Research Article

In Vitro-Based Prediction of Human Plasma Concentrations of Food-Related Compounds

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Abstract

Efforts have been made to replace animal experiments in safety evaluations, including in vitro-based predictions of human internal exposures, such as predicting peak plasma concentration (Cmax) values for xenobiotics and comparing these values with in vitro-based toxicity endpoints. Herein, the authors predicted the Cmax values of food-related compounds in humans, based on the existing and novel in vitro techniques. In this study, 20 food-related compounds, which have been previously reported in human pharmacokinetic or toxicokinetic studies were evaluated. Human-induced pluripotent stem cell-derived small intestinal epithelial cells (hiPSC-SIEC) and Caco-2 cells, HepaRG cells, equilibrium dialysis of human plasma, and LLC-PK1 cell monolayer were used to assess the intestinal absorption and availability, hepatic metabolism, unbound plasma fraction, and secretion and reabsorption in renal tubular cells, respectively. After conversion of these parameters into human kinetic parameters, the plasma concentration profiles of these compounds were predicted using in silico methods, and the obtained Cmax values were found to be 0.017–183-times higher than the reported Cmax values. When the in silico-predicted parameters were modified with in vitro data, the predicted Cmax values were almost within 0.1–10-fold because the metabolic activities of hiPSC-SIECs, such as uridine 5\'-diphospho-glucuronosyl transferase, were closer to human primary enterocytes. Thus, combining in vitro test results with the plasma concentration simulations resulted in more accurate and transparent predictions of Cmax values of food-related compounds than those obtained using in silico-derived predictions. This method facilitated accurate safety evaluation without the need for animal experiments.

1 Introduction

Conventional risk assessment methods heavily rely on animal testing. Therefore, alternative testing methods have focused on hazard identification and characterization (EFSA, 2014). Recently, extensive efforts have been made to replace animal experiments in safety evaluations of chemicals (Gocht et al., 2015; Kojima, 2019). A new paradigm called next generation risk assessment (NGRA) was proposed for quantitative risk assessment without animal testing, which is defined as an exposure-led, hypothesis-driven risk assessment approach that integrates in silico, in chemico, and in vitro approaches (Dent et al., 2018). Using NGRA, human physiological conditions can be reproduced more closely by using the human

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Abbreviations

ADME, absorption, distribution, metabolism, and elimination; Cmax, peak plasma concentration; CYP, cytochrome P450; DMEM, Dulbecco’s modified Eagle’s medium; DMSO, dimethyl sulfoxide; Fext, fraction absorbed from the intestine; Fhep, fraction escaping hepatic metabolism; Fbs, fetal bovine serum; HBSS, Hanks’ balanced salt solution; hiPSC-SIEC, human induced pluripotent stem cell-derived small intestinal epithelial cell; MelQx, 2-amino-3,8-dimethylimidazo[4,5-f]quinoxaline; MES, 2-(N-morpholino)ethanesulfonic acid; NAMs, new approach methods; NEAA, nonessential amino acids solution; NGRA, next generation risk assessment; Papp, apparent permeability coefficient; PBK, physiologically based kinetic; UGT, uridine 5'-diphospho-glucuronosyl-glucuronosyltransferase; UPLC-MS/MS, ultraperformance liquid chromatography-tandem mass spectrometry
physiologically based kinetic (PBK) model, rather than relying on the conventional in vitro-based toxicity assays alone, as shown by several case studies (Baltazar et al., 2020; Vandecasteele et al., 2021; Bury et al., 2021; Terasaka et al., 2022). NGRA consists of predicting peak plasma concentrations (C\text{max}), determining in vitro toxicity endpoints, and performing in vitro refinements.

In addition to the recent NGRA applications for risk assessments of chemicals, novel in vitro and/or in silico-based methods known as new approach methods (NAMs) have been developed, which are necessary for improving NGRA. Especially, for oral ingested chemicals, these efforts include in silico and/or in vitro-based predictions of human internal exposures, such as C\text{max} values for xenobiotics (Punt et al., 2022; Terasaka et al., 2022; Kamiya et al., 2022). Then, these predicted values are compared with the in vitro-based toxicity endpoints.

Food consists of a mixture of several compounds, including several chemicals produced during their processing and storage stages. Limited toxicological information about the absorption, distribution, metabolism, and elimination (ADME) for assessing the risk of certain compounds raises concerns regarding human health. NGRA applications are effective not only for cosmetics, but also for food-related compounds (Ohta et al., 2022). Although in silico prediction is especially useful for the initial risk assessment screening, the prediction accuracy is highly dependent on the data sets used to create the prediction models. These data sets often use pharmaceuticals due to the availability of detailed pharmacokinetic information for humans. As the pharmacokinetic information regarding certain food-related chemicals is scarce, its application for predicting the pharmacokinetics of these compounds is limited. An in vitro-based approach is required to overcome the above-mentioned issues as it includes mechanistic information obtained using cellular and/or tissue-mimicking assay systems.

