity in MXR/BCRP/ABCP-overexpressing cells. *Cancer Res.*, **61**: 6635-6639 (2001).
14) Honjo, Y., Morisaki, K., Huff, L. M., Robey, R. W., Hung, J., Dean, M. and Bates, S. E.: Single-nucleotide polymorphism (SNP) analysis in the ABC half-transporter ABCG2 (MXR/BCRP/ABCP1). *Cancer Biol. Ther.*, **1**: 696-702 (2002).
15) Iida, A., Saito, S., Sekine, A., Mishima, C., Kitamura, Y., Kondo, K., Harigae, S., Osawa, S. and Nakamura, Y.: Catalog of 605 single-nucleotide polymorphisms (SNPs) among 13 genes encoding human ATP-binding

cassette transporters: ABCA4, ABCA7, ABCA8, ABCD1, ABCD3, ABCD4, ABCE1, ABCF1, ABCG1, ABCG2, ABCG4, ABCG5, and ABCG8. *J. Hum. Genet.*, **47**: 285-310 (2002).

16) Imai, Y., Nakane, M., Kage, K., Tsukahara, S., Ishikawa, E., Tsuruo, T., Miki, Y. and Sugimoto, Y.: C421A polymorphism in the human breast cancer resistance protein gene is associated with low expression of Q141K protein and low-level drug resistance. *Mol. Cancer Ther.*, **1**: 611-616 (2002).
17) Itoda, M., Saito, Y., Shirao, K., Minami, H., Ohtsu, A., Yoshida, T., Saijo, N., Suzuki, H., Sugiyama, Y., Ozawa, S. and Sawada, J.: Eight novel single nucleotide polymorphisms in ABCG2/BCRP in Japanese cancer patients administered irinotacan. *Drug Metab. Pharmacokinet.*, **18**: 212-217 (2003).
18) Zamber, C. P., Lamba, J. K., Yasuda, K., Farnum, J., Thummel, K., Schuetz, J. D. and Schuetz, E. G.: Natural allelic variants of breast cancer resistance protein (BCRP) and their relationship to BCRP expression in human intestine. *Pharmacogenetics*, **13**: 19-28 (2003).
19) Backstrom, G., Taipalensuu, J., Melhus, H., Brandstrom, H., Svensson, A. C., Artursson, P. and Kindmark, A.: Genetic variation in the ATP-binding cassette transporter gene ABCG2 (BCRP) in a Swedish population. *Eur. J. Pharm. Sci.*, **18**: 359-364 (2003).
20) Wang, H., Hao, B., Zhou, K., Chen, X., Wu, S., Zhou, G., Zhu, Y. and He, F.: Linkage disequilibrium and haplotype architecture for two ABC transporter genes (ABCC1 and ABCG2) in Chinese population: implications for pharmacogenomic association studies. *Ann. Hum. Genet.*, **68**: 563-573 (2004).
21) Bosch, T. M., Kjellberg, L. M., Bouwers, A., Koeleman, B. P., Schellens, J. H., Beijnen, J. H., Smits, P. H. and Meijerman, I.: Detection of single nucleotide polymorphisms in the ABCG2 gene in a Dutch population. *Am. J. Pharmacogenomics*, **5**: 123-131 (2005).
22) Zamboni, W. C., Bowman, L. C., Tan, M., Santana, V. M., Houghton, P. J., Meyer, W. H., Pratt, C. B., Heideman, R. L., Gajjar, A. J., Pappo, A. S. and Stewart, C. F.: Interpatient variability in bioavailability of the intravenous formulation of topotecan given orally to children with recurrent solid tumors. *Cancer Chemother Pharmacol.*, **43**: 454-460 (1999).
23) Kobayashi, D., Ieiri, I., Hirota, T., Takane, H., Maegawa, S., Kigawa, J., Suzuki, H., Nanba, E., Oshimura, M., Terakawa, N., Otsubo, K., Mine, K. and Sugiyama, Y.: Functional assessment of ABCG2 (BCRP) gene polymorphisms to protein expression in human placenta. *Drug Metab. Dispos.*, **33**: 94-101 (2005).
