The in vitro inhibitory effects of gemfibrozil on cytochrome P450 (CYP) 1A2 (phenacetin O-deethylation), CYP2A6 (coumarin 7-hydroxylation), CYP2C9 (tolbutamide hydroxylation), CYP2C19 (S-mephenytoin 4'-hydroxylation), CYP2D6 (dextromethorphan O-deethylation), CYP2E1 (chlorozoxazone 6-hydroxylation), and CYP3A4 (midazolam 1'-hydroxylation) activities were examined using pooled human liver microsomes. The in vivo drug interactions of gemfibrozil were predicted in vitro using the [I]/([I] + K) values. Gemfibrozil strongly and competitively inhibited CYP2C9 activity, with a K<sub>i</sub> (IC<sub>50</sub>) value of 5.8 (9.6) μM. In addition, gemfibrozil exhibited somewhat smaller inhibitory effects on CYP2C19 and CYP1A2 activities, with K<sub>i</sub> (IC<sub>50</sub>) values of 24 (47) μM and 82 (136) μM, respectively. With concentrations up to 250 μM, gemfibrozil showed no appreciable effect on CYP2A6, CYP2D6, CYP2E1, and CYP3A4 activities. Based on [I]/([I] + K) values calculated using peak total (or unbound) plasma concentration of gemfibrozil, 96% (56%), 86% (24%), and 64% (8%) inhibition of the clearance of CYP2C9, CYP2C19, and CYP1A2 substrates could be expected, respectively. In conclusion, gemfibrozil inhibits the activity of CYP2C9 at clinically relevant concentrations, and this is the likely mechanism by which gemfibrozil interacts with CYP2C9 substrate drugs, such as warfarin and glyburide. Gemfibrozil may also impair clearance of CYP2C19 and CYP1A2 substrates, but inhibition of other CYP isoforms is unlikely.

Materials. Gemfibrozil, dextromethorphan, and dextropropoxyphene were obtained from Orion Pharma (Espoo, Finland). Phenacetin, paracetamol, coumarin, 7-hydroxycoumarin, tolbutamide, chloroxazone, and NADPH were purchased from Sigma (St. Louis, MO). Hydroxytolbutamide, 6-hydroxychloroxazone, S-mephenytoin, and 4'-hydroxymephenytoin were purchased from Ultrafine (ASD, U.K.). Hydroxytolbutamide, 6-hydroxychloroxazone, S-mephenytoin, and 4'-hydroxymephenytoin were purchased from Ultrafine (ASD, U.K.). Hydroxytolbutamide, 6-hydroxychloroxazone, S-mephenytoin, and 4'-hydroxymephenytoin were purchased from Ultrafine (ASD, U.K.). Hydroxytolbutamide, 6-hydroxychloroxazone, S-mephenytoin, and 4'-hydroxymephenytoin were purchased from Ultrafine (ASD, U.K.). Hydroxytolbutamide, 6-hydroxychloroxazone, S-mephenytoin, and 4'-hydroxymephenytoin were purchased from Ultrafine (ASD, U.K.). Hydroxytolbutamide, 6-hydroxychloroxazone, S-mephenytoin, and 4'-hydroxymephenytoin were purchased from Ultrafine (ASD, U.K.). Hydroxytolbutamide, 6-hydroxychloroxazone, S-mephenytoin, and 4'-hydroxymephenytoin were purchased from Ultrafine (ASD, U.K.). Hydroxytolbutamide, 6-hydroxychloroxazone, S-mephenytoin, and 4'-hydroxymephenytoin were purchased from Ultrafine (ASD, U.K.). Hydroxytolbutamide, 6-hydroxychloroxazone, S-mephenytoin, and 4'-hydroxymephenytoin were purchased from Ultrafine (ASD, U.K.). Hydroxytolbutamide, 6-hydroxychloroxazone, S-mephenytoin, and 4'-hydroxymephenytoin were purchased from Ultrafine (ASD, U.K.). Hydroxytolbutamide, 6-hydroxychloroxazone, S-mephenytoin, and 4'-hydroxymephenytoin were purchased from Ultrafine (ASD, U.K.). Hydroxytolbutamide, 6-hydroxychloroxazone, S-mephenytoin, and 4'-hydroxymephenytoin were purchased from Ultrafine (ASD, U.K.). Hydroxytolbutamide, 6-hydroxychloroxazone, S-mephenytoin, and 4'-hydroxymephenytoin were purchased from Ultrafine (ASD, U.K.). Hydroxytolbutamide, 6-hydroxychloroxazone, S-mephenytoin, and 4'-hydroxymephenytoin were purchased from Ultrafine (ASD, U.K.). Hydroxytolbutamide, 6-hydroxychloroxazone, S-mephenytoin, and 4'-hydroxymephenytoin were purchased from Ultrafine (ASD, U.K.). Hydroxytolbutamide, 6-hydroxychloroxazone, S-mephenytoin, and 4'-hydroxymephenytoin were purchased from Ultrafine (ASD, U.K.). Hydroxytolbutamide, 6-hydroxychloroxazone, S-mephenytoin, and 4'-hydroxymephenytoin were purchased from Ultrafine (ASD, U.K.). Hydroxytolbutamide, 6-hydroxychloroxazone, S-mephenytoin, and 4'-hydroxymephenytoin were purchased from Ultrafine (ASD, U.K.). Hydroxytolbutamide, 6-hydroxychloroxazone, S-mephenytoin, and 4'-hydroxymephenytoin were purchased from Ultrafine (ASD, U.K.). Hydroxytolbutamide, 6-hydroxychloroxazone, S-mephenytoin, and 4'-hydroxymephenytoin were purchased from Ultrafine (ASD, U.K.).