Previously, the authors had demonstrated the membrane permeability of food-related compounds using uridine 5′-diphospho-glucuronosyl transferase (UGT)-mediated intestinal metabolism in human-induced pluripotent stem cell-derived small intestinal cells (hiPSC-SIECs). These cells are more predictive than Caco-2 cells (derived from cultured human colon cancer cells) that are used as a golden standard (Kitaguchi et al., 2021). This study mimicked the typical human ADME processes with existing and novel in vitro techniques, converted the in vitro data into human PBK parameters, and performed simulations using a human PBK model to evaluate the pharmacokinetic parameters of food-related compounds. Finally, the prediction accuracy of the C\text{max} values of 20 food-related test compounds with the corresponding plasma concentrations in humans was demonstrated in this study.

2 Materials and Methods

2.1 Cells and reagents

hiPSC-SIECs were purchased from Fujifilm Wako (F-hiSIEC™, Osaka, Japan), which included seeding and maintenance medium. Preplated human colon carcinoma Caco-2 cells (passage numbers 55–65) were purchased from ReadyCell (CacoReady™ Plate, Barcelona, Spain). The human hepatoma cell line HepRaG² was purchased from KAC (Kyoto, Japan). LLC-PK1 porcine kidney proximal tubular cells at passage 196 (ATCC CL-101™) were obtained from the American Type Culture Collection (ATCC, Manassas, VA). Dulbecco’s modified Eagle’s medium (DMEM), penicillin-streptomycin solution, non-essential amino acids solution (NEAA), and fetal bovine serum (FBS) were purchased from Thermo Fisher Scientific (Waltham, MA, USA). Hanks’ balanced salt solution (HBSS) and dimethyl sulfoxide (DMSO) were procured from Fujifilm Wako.

All drugs, food-related compounds, and metabolites listed below were dissolved in DMSO and stored at –20°C until further use. Curcumin, bisphenol A, and 2-amino-3,8-dimethylimidazo[4,5-f] quinoxaline (MeIQx), and 7-hydroxycoumarin were procured from Fujifilm Wako. Acrylamide, fenitrothion, and β-estradiol were purchased from Sigma-Aldrich (St. Louis, MO, USA). Bisphenol S, picloram, and raloxifene were purchased from Tokyo Chemical Industry (Tokyo, Japan). Daidzein and genistein were purchased from LC Laboratories (Woburn, MA, USA). Quercetin, diclofenac, telmisartan, and troglitazone were purchased from Nacalai Tesque (Kyoto, Japan).

2.2 Membrane permeability assay using hiPSC-SIECs and Caco-2 cells

hiPSC-SIECs were thawed and seeded at an initial density of 1 × 10⁵ cells/well in Matrigel-coated 24-well cell culture inserts (Merck Millipore, Burlington, MA, USA), and then maintained for 9–13 days according to the manufacturer’s instruction. Preplated Caco-2 cells were shipped on day 18 after seeding into 24-well cell culture inserts and maintained with DMEM supplemented with 1% NEAA, 10% FBS, and 50 U/mL penicillin/streptomycin for an additional 3–7 days according to the suppliers’ instructions. Transepithelial electronic resistance (TEER) values were measured with Millicell ERS-2 (Merck Millipore) immediately before and after the membrane permeability assays to ensure the maintenance of the membrane barrier during the assays.

The assays were conducted according to a previously described method (Kitaguchi et al., 2021). Briefly, hiPSC-SIECs (n = 2) and Caco-2 cells (n = 3) were washed thrice with apical and basal transport buffers (HBSS containing 10 mM MES and 4.5 g/L glucose at pH 6.5 and 7.4, respectively) in chambers and incubated at 37°C for at least 30 min. Membrane transport assays were performed at 37°C for 30, 60, and 90 min after replenishing the apical chambers with transport buffer containing each substrate at a final concentration of 10 μM. The solution was collected from the basal chambers at 30 min intervals, diluted with an equal volume of acetonitrile, and stored at –20°C. Unreacted substrates were measured using ultraperformance liquid chromatography-tandem mass spectrometry (UPLC-MS/MS).

The apparent permeability coefficients (P\text{app}) were calculated using the following equation:

\[ P_{\text{app}} = \frac{\text{Intercept}}{\text{Slope}} \]
\[ P_{\text{app}} = \frac{dQ}{dt} \times \left[ \frac{1}{(A \times C_0)} \right] \]  
\text{Eq. 1}

where \( dQ/dt, A, \) and \( C_0 \) represent the amount of permeated compound per unit of time, the surface area of the transport membrane, and the initial compound concentration in the donor chamber, respectively.

