Determination of Human Hepatocyte Intrinsic Clearance for Slowly Metabolized Compounds: Comparison of a Primary Hepatocyte/Stromal Cell Co-culture with Plated Primary Hepatocytes and HepaRG®

Britta Bonn, Petter Svanberg, Annika Janefeldt, la Hultman, and Ken Grime

RI A IMED DMPK (B.B., P.S., K.G.), CVMD IMED DMPK (A.J.), Drug Safety and Metabolism (I.H.), AstraZeneca R&D, Gothenburg, Sweden

Received October 10, 2015; accepted February 4, 2016

ABSTRACT

A key requirement in drug discovery is to accurately define intrinsic clearance (CLint) values of less than 1 μl/min/10⁶ hepatocytes, which requires assays that allow for longer incubation time as a complement to suspended hepatocytes. This study assessed the effectiveness of plated HepaRG cells, plated primary human hepatocytes (PHHs), and the H₂REL human hepatocyte/stromal cell co-cultures for determination of low CLint values. The investigation demonstrated that the systems were capable of providing statistically significant CLint estimations down to 0.2 μl/min/10⁶ cells. The H₂REL assay provided a higher level of reproducibility, with repeat significant CLint values being defined in a minimum of triplicate consecutive assays for six of seven of the low CLint compounds compared with four of seven for PHHs and two of seven for HepaRG. The assays were also compared with a suspension assay using drugs with higher CLint values and diverse enzymology. The CLint values from the PHH and H₂REL assays were similar to those defined by a hepatocyte suspension assay, indicating that they can be used interchangeably alongside a standard assay. Finally, data from these two assays could also predict in vivo hepatic metabolic CLint to within 3-fold for greater than 70% of the compounds tested, with average fold errors (AFE) of 1.6 and 2.3, respectively, whereas the HepaRG data were predictive to within 3-fold for only 50% of compounds (AFE 2.9). In summary, all systems have utility for low CLint determination, but the H₂REL co-culture appears slightly superior regarding overall assay performance.

Introduction

A crucial task for drug metabolism and pharmacokinetics (DMPK) scientists in drug discovery is to predict human pharmacokinetics (PK) and to design drug candidates with PK properties commensurate with effective and safe therapeutic treatment. In this context, clearance (CL) is a critical parameter. Particularly when distribution volume is low, CL is consequently required to be low for an effective half-life with a minimum Cmax/Cmin ratio.

Hepatic metabolism is responsible for the clearance of approximately 70% of marketed drugs (Wienkers and Heath, 2005). Human metabolic CL is commonly predicted using in vitro hepatocyte or hepatic microsomal intrinsic clearance (CLint) data (Houston, 1994; Laine, 2008; Obach, 2011), with primary hepatocytes accepted as the most appropriate in vitro system (Soars et al., 2007; Di et al., 2013). Determination of CLint can be performed using either metabolite formation or depletion of parent, but since knowledge of primary metabolites is seldom available in screening phases of drug discovery, the substrate depletion method is more or less exclusively used for this purpose (Obach and Reed-Hagen, 2002; Jones and Houston, 2004).

Despite the improvement in clearance predictions based on analyses of large data sets (Riley et al., 2005; Grime and Riley, 2006; Obach, 2011; Sohlenius-Sternbeck et al., 2012), a remaining difficulty is the ability to accurately define CLint for slowly metabolized compounds. To obtain a meaningful result, the metabolism of the compound over the incubation period must be significantly greater than the variability in procedures used to determine CLint. Sustained primary hepatocytes suffer from rapid loss of drug-metabolizing enzyme activity (Smith et al., 2012), which limits the incubation time and makes this system inappropriate for low CLint determinations for low turnover compounds. For moderate to low volume of distribution compounds, CLint may typically be less than 1 μl/min/10⁶ cells (Grime et al., 2013). Such a CLint relates to only a 2-fold change in drug concentration in the in vitro incubation over 12 hours in an assay format using one million cells/ml. The absence of a robust assay denies the DMPK scientist the ability to discriminate between compounds of interest in the drug discovery and of course signifies a lack of accuracy in predictions of in vivo hepatic metabolic CL.