Inhibition Studies. The effects of gemfibrozil on seven different CYP isoform-specific marker reactions were studied: phenacetin O-deethylation for CYP1A2, coumarin 7-hydroxylation for CYP2A6, tolbutamide hydroxylation for CYP2C9, S-mephenytoin 4'-hydroxylation for CYP2C19, dextromethorphan O-deethylation for CYP2D6, chloroxazone 6-hydroxylation for CYP2E1, and midazolam 1'-hydroxylation for CYP3A4. The incubation conditions used to study the metabolism of the various substrates and the effects of specific inhibitors have been reported elsewhere (Wen et al., 2001). The time of incubation and concentration of microsomal protein (100 μg/ml) used in each assay were determined to be in the linear range for the rate of metabolite formation.

All incubations were performed in duplicate, and the mean values were used. Briefly, gemfibrozil was dissolved in acetonitrile. After evaporation of acetonitrile to dryness, gemfibrozil was reconstituted in an incubation medium (final concentrations, 0–250 μM) containing 0.1 M sodium phosphate buffer, pH 7.4, 5 mM MgCl<sub>2</sub>, and 1.0 mM NADPH. The reaction was started by the addition of the marker substrate either without or after preincubation of the sample at 37°C for 15 min. After a specific period of time, the reactions were terminated by adding the appropriate chemicals to precipitate the proteins (Wen et al., 2001). After centrifugation at 10,000g for 5 min, an aliquot of the supernatant was subjected to analysis of the metabolites by high-performance liquid chromatography, as described previously (Wen et al., 2001). The intra- and interday coefficients of variation were <7% at relevant concentrations (n = 6).

Data Analysis. The IC<sub>50</sub> values were determined graphically. The apparent inhibitory constant (K<sub>i</sub>) values were calculated by nonlinear regression analysis by fitting different models of enzyme inhibition to the kinetic data using SYSTAT for Windows 6.0.1 (SPSS, Inc., Chicago, IL).

Results and Discussion

Gemfibrozil strongly inhibited CYP2C9-catalyzed tolbutamide hydroxylation (Fig. 1A). The double reciprocal plots, Dixon plots, and
A, effects of gemfibrozil (0–250 μM) on CYP1A2-catalyzed phenacetin O-deethylation (●), CYP2A6-catalyzed coumarin 7-hydroxylation (○), CYP2C9-catalyzed tolbutamide hydroxylation (■), CYP2C19-catalyzed S-mephenytoin 4′-hydroxylation (▲), CYP2D6-catalyzed dextromethorphan O-demethylation (▲), CYP2E1-catalyzed chlorozoxazone 6-hydroxylation (△), and CYP3A4-catalyzed midazolam 1′-hydroxylation (◇). When 50 μM phenacetin, 1 μM coumarin, 50 μM tolbutamide, 40 μM S-mephenytoin, 1.5 μM dextromethorphan, 25 μM chlorozoxazone, and 2 μM midazolam were used as substrates in the absence of inhibitor; the corresponding metabolic activities were 722, 701, 104, 100, 90, 104, 294, and 1464 pmol/mg/min, respectively. B, a representative Dixon plot obtained from a 60-min incubation with 25 (■), 50 (●), 100 (◇), and 250 μM (○) of tolbutamide (CYP2C9 marker) in the absence or presence of gemfibrozil (2.5–25 μM). C, a double reciprocal plot obtained from a 60-min incubation of human liver microsomes with NADPH and tolbutamide (25–250 μM) in the absence (▲) or presence of 2.5 (△), 5 (◇), 10 (○) or 25 μM (●) gemfibrozil. D, a secondary plot of slopes taken from double reciprocal plots versus gemfibrozil concentration. Each data point represents the average of duplicate determinations.

Gemfibrozil has been reported to enhance the anticoagulant effect of warfarin, resulting in severe hypoprothrombinemia and bleeding (Ahmad, 1990; Rindone and Keng, 1998). The biotransformation of the pharmacologically more active S-enantiomer of warfarin is catalyzed mainly by CYP2C9, whereas the metabolism of R-warfarin is catalyzed by CYP1A2 and CYP3A4 (Yamazaki and Shimada, 1997). Because the binding of warfarin to human serum albumin is not influenced by gemfibrozil (Hamberger et al., 1986), the gemfibrozil-
warfarin interaction can be explained by inhibition of the CYP2C9-mediated metabolism of S-warfarin. Minor inhibition of the CYP1A2-mediated metabolism of R-warfarin by gemfibrozil may also contribute to the interaction. In one case report, gemfibrozil has been reported to interact with glyburide, resulting in hypoglycemia (Ahmad, 1991). Glyburide is extensively metabolized in the liver, with CYP2C9 being the predominant enzyme (Brian, 2000). Our in vitro inhibition studies suggest that inhibition of CYP2C9 activity by gemfibrozil is the likely mechanism of the gemfibrozil-glyburide interaction.