2.3 Plasma protein binding assays for predicting the volume of distribution

The unbound fraction in human plasma (\( f_{up} \)) was determined by the equilibrium dialysis method with a Rapid Equilibrium Dialysis device (Thermo Fisher Scientific) according to the manufacturer’s instructions. Briefly, the human plasma (Takara Bio) was dialyzed against phosphate buffer (pH 7.2) using a membrane with a nominal cutoff of 8 kDa at 37°C for 4 h with gentle agitation (\( n = 3 \)). The final concentration of each compound added to the plasma was 2 or 20 \( \mu M \) depending on the detection sensitivity of UPLC-MS/MS. Equal volumes of either buffer (to the plasma samples) or compound-free plasma (to the buffer samples) were added, followed by protein precipitation with acetonitrile (performed four times) and filtered with FastRemover (GL Science, Tokyo, Japan) for UPLC-MS/MS.

The \( f_{up} \) of each compound was the concentration of the buffer sample divided by the concentration of the plasma sample.

2.4 Metabolic stability assay using HepaRG cells for predicting hepatic clearance

The HepaRG cell culture and metabolic stability assays were performed as mentioned previously (Bonn et al., 2016). Briefly, the cryopreserved HepaRG cells were thawed and 100 \( \mu L \) of cell suspension (0.72 \( \times 10^6 \) cells/mL) were seeded into each well of flat-bottomed 96-well plates coated with type 1 collagen. They were allowed to attach for approximately 24 h in a CO\(_2\) incubator, and the medium was renewed with HepaRG culture medium at room temperature. After 60 h, the medium was renewed with HepaRG serum-free induction medium, and 24 h later, the cells were exposed to the compounds for 0.25, 0.5, 1, 2, 4, 8, and 24 h (\( n = 3 \)). After the incubation, the supernatants from each well were collected and diluted three times with ice-cold acetonitrile containing 0.8% formic acid. The samples were centrifuged at 4°C for 10 min at 10,000 g, and aliquots of the clear supernatant were diluted with equal amounts of water and kept at 4°C until UPLC-MS/MS analysis.

\text{In vitro} intrinsic hepatic clearance (\( CL_{h,\text{int}} \)) was calculated from the parent compound loss data according to previous literature (Bonn et al., 2016) using the following equation:

\[ CL_{h,\text{int}} = \frac{-\text{slope of ln (% drug remaining) vs time plot} \times \text{ml incubation} \times 10^6 \text{ cells} (\mu L \cdot \text{min}^{-1} \cdot 10^6 \text{ cells}^{-1})}{\text{Eq. 2}} \]

2.5 Bidirectional membrane permeability assay using LLC-PK1 cells for predicting urinary clearance

These assays were conducted as previously described by Kunze et al. (2014) with minor modifications. The LLC-PK1 cells were cultured in medium 199 (Thermo Fisher Scientific) supplemented with 10% FBS at 37°C in a 5% CO\(_2\) incubator. The medium was changed every second to third day. The cells were cultured for a maximum period of 2 months and were passaged 16 times.

The bidirectional transport assays were conducted in 24-well cell culture inserts (Corning, Corning, NY). The LLC-PK1 cells were seeded into 24-well cell culture inserts with a microporous polyethylene terephthalate membrane (0.4 \( \mu \text{m} \) pore size; 0.33 cm\(^2\) surface area) at a density of 4 \( \times 10^6 \) cells/cm\(^2\). The cells were maintained for four days as described above. The experiments were performed in modified Krebs buffer adjusted to pH 7.4 and 6.8 for the basolateral (lower chamber, 1 mL) and apical (upper chamber, 0.2 mL) compartments, respectively. The cell culture medium was washed thrice with prewarmed assay buffer and the cell monolayers were preincubated for at least 30 min. Subsequently, the buffer was aspirated and replaced with buffer containing each compound (1 \( \mu M \)) to the donor compartment. The cell monolayers were incubated for 30 and 60 min at 37°C (\( n = 3 \)). Aliquots (0.1 mL) of both compartments were sampled and quantified with UPLC-MS/MS.

The \( P_{\text{app}} \) values in basolateral to apical (\( P_{\text{app,BA}} \)) and apical to basolateral (\( P_{\text{app,AB}} \)) directions were determined using eq.1. The \( P_{\text{app,BA}} \) and \( P_{\text{app,AB}} \) values were upscaled to human intrinsic renal clearances (\( CL_{r,\text{int,BA}} \) and \( CL_{r,\text{int,AB}} \)) using the following equation:

\[ CL_{r,\text{int}} = P_{\text{app}} \times \pi \times l_{PT} \times d_{PT} \times n_{\text{neph}} \times n_{\text{kid}} / BW \]  
\text{Eq. 3}

where the surface of a human proximal tubule is calculated as the product of its length \( l_{PT} \) (1.5 cm), its diameter \( d_{PT} \) (7 \( \times 10^{-3} \) cm), and the number \( \pi \) (\( \pi = 3.14 \)), \( n_{\text{neph}} \) is the number of nephrons per kidney (1.5 \( \times 10^6 \)), \( n_{\text{kid}} \) the number of kidneys per human (2), and \( BW \) is the average human body weight (70 kg).