Despite these difficulties, recent studies have demonstrated that, with care, progress can be made using hepatocyte suspension incubations. The Relay method in which supernatants from hepatocyte suspension incubations are repeatedly transferred to fresh cells, enables continual metabolism of parent compound by fresh metabolic enzymes for times exceeding 4 hours (Di et al., 2012, 2013). Nonetheless, the technical

ABBREVIATIONS: AFE, average fold error; AZ02, 4-amino-N-[[1S]-1-cyano-2-[[4-[4-cyanophenyl]phenoxy]ethyl]tetrahydropropyran-4-carboxamide; AZ02, N-[2-[[2,3-difluorophenyl]methylsulfanyl]]-6-[[1R,2R]-2,3-dihydroxy-1-methyl-propyl]amino]pyrimidin-4-yl]azetidine-1-sulfonamide; CYP, cytochrome P450; DMPK, drug metabolism and pharmacokinetics; DMSO, dimethyl sulfoxide; fu, fraction of drug unbound in blood; fuinc, fraction of drug unbound in vitro incubation; LC-MS/MS, liquid chromatography-tandem mass spectroscopy; PHH, plated primary human hepatocytes; PK, pharmacokinetics.
manipulation issues can make even this assay challenging, and since the method represents a mathematical approach to integrate several separate 4-hour incubations into one algorithm, there is a potential issue with error propagation and statistical significance of the defined CLint. Beyond two-dimensional cultures of primary or immortalized hepatocytes, three-dimensional and co-cultures are becoming readily available (Godoy et al., 2013). Examples include HepatoPac (Chan et al., 2013), hepatocyte spheroids (Ohkura et al., 2014), and H2REL (Novik et al., 2010), all of which have been shown to maintain liver-specific functions for several days. A recent article has reviewed the available literature on different CLint assays, with particular emphasis on slowly metabolized compounds and advantages or disadvantages with regard to prediction of human hepatic CL (Hutzler et al., 2015). The review highlighted the fact that although several assay options are emerging around the low CLint issue, data supporting definitive evaluation are still sparse. Evident from the analysis compiled by Hutzler and colleagues is that there is requirement for greater knowledge on the functionality of multidonor pools of plated primary human hepatocytes (PHHs) and the need for comparisons of the same hepatocyte batch in different in vitro systems.

In this work, we appraised three different assay formats regarding the ability to determine CLint values to 1 μL/min/10⁷ hepatocytes and below and for accuracy of human in vivo CL prediction. The assay formats were chosen to facilitate longer incubation times as well as having a reasonable throughput appropriate for early drug discovery. The three assays evaluated were a five-donor pool of PHH plated on type I collagen, the same hepatocyte pool in the H2REL co-culture of primary hepatocytes/stromal cells, and finally plated HepaRG cells, a human hepatoma cell line that can be differentiated toward hepatocyte-like cells showing stable phenotype (Animat et al., 2006; Kanebratt and Andersson, 2008). These three assays serve as potential tools for drug discovery to determine CLint and to more accurately predict human hepatic CL for low turnover compounds.

### Materials and Methods

#### Chemicals and Materials

Cryopreserved HepaRG cells (lot 2279582 and 2207183) plus additives for cell culture medium (HepaRG Thawing/Plating Medium, HepaRG Culture Medium and HepaRG Serum Free Induction Medium) were purchased from Millipore (Molsheim, France). For monoculture experiments, a five-donor pool of platable cryopreserved human hepatocytes (lot 1310168, 3 females and 2 males), thawing kit (K2000), resuspension medium (K2200), and culture medium (K2300) were purchased from XenoTech (Kansas City, KS). Co-culture of the five-donor pool (lot 1310168, XenoTech) and nonparenchymal stromal cells (stromal cell type and ratio of hepatocyte per stromal cell are proprietary information) in type I collagen coated 24-well plates were purchased from H2REL (North Brunswick, NJ). A ten-donor pool of cryopreserved human hepatocytes (lot IRK), used for the hepatocyte suspension assay, were obtained from Celsis In Vitro Technologies (Brussels, Belgium). Leibovitz’s L-15 medium, without phenol red, with l-glutamine (Gibco 21083-027), was purchased from Invitrogen (Stockholm, Sweden). Trypan blue was purchased from Tebu-bio (Le Perray-en-Yvelines, Cedex, France).