24) Kondo, C., Suzuki, H., Itoda, M., Ozawa, S., Sawada, J., Kobayashi, D., Ieiri, I., Mine, K., Ohtsubo, K. and Sugiyama, Y.: Functional analysis of SNPs variants of BCRP/ABCG2. *Pharm. Res.*, **21**: 1895-1903 (2004).
25) Mizuarai, S., Aozasa, N. and Kotani, H.: Single nucleotide polymorphisms result in impaired membrane localization and reduced ATPase activity in multidrug transporter ABCG2. *Int. J. Cancer.*, **109**: 238-246 (2004).
26) Morisaki, K., Robey, R. W., Ozvegy-Laczka, C., Honjo, Y., Polgar, O., Steadman, K., Sarkadi, B. and Bates, S. E.: Single nucleotide polymorphisms modify the transporter activity of ABCG2. *Cancer Chemother. Pharmacol.*, **56**: 161-172 (2005).
27) de Jong, F. A., Marsh, S., Mathijssen, R. H., King, C., Verweij, J., Sparreboom, A. and McLeod, H. L.: ABCG2 pharmacogenetics: ethnic differences in allele frequency and assessment of influence on irinotecan disposition. *Clin. Cancer Res.*, **10**: 5889-5894 (2004).
28) Sparreboom, A., Gelderblom, H., Marsh, S., Ahluwalia, R., Obach, R., Principe, P., Twelves, C., Verweij, J. and McLeod, H. L.: Diflomotecan pharmacokinetics in relation to ABCG2 421C>A genotype. *Clin. Pharmacol. Ther.*, **76**: 38-44 (2004).
29) Kitamura, Y., Moriguchi, M., Kaneko, H., Morisaki, H., Morisaki, T., Toyama, K. and Kamatani, N.: Determination of probability distribution of diplotype configuration (diplotype distribution) for each subject from genotypic data using the EM algorithm. *Ann. Hum. Genet.*, **66**: 183-193 (2002).
30) Bailey-Dell, K. J., Hassel, B., Doyle, L. A. and Ross, D. D.: Promoter characterization and genomic organization of the human breast cancer resistance protein (ATP-binding cassette transporter G2) gene. *Biochim. Biophys. Acta.*, **1520**: 234-241 (2001).
31) Zhou, Q., Sparreboom, A., Tan, E. H., Cheung, Y. B., Lee, A., Poon, D., Lee, E. J. and Chowbay, B.: Pharmacogenetic profiling across the irinotecan pathway in Asian patients with cancer. *Br. J. Clin. Pharmacol.*, **59**: 415-424 (2005).
32) Wang, N., Akey, J. M., Zhang, K., Chakraborty, R. and Jin, L.: Distribution of recombination crossovers and the origin of haplotype blocks: the interplay of population history, recombination, and mutation. *Am. J. Hum. Genet.*, **71**: 1227-1234 (2002).
33) Gabriel, S. B., Schaffner, S. F., Nguyen, H., Moore, J. M., Roy, J., Blumenstiel, B., Higgins, J., DeFelice, M., Lochner, A., Faggart, M., Liu-Cordero, S. N., Rotimi, C., Adeyemo, A., Cooper, R., Ward, R., Lander, E. S., Daly, M. J. and Altshuler, D.: The structure of haplotype blocks in the human genome. *Science*, **296**: 2225-2259 (2002).
34) Miwa, M., Tsukahara, S., Ishikawa, E., Asada, S., Imai, Y. and Sugimoto, Y.: Single amino acid substitutions in the transmembrane domains of breast cancer resistance protein (BCRP) alter cross resistance patterns in transfectants. *Int. J. Cancer*, **107**: 757-763 (2003).
35) Zhang, K., Calabrese, P., Nordborg, M. and Sun, F.: Haplotype block structure and its applications to association studies: power and study designs. *Am. J. Hum. Genet.*, **71**: 1386-1394 (2002).