2.6 Data conversion from in vitro data to human PBK parameters

2.6.1 Determination of absorptive constant (\( k_a \))

The experimental \( P_{\text{app}} \) values of Caco-2 cells were converted to effective permeability coefficient (\( P_{\text{eff}} \)) using GastroPlus (ver. 9.8.2., Simulations Plus, Lancaster, CA) Per converter with human \( P_{\text{eff}} \) reported compounds. \( k_a \) (10\(^{-3} \) min\(^{-1} \)) was derived from \( P_{\text{eff}} \) according to the previous literature (Sugano, 2012) with the following equation:

\[ k_a = 2 \times DF / R_{\text{cl}} \times P_{\text{eff}} \]  
\text{Eq. 4}

where \( DF \) is the degree of flatness of the gastrointestinal tract (1.7), and \( R_{\text{cl}} \) is the radius of the gastrointestinal tract (1.5 cm).
2.6.2 Determination of fraction escaping intestinal metabolism ($F_{i}$)

$F_{i}$ was estimated using a previously described method (Michiba et al., 2022) using the following equation:

$$F_{i} = 1 / [(2 \times CL_{AtoB_{-inh}} / CL_{AtoB_{-inh}}) - 1]$$  \hspace{1cm} \text{Eq. 5}

where $CL_{AtoB_{-inh}}$ and $CL_{AtoB_{-inh}}$ represent the apical-to-basolateral transcellular transport clearance in the absence and presence of a metabolic inhibitor, respectively.

In this study, Caco-2 cells were assumed to possess negligible metabolic activity (Kitaguchi et al., 2021), whereas other factors, such as transporter- and paracellular-mediated permeation, were assumed to be similar in Caco-2 cells and hiPSC-SIECs. These assumptions suggested that the relationship of $CL_{AtoB_{-inh}}/CL_{AtoB_{-inh}}$ ratio and $P_{app}$ of Caco-2 cells/P_{app} of hiPSC-SIECs ratio are equal and these values were substituted in the above equation.

2.6.3 Determination of hepatic clearance ($CL_{h}$) and fraction escaping hepatic metabolism ($F_{h}$)

$CL_{h}$ (mL/min/kg) was estimated based on a previous study (Bonn et al., 2016) using the following equation:

$$CL_{h} = CL_{int} \times 120 \times 10^{6} \text{ cells/g liver} \times 24 \text{ g liver/}W \times f_{ub} / f_{unc}$$  \hspace{1cm} \text{Eq. 6}

where $f_{ub}$ is a fraction of compound unbound in the blood and was calculated as per a previous report (Hallifax et al., 2010), and $f_{unc}$ is a fraction of compound unbound after in vitro incubation predicted from a previous report (Kilford et al., 2008). The $F_{h}$ was calculated from $CL_{h}$ and $f_{ub}$ using the following equation according to a well-stirred model.

$$F_{h} = Q_{h} / (Q_{h} + f_{ub} \times CL_{h})$$  \hspace{1cm} \text{Eq. 7}

$Q_{h}$ represents the hepatic blood flow rate [20.7 mL/(min \cdot kg)].

2.6.4 Determination of renal clearance ($CL_{r}$)

The $CL_{r}$ (mL/min/kg) is a composed process involving glomerular filtration clearance ($CL_{r_{filt}}$), tubular secretion clearance ($CL_{r_{sec}}$), metabolic clearance, and reabsorption of a fraction of the drug from the tube fluid back into the blood ($f_{reab}$).

Assuming that the contribution of renal metabolic clearance is negligible, $CL_{r_{long}}$ can be expressed using the following equations (Kunze et al., 2014):

$$CL_{r} = CL_{r_{filt}} + CL_{r_{sec}} \cdot (1 - f_{reab})$$  \hspace{1cm} \text{Eq. 8.1}

$$CL_{r_{filt}} = f_{ub} \cdot GFR$$

$$CL_{r_{sec}} = Q_{r_{filt}} \cdot f_{ub} \cdot CL_{r_{int,BA}} / (Q_{r_{filt}} + f_{ub} \cdot CL_{r_{int,BA}})$$

$$f_{reab} = CL_{r_{int,AB}} / (GFR + CL_{r_{int,AB}})$$

where $GFR$ is the glomerular filtration rate [1.79 mL/(min \cdot kg)], $Q_{h}$ is the renal blood flow rate [17.14 mL/(min \cdot kg)].

2.6.5 Determination of the volume of distribution ($V_d$)

The $V_d$ (L) was calculated according to previous reports (Oie and Tozer, 1979; Waters and Lombardo, 2010) using the following equation:

$$V_d = V_T \cdot (1 + R_{E/J}) + f_{ub} \cdot V_T \cdot f_{ub} / f_{fat}$$  \hspace{1cm} \text{Eq. 9}

where $f_{ub}$ is the fraction unbound in tissues, $R_{E/J}$ is the extravascular: intravascular ratio of binding proteins (usually 1.4 for albumin), $V_T$, $V_L$, and $V_S$ refers to the volumes of plasma, extracellular fluid, and remainder fluid with values of 0.0436, 0.151, and 0.38 L/kg, respectively, in humans.