S-warfarin, diazepam, dipyrismidamole, metoprolol, theophylline, sildenafil, carvedilol, imipramine, ketaserin, ketoprofen and 5,5-dietyl-1,3-diphenyl-2-iminobutaric acid (no. 39) were purchased from Sigma-Aldrich (St. Louis, MO). AZ01 (4-amino-N-(1S)-[1]-cyano-2-[4-(cyanopyrrolinophenyl)ethy] tetrahydropryan-4-carboxamide), and AZ02 (N-[2-[2,3-difluorophenyl methylsulfaftanil]-6-[1R,2K]-3,3-dihydroxy-1-methyl-propyl]-aminopyrinoxidin-4 yl]acetamide-1-sulfonamide) were obtained as dimethyl sulfoxide (DMSO) stock solutions from AstraZeneca compound management team (Gothenburg, Sweden). Acetonitrile and methanol were purchased from Rathburn Chemicals Ltd. (Walkerburn, Scotland). All other chemicals were of analytical grade and highest quality available.

#### CLint Validation Set

For validation of the different hepatocyte assay formats and their potential to determine CLint, a set of slowly metabolized compounds was selected (Table 1). In addition, five compounds with intermediate to high CLint values (5-40 μL/min/10⁷ cells) were assayed to validate the novel systems through agreement of the recognized standard system of hepatocyte suspension incubations (Table 1). Chemical structures of the test set are available in supplemental information (Supplemental Fig. 1). All compounds were incubated at 1 μM.

#### Culture of HepaRG Cells

The cryopreserved HepaRG cells were thawed and washed according to protocol from the vendor. The HepaRG cells were thawed in prewarmed (37°C) HepaRG Thawing/Plating Medium, followed by centrifugation at room temperature. The supernatant was removed, and the cell pellet was resuspended in HepaRG Thawing/Plating Medium at room temperature. The amount of cells and the viability were determined by the trypsin blue exclusion method. Aliquots of 100 μL of cell suspension (0.72 million cells/ml) were seeded into each well of flat-bottom 96-well plates, coated with type I collagen and allowed to attach for about 24 hours in incubator at 37°C in humidified atmosphere containing 95% air and 5% CO2. After 24 hours, the cell morphology was checked and the medium was renewed with HepaRG Culture Medium at room temperature. After about 60 hours, the medium was renewed with HepaRG serum free induction medium, and 24 hours later, the cells were ready to be exposed to the test compounds. The test compounds were dissolved and diluted in 50% acetonitrile before addition to serum-free Induction Medium giving final concentrations of solvent in the incubations of less than 1% acetonitrile and 0.005% DMSO. The incubations were initiated by addition of 100 μL of test compound to each well using one well per time point. Plates were kept without shaking in the incubator during the experiments, and eight samples, evenly distributed over 24 hours, were withdrawn during incubation. At termination, 50 μL of medium from each well (one well per time point) was transferred to a 96 deep-well plate and quenched in 150 μL of ice-cold acetonitrile containing 0.8% formic acid and 25–200 nM verapamil and/or no. 39 as the bioanalytical internal standard. Samples were centrifuged at 4°C for 20 minutes at 3202g, after which clear aliquots of supernatant were diluted in equal amounts of water and kept at ~20°C until quantification of parent using liquid chromatography mass spectroscopy (LC-MS/MS). Compounds were incubated in singlicate, and incubations were repeated three times.

#### Monoculture of Primary Human Hepatocytes

The five-donor pools of cryopreserved human hepatocytes (lot 1310168, XenoTech) were thawed and washed according to vendor protocol. Hepatocytes were thawed in DMEM and subsequently washed in isotonic Percoll gradient (material included in thawing kit K2000), after which the amount of cells and viability were determined by the trypsin blue exclusion method. Viability exceeded 80% before seeding of 0.4 million hepatocytes in 300 μL of resuspension medium into each well of type I collagen-coated flat-bottom 24-well plates. Hepatocytes were left to attach for about 4 hours in incubator at 37°C in humidified atmosphere containing 95% air and 5% CO2. Test compound was dissolved in DMSO, acetonitrile, and water and finally diluted to 1 μM in culture medium, giving final concentrations of solvent in incubations of less than 1% acetonitrile and 0.005% DMSO. Compound incubation was initiated by aspiration of resuspension medium, washed with 200 μL of blank culture medium, followed by the addition of 600 μL of culture medium per well containing 1 μM test compound. Plates were kept without shaking in the incubator during the experiments. Depending on the expected depletion rate, 8–18 samples of 10 μL medium, evenly distributed over 12 hours, were withdrawn from each well during incubation. Samples were quenched with 90 μL of ice-cold acetonitrile containing 0.8% formic acid and 25–200 nM verapamil and/or no. 39 as the bioanalytical internal standard. Samples were centrifuged at 4°C for 20 minutes at 3202g, after which clear aliquots of supernatant were diluted in equal amount of water and kept at ~20°C until quantification of parent using LC-MS/MS. Compounds were incubated in singlicate, and incubations where repeated three times.