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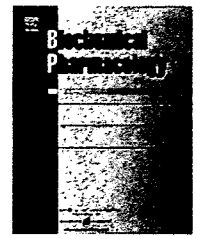

Oxidative metabolism of 5-methoxy-N, N-diisopropyltryptamine (Foxy) by human liver microsomes and recombinant cytochrome P450 enzymes

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ABSTRACT

In vitro quantitative studies of the oxidative metabolism of (5-methoxy-*N*,*N*-diisopropyltryptamine, 5-MeO-DIPT, Foxy) were performed using human liver microsomal fractions and recombinant CYP enzymes and synthetic 5-MeO-DIPT metabolites. 5-MeO-DIPT was mainly oxidized to O-demethylated (5-OH-DIPT) and *N*-deisopropylated (5-MeO-IPT) metabolites in pooled human liver microsomes. In kinetic studies, 5-MeO-DIPT O-demethylation showed monophasic kinetics, whereas its *N*-deisopropylation showed triphasic kinetics. Among six recombinant CYP enzymes (CYP1A2, CYP2C8, CYP2C9, CYP2C19, CYP2D6 and CYP3A4) expressed in yeast or insect cells, only CYP2D6 exhibited 5-MeO-DIPT O-demethylase activity, while CYP1A2, CYP2C8, CYP2C9, CYP2C19 and CYP3A4 showed 5-MeO-DIPT *N*-deisopropylase activities. The apparent K_m value of CYP2D6 was close to that for 5-MeO-DIPT O-demethylation, and the K_m values of other CYP enzymes were similar to those of the low-K_m (CYP2C19), intermediate-K_m (CYP1A2, CYP2C8 and CYP3A4) and high-K_m phases (CYP2C9), respectively, for *N*-deisopropylation in human liver microsomes. In inhibition studies, quinidine (1 μM), an inhibitor of CYP2D6, almost completely inhibited human liver microsomal 5-MeO-DIPT O-demethylation at a substrate concentration of 10 μM.

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Abbreviations:
CYP, cytochrome P450
OR, NADPH-cytochrome P450 reductase
5-MeO-DIPT, 5-methoxy-*N*,*N*-diisopropyltryptamine
5-MeO-IPT, 5-methoxy-*N*-ispropyltryptamine
5-OH-DIPT, 5-hydroxy-*N*,*N*-diisopropyltryptamine
G-6-P, glucose 6-phosphate
HPLC, high-performance liquid chromatography
LC/MS, liquid chromatography–mass spectrometry
PCR, polymerase chain reaction

Furafylline, a CYP1A2 inhibitor, quercetin, a CYP2C8 inhibitor, sulfaphenazole, a CYP2C9 inhibitor and ketoconazole, a CYP3A4 inihibitor (5 μM each) suppressed about 60%, 45%, 15% and 40%, respectively, of 5-MeO-DIPT *N*-deisopropylation at 50 μM substrate. In contrast, omeprazole (10 μM), a CYP2C19 inhibitor, suppressed only 10% of *N*-deisopropylation by human liver microsomes, whereas at the same concentration the inhibitor suppressed the reaction by recombinant CYP2C19 almost completely. These results indicate that CYP2D6 is the major 5-MeO-DIPT O-demethylase, and CYP1A2, CYP2C8 and CYP3A4 are the major 5-MeO-DIPT *N*-deisopropylase enzymes in the human liver.

1. Introduction

Various kinds natural and synthetic hallucinogenic indolethylamines have been produced and abused worldwide, including in Japan [1,2]. Among the many hallucinogenic indolethylamines, the following five compounds are legally controlled in Japan: *N*,*N*-dimethyltryptamine, *N*,*N*-diethyltryptamine, α-ethyltryptamine, psilocine and psilocybin [2]. In addition, α-methyltryptamine and 5-methoxy-*N*,*N*-diisopropyltryptamine (5-MeO-DIPT, Foxy) have newly come under legal control as of 2005.

5-MeO-DIPT is one of the designer drugs, and its properties such as pharmacological activities and toxicities have not been fully elucidated [3]. 5-MeO-DIPT is taken orally because it is resistant to the degradation by monoamine oxidase [3]. It is thought that 5-MeO-DIPT undergoes oxidative metabolism in the liver after oral intake. In fact, there are two case reports in which several oxidative metabolites were detected in human serum and urine samples [4,5] using gas chromatography–mass spectrometry (GC–MS) techniques. However, most of the oxidative metabolites of 5-MeO-DIPT were only speculated to be produced on the basis of fragment ions in the GC–MS analysis.