$f_{fat}$ was predicted according to a previous study (Berellini and Lombardo, 2019) using the following equation:

$$\log f_{fat} = -0.249 \cdot \log D_{7,4} - 0.999 \cdot f_{7,4} + 0.735 \cdot \log f_{ub} + 0.070$$  \hspace{1cm} \text{Eq. 10}

where $f_{7,4}$ is the cationic fraction ionized at pH 7.4.

2.6.6 Determination of elimination constant ($k_e$)

The $k_e$ ($10^{-3}$ min$^{-1}$) was calculated using the following equation:

$$k_e = (CL_{r} + CL_{r_{filt}}) / V_d$$  \hspace{1cm} \text{Eq. 11}

2.6.7 Prediction of in silico physicochemical and human kinetic parameters

All physicochemical and kinetic parameters (pKa, LogP, $k_e$, first pass, $k_o$, and $V_d$) were directly predicted using ACD/Percepta (2017.2). Prediction of LogP and pKa are from QSAR (quantitative structure activity relationships) model on the basis of GALAS (global, adjusted locally according to similarity) modeling methodology (Sazonovas et al., 2010). Prediction of $k_e$ and $V_d$ are from previously reported QSAR models (Reynolds et al., 2009; Lannevik et al., 2010), and $k_o$ and first pass are from the empirical model based on fragment structure descriptors and partial least squares regression statistics (personal communication).

2.7 Prediction of human plasma concentrations using simulation software

The PK Explorer module in ACD/Percepta (2017.2) was used to predict human plasma concentration profiles. The module consisted of differential equations involving solubility in the gastrointestinal tract, $k_e$, first-pass metabolism in the gut and liver ($1 - F_{L} \times F_{G}$), $V_d$, and $k_e$. The solubility in the gastrointestinal tract was predicted from aqueous solubility corrected for solubilizing effect of bile salts, and the other parameters were replaced with the in silico-predicted values described above. The predictions of human plasma concentrations were based on the compartmental absorption and transit model as previously reported (Yu and Amidon, 1999) (personal communication).
Tab. 1: $P_{app}$ values using Caco-2 cells and hiPSC-SIECs, and calculated $F_a$ or $F_a \times F_g$ of reported drugs and food-related compounds

<table>
<thead>
<tr>
<th>Compound</th>
<th>$P_{app}$ (×10⁻⁶ cm/s)</th>
<th>Caco-2 cells</th>
<th>hiPSC-SIECs</th>
<th>Calculated $F_a$</th>
<th>Reported $F_a$</th>
<th>Reported $F_a \times F_g$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Quercetin</td>
<td>9.89 ± 0.636</td>
<td>0.463</td>
<td>0.025</td>
<td>–</td>
<td>0.003³, 0.0165⁴</td>
<td></td>
</tr>
<tr>
<td>Curcumin</td>
<td>3.50 ± 0.805</td>
<td>0.0666</td>
<td>0.0096</td>
<td>–</td>
<td>–</td>
<td></td>
</tr>
<tr>
<td>Daidzein</td>
<td>36.8 ± 1.55</td>
<td>1.59</td>
<td>0.022</td>
<td>–</td>
<td>–</td>
<td></td>
</tr>
<tr>
<td>Daidzin*</td>
<td>0.0574 ± 0.00854</td>
<td>0.0150</td>
<td>0.150</td>
<td>–</td>
<td>–</td>
<td></td>
</tr>
<tr>
<td>Genistein</td>
<td>33.7 ± 1.02</td>
<td>2.68</td>
<td>0.041</td>
<td>–</td>
<td>0.0375³</td>
<td></td>
</tr>
<tr>
<td>Genistin*</td>
<td>0.0910 ± 0.0275</td>
<td>0.00925</td>
<td>0.054</td>
<td>–</td>
<td>–</td>
<td></td>
</tr>
<tr>
<td>Bisphenol A</td>
<td>29.7 ± 2.23</td>
<td>4.29</td>
<td>0.078</td>
<td>–</td>
<td>–</td>
<td></td>
</tr>
<tr>
<td>Bisphenol S</td>
<td>23.4 ± 0.742</td>
<td>5.85</td>
<td>0.143</td>
<td>–</td>
<td>–</td>
<td></td>
</tr>
<tr>
<td>Ferulic acid</td>
<td>24.6 ± 2.03</td>
<td>7.86</td>
<td>0.190</td>
<td>–</td>
<td>–</td>
<td></td>
</tr>
<tr>
<td>Raloxifene</td>
<td>2.44 ± 0.327</td>
<td>0.164</td>
<td>0.035</td>
<td>–</td>
<td>0.069³</td>
<td></td>
</tr>
<tr>
<td>Diclofenac</td>
<td>47.5 ± 1.43</td>
<td>35.3</td>
<td>0.591</td>
<td>0.685⁴</td>
<td>0.738³</td>
<td></td>
</tr>
<tr>
<td>Telmisartan</td>
<td>35.3 ± 0.707</td>
<td>30.4</td>
<td>0.758</td>
<td>0.674⁴</td>
<td>1.00³</td>
<td></td>
</tr>
<tr>
<td>Troglitazone</td>
<td>7.34 ± 0.308</td>
<td>4.80</td>
<td>0.486</td>
<td>0.558⁵</td>
<td>–</td>
<td></td>
</tr>
</tbody>
</table>

Each $P_{app}$ data represents the mean ± S.D. of n = 3 (Caco-2 cells) or means of n = 2 (hiPSC-SIECs).