#### H2REL-Co-cultured Primary Human Hepatocytes and Stromal Cells

Co-culture plates were carefully shipped in maintenance medium, at 37°C, from H2REL (North Brunswick, NJ). Amount of seeded viable hepatocytes was 0.188 million per well. The cells were co-cultured for 6 days before arrival at AstraZeneca R&D Gothenburg, Sweden, where the cells were left to acclimatize in H2REL PlatinumHeps maintenance medium overnight in incubator at 37°C in humidified atmosphere containing 95% air and 5% CO2. Test compound was dissolved in DMSO, acetonitrile, and water and finally diluted to 1 μM in H2REL PlatinumHeps media. Final concentration of solvent in the incubations
was less than 1% acetonitrile and 0.005% DMSO. Compound incubation was initiated by careful aspiration of resuspension media, washed with 200 μl of blank culture media, followed by the addition of 600 μl of culture media containing 1 μM test compound per well. Plates were kept without shaking in the incubator during the experiments. Depending on the expected depletion rate, 12–22 samples of 10 μl of medium evenly distributed over 72 hours, were withdrawn from each well during incubation. Samples were quenched with 90 μl of ice-cold acetonitrile containing 0.8% formic acid and 25–200 nM verapamil and/or no. 39 as bioanalytical volume reference. Samples were centrifuged at 4°C for 20 minutes at 3220g, after which clear aliquots of supernatant were diluted in equal amount of water and kept in a freezer until quantification of parent using LC-MS/MS. Compounds were incubated in singlicates and incubations were repeated four times.

Primary Human Hepatocytes in Suspension. Data from suspended hepatocytes were from historical in-house data generated using a standard automated hepatocyte assay a minimum of three times. The 10-donor pool of cryopreserved human hepatocytes (lot IRK, Celsis) were thawed and washed in Leibovitz’s L-15 medium. The cells were thawed in prewarmed (37°C) medium and subsequently washed in two steps in room temperature medium, after which the amount of cells and viability were determined by the trypsin blue exclusion method. The cell-suspension was diluted to one million cells/ml (viability > 80%) and seeded into round-bottom 96-well plates (247.5 μl/well). The test compounds were dissolved in DMSO and further diluted in 50% acetonitrile, blank culture media, followed by the addition of one test compound/well, giving a final concentration of 1 μM per well. Plates were kept without shaking in the incubator during the experiments. Depending on the expected depletion rate, 10-22 samples of 10 μl of medium evenly distributed over 72 hours, were withdrawn from each well during incubation. Samples were quenched in 45 μl of ice-cold acetonitrile containing 0.8% formic acid and 0.005% DMSO. Compound incubation was performed with agitation at a frequency of 13 Hz. The cells were preincubated for 15 minutes, and the reaction was initiated by the addition of one test compound/well, giving a final concentration of 1 μM and a final incubation volume of 250 μl/well. Ten samples evenly distributed over 120 minutes were withdrawn from each well during incubation. At termination, 15 μl of medium was quenched in 45 μl of ice-cold acetonitrile containing 0.8% formic acid and 100 mM no. 39 as a bioanalytical volume reference. The samples were centrifuged for 30 minutes at 4°C and 3220g. Clear aliquots of supernatant were diluted in equal amount of water and kept at 4°C until quantification of parent using LC-MS/MS. All incubations were performed using a Tecan Freedom Evo 200 robot with integrated plate centrifuge Rotanta 46 RSC (Hettich), plate shaker VarioMag Teleshake 70 with TEC Control 485, Tecan Freedom Evo-2 200.