There have thus far been no quantitative reports describing detailed in vitro studies on the oxidative metabolism of 5-MeO-DIPT. In the present study, we therefore investigated the in vitro oxidative metabolism of 5-MeO-DIPT using human liver microsomal fractions and recombinant cytochrome P450 enzymes as enzyme sources, and synthetic metabolites of 5-MeO-DIPT as standards for analysis.

2. Materials and methods

2.1. Materials

5-MeO-DIPT was supplied by Dr. M. Funada, National Institute of Mental Health, National Center of Neurology and Psychiatry (Kodaira, Japan). Because this compound showed the purity of above 99% in ^{1}H NMR and HPLC, it was used without further purification. 5-Hydroxy-*N*,*N*-diisopropyltryptamine (5-OH-DIPT) and 5-methoxy-*N*-isopropyltryptamine (5-MeO-IPT) were synthesized as described below. Furafylline, quercetin, sulfaphenazole, omeprazole and quinidine were purchased from Sigma–Aldrich (St. Louis, MO); glucose 6-phosphate (G-6-P) and NADPH were from Oriental Yeast Co. (Tokyo, Japan). Ketoconazole was supplied by Dr. Y. Yoshida, School of Pharmaceutical Sciences, Mukogawa Women's University. Pooled human liver microsomal fractions were obtained from BD Biosciences Discovery Labware (Bedford, MA). Recombinant CYP2D6 [6] was expressed in yeast cells according to the published methods. Recombinant CYP1A2, CYP2C8, CYP2C9, CYP2C19 and CYP3A4 were expressed in yeast cells as described below. Insect cell microsomal fractions (Supersomes) expressing CYP3A4, cytochrome b_5 and NADPH-cytochrome P450 reductase (OR), and expressing CYP3A4 and OR (without cytochrome b_5) were purchased from Gentest (Woburn, MA).

2.2. Chemical synthesis of 5-OH-DIPT and 5-MeO-IPT

To a solution of 5-MeO-DIPT (50 mg, 0.18 mmol) in CH_2Cl_2 (2.0 ml), 1.0 M BBr_3 in CH_2Cl_2 (0.92 ml, 0.92 mmol) was added at −12 °C and the whole was stirred at −12 °C for 3 h. After cooling the reaction mixture with an ice bath, 30% aq. NaOH was added to pH 9–10 and the whole was extracted with a mixture of $CHCl_3$ and MeOH (9:1, 1 × 10 ml, 3 × 5 ml). The combined organic layer was washed with brine (10 ml) and was dried over Na_2SO_4. The solvent was evaporated in vacuo and the residue was purified by column chromatography (NH silica, $CHCl_3$:MeOH:Et_3N = 20:1:0.1) to give pale yellow crystals (21 mg, 44%); m.p. 81–83 °C; IR (ATR, cm^{-1}) 3330; ^{1}H NMR (400 MHz, $CDCl_3$) δ (ppm): 1.12 (total 12H, d, *J* = 6.3 Hz, 4 × CH_3), 2.76, 2.84 (each 2H, m, 2 × CH_2), 3.17 (total 2H, m, 2 × CH), 6.77 (1H, dd, *J* = 8.8, 2.4 Hz, H-6), 7.01 (1H, d, *J* = 2.2 Hz, H-4), 7.03 (1H, d, *J* = 2.2 Hz, H-2), 7.21 (1H, d, *J* = 8.8 Hz, H-7), 7.83 (1H, s, NH, exchangeable with D_2O); ^{13}C NMR (125 MHz, $CDCl_3$) δ (ppm): 20.3, 27.5, 47.0, 49.7, 50.6, 103.2, 111.8, 112.0, 122.3, 128.2, 131.3, 150.1; HRFABMS found: 261.1982 (calculated for $C_{16}H_{25}N_2O$:261.1967). These analytical data supported the conclusion that the synthesized compound was 3-(2-diisopropylaminoethyl)-1H-indol-5-ol (5-hydroxy-*N*,*N*-diisopropyltryptamine, 5-OH-DIPT) (Fig. 1).

To a solution of 5-methoxytryptamine (93 mg, 0.49 mmol) in MeOH (1.0 ml), 36% HCl (0.13 ml, 1.31 mmol), acetone