³Nakamori et al., 2012. The values are calculated using the hepatic blood flow rate of 20.7 mL/min/kg.

⁴Nishimuta et al., 2011.

⁵Kikuchi et al., 2022. The values are from the allometric scaling-based-$F_a \times F_g$ calculation method.

3 Results

3.1 Assessment of absorption and $F_a$ by using Caco-2 cells and hiPSC-SIECs

Figure 1 shows the $P_{app}$ values obtained using Caco-2 cells and hiPSC-SIECs of 20 food-related compounds. The $P_{app}$ values in hiPSC-SIECs were 3.1–53 times lower than those in Caco-2 cells for quercetin, curcumin, daidzein, daidzin, genistein, bisphenol A, bisphenol S, and ferulic acid, which are known UGT-metabolized compounds. However, the $P_{app}$ values of cyanidin-3-glucoside and caffeic acid in hiPSC-SIECs were 5.6–7.7 times higher than those in Caco-2 cells. Furthermore, $P_{app}$ values were determined using Caco-2 cells and hiPSC-SIECs for the reported UGT-metabolized drugs in the small intestine, including raloxifene, diclofenac, telmisartan, and troglitazone. As shown in Tab. 1, the $P_{app}$ values for these drugs were 1.2–15 times lower in hiPSC-SIECs than in Caco-2 cells.

The $F_a$ values of these drugs were calculated using the conversion formula (Michiba et al., 2022). As shown in Tab. 1, the calculated $F_a$ values of the four drugs with reported $F_g$ (fraction absorbed from the intestine) × $F_a$ or $F_g$ values were comparable to the previously reported $F_a$ × $F_g$ or $F_a$ values in humans in humans (Nakamori et al., 2012; Nishimuta et al., 2011; Kikuchi et al., 2022). Therefore, the $F_a$ conversion formula was also applied to the test compounds, which exhibited higher $P_{app}$ values in Caco-2 cells than in hiPSC-SIECs (Tab. 1). The $F_a$ ranged from 0.0096 to 0.19. Moreover, the calculated $F_a$ values of quercetin (0.025) and genistein (0.041) were comparable to their reported $F_a$ × $F_g$ values (quercetin: 0.003 and 0.0165; genistein: 0.0375, respectively).

Fig. 1: Comparison between the $P_{app}$ values of Caco-2 cells and hiPSC-SIECs obtained using membrane permeability assays

The $P_{app}$ values obtained from Caco-2 cells and hiPSC-SIECs were plotted. The dotted and dashed lines represent the $P_{app}$ values of Caco-2 cells and hiPSC-SIECs that were within 3-fold and 10-fold, respectively. The compounds used are as follows: Dzi, daidzin*; Dze, daidzein; Gsi, genistin*; Gse, genistein; Que, quercetin; GA, gallic acid; CA, caffeic acid; AA, acrylamide; FA, ferulic acid; CG, cyanidin 3-glucoside; Cur, curcumin; C, caffeine; AA, acrylamide; BHA, butylated hydroxyanisole; BHT, butylated hydroxytoluene; AFB, aflatoxin B1; OTA, ochratoxin A; BPA, bisphenol A; BPS, bisphenol S; CLP, chlorpyrifos; PLR, pilocarpine. These compounds were tested at a concentration of 10 µM. Each plot represents the mean of n = 3 (Caco-2 cells) or n = 2 (hiPSC-SIECs). The $P_{app}$ values of daidzin and genistein were detected as daidzein and genistein.
Fig. 2: The comparison between in silico-predicted and in vitro-derived or reported values for evaluating kinetic and physicochemical parameters

The in silico-predicted and in vitro-derived values of the test compounds were plotted for the following parameters: A) absorption rate constant ($k_a$) from Caco-2 cells, B) first pass, C) elimination rate constant ($k_e$), and D) volume of distribution ($V_d$); the dotted and dashed lines represent the values that are within 3-fold and 10-fold, respectively. The in silico-predicted and reported values were plotted against E) partition coefficient (Log P) and F) acidity constant (pKa); the dotted lines represent the values that are between $-1$ and $1$. The compounds plotted are as follows: Dze, daidzein; Gse, genistein; Que, quercetin; GA, gallic acid; CA, caffeic acid; FA, ferulic acid; C3G, cyanidin 3-glucoside; Cur, curcumin; Caf, caffeine; AA, acrylamide; BHA, butylated hydroxyanisole; BHT, butylated hydroxytoluene; AFB, aflatoxin B1; OTA, ochratoxin A; BPA, bisphenol A; BPS, bisphenol S; CLP, chlorpyrifos; PLR, picloram.
3.2 Comparison between the in silico-predicted and in vitro-derived values for the human PBK parameters

The in vitro-derived parameters were converted to human PBK parameters ($k_a$, first-pass metabolism in the gut and liver, $k_e$, and $V_d$) with a previously reported conversion formula described in the Materials and Methods section. The obtained values were then compared with the in silico-predicted values (Figs. 2A–2D). Moreover, the predicted values for the physicochemical parameters, Log P and pKa were compared with those available in the literature (Figs. 2E and 2F). The details of these values are provided in Tabs. S1 and S21.