Bioanalytical. The concentration of test compound and bioanalytical internal standard in all samples was analyzed by high-performance liquid chromatography connected to a triple quadrupole tandem mass spectrometer using electrospray ionization and multiple reaction monitoring. A typical bioanalytical setup was an Agilent ultra-performance liquid chromatography system coupled to a Waters Xevo TQ MS mass spectrometer with an atmospheric pressure electrospray interface (Waters, Zellik, Belgium). Separation was performed on a CSH C18 column (1.7 mm × 2.1 mm × 30 mm, Waters). A gradient composed of

### TABLE 1

<table>
<thead>
<tr>
<th>Ion Class, observed in vivo CLint</th>
<th>MW (g/mol)</th>
<th>LogD7.4</th>
<th>Main Responsible Enzyme</th>
<th>In Vivo CLint (mL/min/kg)</th>
<th>fuinc</th>
<th>fub</th>
<th>Observed In Vivo CLint (mL/min/kg)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Low CLint compounds</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>S-Warfarin</td>
<td>Neutral</td>
<td>308.3</td>
<td>2C9 &gt; 3A4</td>
<td>0.06(^a)</td>
<td>0.018(^a)</td>
<td>0.953</td>
<td>0.06(^a)</td>
</tr>
<tr>
<td>Diazepam</td>
<td>Neutral</td>
<td>284.7</td>
<td>2C9 &gt; 3A4</td>
<td>0.5(^a)</td>
<td>0.036(^a)</td>
<td>0.808</td>
<td>0.5(^a)</td>
</tr>
<tr>
<td>Disopyramide</td>
<td>Base</td>
<td>339.9</td>
<td>3A4</td>
<td>0.9(^a)</td>
<td>0.16(^a)</td>
<td>0.827</td>
<td>0.9(^a)</td>
</tr>
<tr>
<td>Metoprolol</td>
<td>Base</td>
<td>257.4</td>
<td>2D6</td>
<td>13(^a)</td>
<td>0.88(^a)</td>
<td>0.922</td>
<td>1.4(^a)</td>
</tr>
<tr>
<td>Theophylline</td>
<td>Neutral</td>
<td>180.2</td>
<td>1A2</td>
<td>1.3(^a)</td>
<td>0.53(^a)</td>
<td>0.956</td>
<td>37.1(^a)</td>
</tr>
<tr>
<td><strong>Intermediate to high CLint compounds</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ketoprofen</td>
<td>Acid</td>
<td>254.3</td>
<td></td>
<td>0.3</td>
<td>0.85</td>
<td>1.27</td>
<td>2.4</td>
</tr>
<tr>
<td>Sildenafil</td>
<td>Base</td>
<td>474.6</td>
<td>2C9/2C29/3A4</td>
<td>6.0(^a)</td>
<td>0.094(^a)</td>
<td>0.892</td>
<td>8.6</td>
</tr>
<tr>
<td>Carvedilol</td>
<td>Base</td>
<td>406.5</td>
<td>2D6 &gt; 2C9</td>
<td>8.7(^a)</td>
<td>0.030(^a)</td>
<td>0.434</td>
<td>15.4</td>
</tr>
<tr>
<td>Imipramine</td>
<td>Base</td>
<td>280.4</td>
<td>2C9 &gt; 2D6 &gt; 3A4 &gt; 1A2</td>
<td>13.5(^a)</td>
<td>0.13(^a)</td>
<td>0.127</td>
<td>41.5</td>
</tr>
<tr>
<td>Ketanserin</td>
<td>Base</td>
<td>395.4</td>
<td>AKR/CR</td>
<td>6.7(^a)</td>
<td>0.094(^a)</td>
<td>0.752</td>
<td>10.1</td>
</tr>
</tbody>
</table>

MW, molecular weight; na, not available.

\(^a^{Halifax et al., 2010.}\)

\(^b^{Obach et al., 2008.}\)
where $Q_H$ is hepatic blood flow (20 ml/min/kg) and $CL_b$ is hepatic blood clearance.