Gemfibrozil can interact with several statins, such as lovastatin (Pierce et al., 1990) and simvastatin (Tal et al., 1997), resulting in an increased incidence of myopathy and rhabdomyolysis. The exact mechanism that underlies these drug interactions is unknown. However, it was found recently that gemfibrozil markedly increases the plasma concentrations of active simvastatin acid and lovastatin acid, whereas the concentrations of parent simvastatin and lovastatin are not altered (Backman et al., 2000; Kyrklund et al., 2001). Parent simvastatin and lovastatin are metabolized mainly by CYP3A4 (Vickers et al., 1990). Because gemfibrozil is not a CYP3A4 inhibitor, the gemfibrozil-simvastatin and gemfibrozil-lovastatin interactions cannot be explained by inhibition of the CYP3A4-mediated simvastatin and lovastatin metabolism, as is the case with itraconazole-lovastatin and itraconazole-simvastatin interactions. The present finding that gemfibrozil strongly inhibits the activity of CYP2C9 and, to a lesser extent, that of CYP2C19 and CYP1A2 raises the possibility that some of these CYP isofoms might be involved in the metabolism of simvastatin and lovastatin acid. However, inhibition of some other pathways that regulate the levels of the statin acids by gemfibrozil cannot be ruled out.

To conclude, the present in vitro study demonstrates that gemfibrozil in clinically relevant concentrations is a potent inhibitor of CYP2C9 and a modest inhibitor of CYP2C19 and CYP1A2. However, the activity of CYP2A6, CYP2D6, CYP2E1, and CYP3A4 is not affected by gemfibrozil. Inhibition of CYP2C9 seems to explain the observed interactions of gemfibrozil with warfarin and glyburide. Also, because other substrates of CYP2C9 with a narrow therapeutic range may be affected by gemfibrozil, care is warranted in the use of such drug combinations.

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References


TABLE 1
The constants and types of inhibition of gemfibrozil for human P450 isoform activities and the predicted in vivo inhibition of the metabolism of coadministered CYP2C9, CYP2C19, and CYP1A2 substrates by gemfibrozil from in vitro data

<table>
<thead>
<tr>
<th></th>
<th>P450 [K_{i}(\mu M), type of inhibition]</th>
<th>C_{max}</th>
<th>C_{mean}</th>
<th>C_{max,lu}</th>
<th>C_{mean,lu}</th>
</tr>
</thead>
<tbody>
<tr>
<td>[I] (\mu M)</td>
<td>(151 ± 39)</td>
<td>(18 ± 39)</td>
<td>(6 ± 13)</td>
<td>(0.9 ± 4.7)</td>
<td></td>
</tr>
<tr>
<td>[I]/(I + K_{i}) (%)</td>
<td>CYP2C9</td>
<td>(96 ± 1)</td>
<td>(85 ± 5)</td>
<td>(56 ± 5)</td>
<td>(24 ± 9)</td>
</tr>
<tr>
<td></td>
<td>(5.8, competitive)</td>
<td>(95 ± 98)</td>
<td>(76 ± 94)</td>
<td>(52 ± 68)</td>
<td>(14 ± 45)</td>
</tr>
<tr>
<td></td>
<td>CYP2C19</td>
<td>(86 ± 2)</td>
<td>(58 ± 11)</td>
<td>(24 ± 4)</td>
<td>7 ± 4</td>
</tr>
<tr>
<td></td>
<td>[2, mixed (a = 7.3)]</td>
<td>(83 ± 91)</td>
<td>(43 ± 80)</td>
<td>(21 ± 34)</td>
<td>(4 ± 16)</td>
</tr>
<tr>
<td></td>
<td>CYP1A2</td>
<td>(64 ± 5)</td>
<td>(30 ± 10)</td>
<td>(8 ± 2)</td>
<td>2 ± 1</td>
</tr>
<tr>
<td></td>
<td>[82, mixed (a = 7.3)]</td>
<td>(59 ± 75)</td>
<td>(18 ± 53)</td>
<td>(7 ± 13)</td>
<td>(1 ± 5)</td>
</tr>
</tbody>
</table>

*Values (mean of duplicate determinations) are derived from nonlinear regression analysis based on coinucubation of the respective CYP specific substrates with various concentrations of gemfibrozil without preincubation at 37°C (see Experimental Procedures for details). IC_{50} values were not calculated for CYP2A6, CYP2D6, CYP2E1, and CYP3A4, because the IC_{50} values were >250 \mu M.

a is the factor by which K_{i} changes when inhibitor occupies the enzyme site.