Regarding $k_a$, the in vitro-derived values tended to be higher than those predicted in silico (Fig. 2A). Especially, the in vitro-derived $k_a$ of cyanidin-3-glucoside, gallic acid, ferulic acid, picloram, and acrylamide, which have high polarity or low molecular weight characteristics, were more than three-fold higher than the in silico-derived values (0.038 vs. 1.2, 0.29 vs. 5.4, 6.7 vs. 56, 4.3 vs. 19, and 12 vs. 65 × 10−7 min⁻¹, respectively).

For the first pass and $k_e$, no apparent relationships were observed between the in silico-predicted and in vitro-derived values (Figs. 2B and 2C). In particular, the $k_e$ of ochratoxin A, quercetin, and chlorpyrifos varied considerably, possibly due to the significantly higher plasma protein binding rate (>99.9%) than the in silico-predicted values (Tab. S11).

The in vitro-derived $V_d$ values were lower than the in silico-predicted values (Fig. 2D). Especially, the in vitro-derived $V_d$ for BHT, BHA, and chlorpyrifos were more than 10-fold lower than the in silico-derived values (248 vs. 5390, 56 vs. 574, and 43 vs. 1680 L/70 kg, respectively). Moreover, the physicochemical parameters (Log P and pKa) were consistent with the in silico-predicted values (Figs. 2E and 2F).

![Fig. 3: Comparison between the predicted and observed C_max values from 20 food-related compounds](image)

The in silico predicted C_max values, in vitro-based C_max values with in silico predicted first pass, and in vitro-based C_max values were divided by the reported human C_max values from previous literature were plotted. The dotted and dashed lines represent the predicted values that are within 3-fold and 10-fold, respectively.

* C_max values of daidzin and genistin were predicted as daidzein and genistein.

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3.3 Comparison between the in silico-predicted and in vitro-derived values for $C_{\text{max}}$

Table 3 shows the results of human pharmacokinetic prediction using the PBK parameters obtained above. Detailed data is provided in Table S3. When the plasma concentrations of the food-related test compounds were predicted using only in silico-predicted parameters, the $C_{\text{max}}$ values of these 20 compounds were 0.017–183-fold to that of the reported $C_{\text{max}}$ values. When the in silico-predicted parameters were replaced with in vitro data obtained in this study and reported physicochemical parameters, the predictivity of $C_{\text{max}}$ values did not improve (ranging from 0.19- to 333-fold). Interestingly, better predictivity was obtained using the $F_{\text{i}}$ values from hiPSC-SIECs as the predicted $C_{\text{max}}$ values of 20 test compounds were almost within 10-fold (0.092–10.1-fold).

4 Discussion

Prediction of human pharmacokinetics is a key factor for NGRA. Recently, the application of safety evaluation methods without conducting animal experiments has been in high demand, not only for excipients of cosmetics but also for general chemicals, including food-related compounds. Since food-related compounds are orally ingested, predicting their gastrointestinal absorption is essential for predicting human pharmacokinetics. However, reports on the pharmacokinetics of food-related compounds and pharmacokinetics-based predictivity without animal testing in humans are limited. This study evaluated the predictivity of $C_{\text{max}}$ values using recently reported alternative testing methods and compared it with human pharmacokinetic data of food-related compounds from existing literature.