For prediction of in vivo human hepatic intrinsic clearance, the accuracy of each prediction was assessed with the average fold error (AFE) of the observed/predicted in vivo $CL_{int}$ (eq. 4):

$$\text{AFE} = \frac{10^{\frac{\text{predicted} - \text{observed}}{\text{number of observations}}}}{1}$$

### Results

**HepaRG Cells.** The mean $CL_{int}$ values and the variation between experiments for the low turnover compounds are presented in Fig. 1, and examples of substrate depletion plots are presented in Fig. 2. In HepaRG, the compounds were incubated up to 24 hours, and $CL_{int}$ values as low as 0.2 μl/min/10⁶ cells were obtained (s-warfarin and disopyramide). However, for only two of the seven low turnover compounds (AZ01 and AZ02), the $CL_{int}$ was reproducible, and approved $CL_{int}$ was obtained in three consecutive experiments. For theophylline, no statistically significant $CL_{int}$ was determined in any experiment. For the comparison of compounds with higher $CL_{int}$, ketoprofen, carvedilol, imipramine, and ketanserin gave no or considerably lower $CL_{int}$ values with HepaRG than with suspended hepatocyte incubations, whereas sildenafil was comparable between the assays (Table 2). The accuracy in predicting human in vivo $CL_{int}$ from HepaRG data was as follows: from the eight compounds where $CL_{int}$ could be determined, the AFE was 2.9 and four of these eight compounds, (diazepam, disopyramide, sildenafil, and carvedilol) gave predictions within 3-fold of observed (Table 2).

**Monoculture of Primary Human Hepatocytes.** In the monoculture assay, compounds were incubated up to 12 hours and a statistically significant value as low as 0.2 μl/min/10⁶ cells (disopyramide) could be determined. However, an approved $CL_{int}$ could not be obtained repeatedly for this compound. For four of the seven low turnover compounds (diazepam, metoprolol, AZ01, and AZ02), $CL_{int}$ values could be defined on replicate occasions, diazepam having the lowest $CL_{int}$ of 0.8 μl/min/10⁶ cells (Fig. 1). No $CL_{int}$ values were obtained for s-warfarin and theophylline. Examples of substrate depletion plots are presented in Fig. 2. For comparison with the standard hepatocyte suspension assay of compounds with higher $CL_{int}$ PHH showed comparable values for four of the five compounds tested (ketoprofen, sildenafil, carvedilol, and imipramine) but a lower turnover for ketanserin (Table 2). Where $CL_{int}$ could be determined for compounds with clinical pharmacokinetic data, seven of nine (diazepam, disopyramide, metoprolol, carvedilol, imipramine, and ketanserin) had predicted human in vivo $CL_{int}$ within 3-fold of the observed values (Table 2); the AFE in the prediction was 1.6.

**HμREL-Co-cultured Primary Human Hepatocytes and Stromal Cells.** The HμREL co-culture assay was carried out for 72 hours and allowed several samples taken on each day of incubation (Fig. 2). In this assay, statistically significant $CL_{int}$ values could be defined on replicate occasions for the compound with the lowest $CL_{int}$, disopyramide (four consecutive assays defined $CL_{int}$ values of 0.3, 0.2, 0.6, and 0.5 with a mean of 0.4 μl/min/10⁶ cells). The assay was able to provide $CL_{int}$ values from a minimum of triplicate consecutive assays for six of seven low $CL_{int}$ compounds assayed (s-warfarin, diazepam, disopyramide, metoprolol, AZ01, and AZ02) (Fig. 1). The only compound for which no $CL_{int}$ was obtained was theophylline. When comparing suspended hepatocytes, this assay gave similar results for the higher turnover compounds, with the exception of imipramine (Table 2). Finally, the HμREL assay data were able to predict human in vivo $CL_{int}$ to within 3-fold of the observed values for seven of 10 compounds (diazepam, disopyramide, AZ02, sildenafil, carvedilol, imipramine, and ketanserin) where $CL_{int}$ could be determined (Table 2), with the AFE in the prediction being 2.3.

### Discussion

An increasingly common problem for DMPK scientists is to define $CL_{int}$ for slowly metabolized compounds using the substrate depletion method. Hepatocytes in suspension incubations suffer a rapid loss of drug-metabolizing enzyme activity (Smith et al., 2012), and such suspension assays are therefore inappropriate for consistent and accurate determination of $CL_{int}$ values in the range of 1 μl/min/10⁶ cells and lower unless the procedure is greatly modified as with the Relay method for example (Di et al., 2012, 2013). The objective of this investigation was to assess the capability of HepaRG and a multidonor primary hepatocyte pool plated as a monoculture and in the HμREL co-culture in robustly defining $CL_{int}$ and accurately predicting human vivo hepatic clearance for slowly metabolized compounds. Whereas the assay setups are more complex than the suspension format on which the Relay method is based, the sampling and sample treatment elements are uncomplicated and minimal. The results indicate that, despite the fact that it was not possible to determine a $CL_{int}$ value for theophylline in any of the plated human hepatocytes assays, all three offer improved potential for $CL_{int}$ determination of slowly metabolized compounds over a standard suspension assay format where incubation time is typically limited to 2–4 hours. All three assays allowed $CL_{int}$ values in the range of 1 μl/min/10⁶ and below to be obtained, and it was possible to define values as low as 0.2 μl/min/10⁶ cells (disopyramide). However, only with the HμREL co-culture assay could $CL_{int}$ values be defined on replicate occasions for disopyramide, the compound with the lowest $CL_{int}$. The three assays did allow for different times of incubation, limited by decline in enzyme activity. Smith et al. (2012) previously reported retained activity for cytochrome P450 3A4 (CYP3A4) and CYP1A2 in monocolourtes of primary human hepatocytes up to approximately 10 hours. This is in line with data from our laboratory on the five-donor hepatocyte pool in monoculture used in this study. Comparison of the same pool of primary human hepatocytes in HμREL co-cultures made it apparent that a log-linear compound concentration-time relationship was retained up to 72 hours. Taking the cell densities and the incubation times for these three systems (see Materials and Methods) into account reliable $CL_{int}$ limiting extrapolation of half-life to twice the incubation time, could
theoretically be determined down to 0.3 μL/min/10⁶ cells in HepaRG, 0.5 μL/min/10⁶ cells in PHH, and 0.2 μL/min/10⁶ cells in H₂REL. Accordingly, the longer incubation times of 24 and 72 hours afforded by the HepaRG and H₂REL assays should contribute to increasing robustness and reproducibility of the data compared with PHH; indeed, the H₂REL co-culture assay was able to provide CLₘ⁰ data from a minimum of triplicate consecutive assays for 85% of the low CLₘ⁰ compounds assayed. Besides a longer incubation time, the number of data points (i.e., replicates and or additional time points) is of importance when trying to assign statistically significant CLₘ⁰ values in the low range, and this possibility also assisted in the H₂REL assay (see example of substrate depletion plots in Fig. 2). The systems tested evidently have too short incubation time spans or too low enzymatic activity to show theophylline depletion. This finding is supported by

Fig. 2. Examples of substrate depletion plots using HepaRG, PHH, and H₂REL.
The in vivo CLint value. Since the H REL assay than the standard assay, resulting in a 2.7-fold underprediction of

2012). To test the extent to which HepaRG, PHH and H REL activity, responsible for the metabolism of ketanserin (Akabane
and CYP2D6 enzymology primarily responsible for imipramine metabo-

sion hepatocyte assay.

For the compounds with available clinical PK data, the ability of each in

vitro assay to accurately predict in vivo human hepatic CLint was

assessed as described previously (Sohlenius-Sternbeck et al., 2012). The H REL and PHH assay data were able to predict in vivo human hepatic CLint to within 3-fold of the observed values for seven of 10 (H REL) and seven of nine (PHH) compounds where CLint could be determined, with the AFE in prediction being 2.3 and 1.7, respectively. This good predictivity shows that, for this purpose, either of these two assay formats offers an alternative to the Relay method and the HepatoPac culture system, both of which have been shown to give good clearance predictions (Di et al., 2012; Chan et al., 2013). For the HepaRG assay, the predictions were less successful, with only four of the eight compounds for which a CLint could be obtained having a predicted in vivo human hepatic CLint within 3-fold of observed.

In summary, all three investigated systems allow for longer incubation times than a standard hepatocyte suspension format and demonstrated the ability to define CLint values as low as 0.2 µmol/min/10^6 hepatocytes. The H REL co-culture assay was able to provide a higher level of reproducibility than the PHH and HepRG assays for low CLint compounds. In addition, both the H REL and PHH assays gave similar CLint values to those defined by a standard hepatocyte suspension assay for a small set of drugs with higher CLint values and diverse enzymology, and data from both assays could predict in vivo human hepatic CLint to within 3-fold for 70% of the compounds tested. Therefore, whereas both PHH and the H REL hepatocyte/stromal cell co-culture appear to be promising solutions to the problem of robustly defining CLint for slowly metabolized compounds, the H REL assay appears somewhat superior regarding overall assay performance, with the opportunity to run incubations up to 72 hours. Apart from accurate estimation of low CLint values, the assay also provides the opportunity for metabolite identification in a human hepatic cell system for compounds that are stable in suspended hepatocyte incubations.

Acknowledgments

The authors thank Malin Darnell and Kajsa Kanebratt for discussions.

Authorship Contributions

Participation in research design: Bonn, Svanberg, Janefeldt, Grime.

Conducted experiments: Svanberg, Janefeldt, Hultman.

Performed data analysis: Bonn, Svanberg, Grime.

Wrote and contributed to the writing of the manuscript: Bonn, Svanberg, Janefeldt, Hultman, Grime.

<table>
<thead>
<tr>
<th>Compounds</th>
<th>S-warfarin</th>
<th>Diazepam</th>
<th>Disopyramide</th>
<th>Theophylline</th>
<th>Metoprolol</th>
<th>AZ01</th>
<th>AZ02</th>
<th>Ketoprofen</th>
<th>Sildenafil</th>
<th>Ketanserin</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>µmol/min/10^6 cells</td>
<td>0.21±b</td>
<td>0.40a</td>
<td>0.16a</td>
<td>0.57a</td>
<td>0.30± 0.2</td>
<td>0.45± 0.2</td>
<td>6.6 ± 0.3</td>
<td>9.6</td>
<td>33.1 ± 3.6</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>n=2</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>TABLE 2</th>
<th>Suspended hepatocytes</th>
<th>HepaRG</th>
<th>PHH</th>
<th>H REL</th>
<th>Predicted In Vivo CLint</th>
<th>Observed In Vivo CLint</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>µmol/min/10^6 cells</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>S-warfarin</td>
<td>0.21±b</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Diazepam</td>
<td>0.40±a</td>
<td>0.79 ± 0.3</td>
<td>1.35 ± 0.09</td>
<td>0.5 (1.0)</td>
<td>0.8 (1.6)</td>
<td>1.2 (2.4)</td>
</tr>
<tr>
<td>Disopyramide</td>
<td>0.16±a</td>
<td>0.21a</td>
<td>0.40 ± 0.2</td>
<td>0.7 (1.3)</td>
<td>0.9 (1.0)</td>
<td>1.5 (1.7)</td>
</tr>
<tr>
<td>Theophylline</td>
<td>0.57±a</td>
<td>0.93 ± 0.2</td>
<td>1.40 ± 0.2</td>
<td>6.3 (5.9)</td>
<td>12.3 (-3.0)</td>
<td>8.0 (-4.6)</td>
</tr>
<tr>
<td>Metoprolol</td>
<td>0.30 ± 0.2</td>
<td>2.2 ± 0.7</td>
<td>0.78 ± 0.15</td>
<td>0.7 (1.3)</td>
<td>1.1 (-4.3)</td>
<td>2.3 (-2.0)</td>
</tr>
<tr>
<td>AZ01</td>
<td>0.45 ± 0.2</td>
<td>1.2 ± 0.2</td>
<td>3.26 ± 0.3</td>
<td>0.5 (9.4)</td>
<td>1.1 (-4.3)</td>
<td>2.3 (-2.0)</td>
</tr>
<tr>
<td>AZ02</td>
<td>6.6 ± 0.3</td>
<td>3.9</td>
<td>4.3</td>
<td>0.5</td>
<td>7.5 (3.1)</td>
<td>8.1 (3.4)</td>
</tr>
<tr>
<td>Ketoprofen</td>
<td>33.1 ± 3.6</td>
<td>8.3 ± 5.8</td>
<td>14.1 ± 0.5</td>
<td>1.5 (-6.7)</td>
<td>10.2 (1.0)</td>
<td>15.3 (1.5)</td>
</tr>
</tbody>
</table>

n=1, n=2.
References


Address correspondence to: Dr. Britta Bonn. RIA IMED DMF/K, AstraZeneca R&D Gothenburg, SE-431 81 Gothenburg, Sweden, E-mail: Britta.Bonn@ astraZeneca.com