Caco-2 cells have microvilli-like structures and can be used to predict the oral absorption of compounds that undergo transcellular permeation by passive diffusion (Lea, 2015). Owing to this property, Caco-2 cell monolayers were used to predict gastrointestinal absorption. These cells also express intestinal efflux transporters, such as P-glycoprotein, multidrug resistant protein 2, and breast cancer resistant protein (Lu et al., 2022). Therefore, this cell line can be used to reproduce the results at low cost. However, Caco-2 cells are colon cancer-derived cells and have characteristics that are different from the human small intestine such as, extremely high TEER value and limited expression of metabolic enzymes, including CYP3A and small intestine-specific UGT isoforms (Kabeya et al., 2020; Kitaguchi et al., 2021). Therefore, the predictivity for human intestinal permeability and availability should be improved to overcome the above-mentioned problems. In line with this assumption, Punt et al. (2022) reported the predictivity of human plasma $C_{\text{max}}$ values of 44 pharmaceuticals and food-related compounds with certain overestimation. They discussed the reasons behind the overestimation based on existing ADME information and identified several compounds involved in intestinal metabolism. Therefore, the predictivity of $F_{\text{i}}$ was assumed to be a key factor. Previously, new cells were developed and human-derived samples were used for $F_{\text{i}}$ prediction (Michiba et al., 2022). The authors had previously reported significant differences in the membrane permeation rates for a group of compounds undergoing glucuronidation in Caco-2 cells and hiPSC-SIECs. The expression and metabolic activities of UGT isoforms in hiPSC-SIECs were similar or higher than those in the human small intestinal cells (Kitaguchi et al., 2021). As several test compounds used in this study are known glucurononated substrates, an attempt was made to apply the first-pass metabolism in the gut by comparing the permeability data of Caco-2 cells and hiPSC-SIECs. The $P_{\text{app}}$ values of hiPSC-SIECs were 3.1–53-fold lower than those in Caco-2 cells. Previously, the authors of this study had reported that the relationships between $P_{\text{app}}$ values and $F_{\text{i}}$ or $F_{\text{i}} \times F_{\text{a}}$ of hiPSC-SIECs correlated better than those in Caco-2 cells. However, regression equation-based $F_{\text{i}} \times F_{\text{a}}$ calculation did not correlate well with the reported $F_{\text{i}} \times F_{\text{a}}$ or $F_{\text{i}}$ (data not shown). Therefore, the conversion formula put forth by Michiba et al. (2022) was used to calculate $F_{\text{i}}$. They calculated CYP3A-derived $F_{\text{i}}$ based on the difference in the permeability of human intestinal organoid-derived cells with and without CYP3A4 inhibitor. It was assumed that Caco-2 cells have negligible UGT metabolic activity, and that other factors are similar in Caco-2 cells and hiPSC-SIECs. Based on these assumptions, $F_{\text{i}}$ was calculated, which was found to be comparable to the reported $F_{\text{i}}$ of drugs in humans. Recently, Kikuchi et al. (2022) reported an allometry-based calculation of human $F_{\text{i}} \times F_{\text{a}}$ values for food-related compounds using existing pharmacokinetic data in rats. This study calculated the $F_{\text{i}} \times F_{\text{a}}$ values for quercetin and genistein, which were 0.0165 and 0.0375, respectively, comparable to predicted $F_{\text{i}}$ values (0.025 and 0.041, respectively). The possible limitation of this calculation method is because of the assumption that the characteristics other than UGT metabolism (ex. Transporter expressions and functions, transcellular permeability, and paracellular permeability) are similar between Caco-2 cells and hiPSC-SIECs. However, the authors did not confirm these characteristics. For example, TEER, which indicated the tightness of the cell-to-cell connection, is significantly different between Caco-2 cells and hiPSC-SIECs. However, the authors reported that the $F_{\text{i}} \times F_{\text{a}}$ and $P_{\text{app}}$ slopes of the 20 known drugs are almost the same, regardless of the difference between the TEER values. Both cells have higher TEER values than the observed values in the human small intestine (Kitaguchi et al., 2021). Other possible differences are expressions and functions of uptake and efflux transporters (Press and Di Grandi, 2008). Further studies are required to confirm these assumptions. Since UGT inhibitors, which cover all types of isoforms, have yet to be reported, the estimation of $F_{\text{i}}$ using UGT inhibitors is limited. Therefore, it is challenging to validate the similarity in the characteristics between Caco-2 cells and hiPSC-SIECs. Hence, additional experimental UGT inhibitor-independent methods, such as UGT knockdown, may be required for validation. Daidzin and genisin, 7-O-glycosides of daidzein and genistein, are deglycosylated in the small intestine (Murota et al., 2002). Therefore, the differences in the $P_{\text{app}}$ values of these compounds may be due to the variation in UGT metabolisms and glycosidase activity between Caco-2 cells and hiPSC-SIECs. Further studies must discuss the differences in the $P_{\text{app}}$ values of daidzin and genisin because the glycosidase activity between Caco-2 cells and hiPSC-SIECs was not well characterized.

HepaRG cells were used for the prediction of $F_{\text{i}}$ and $CL_{\text{amb}}$ because the metabolic activity of these cells is similar to that of cryopreserved human hepatocytes (Zanelli et al., 2012; Bonn et al., 2016). Although cryopreserved human hepatocytes are
used as a golden standard to predict CLh, these cells were not used in this study because they exhibit significant lot-to-lot variation (Araki et al., 2016). Further improvement might be needed to predict CLh by using pooled cryopreserved human hepatocytes by keeping their metabolic activities or culturing the cells with improved metabolic activities, such as 3-dimensional cultures (Lauschke et al., 2019).

\( V_d \) was predicted by conducting equilibrium dialysis of human plasma for obtaining experiment- and physicochemical parameter-based \( f_s \) values (Berellini and Lombardo, 2019). Compared to the experimental \( f_s \), the in silico-predicted \( f_s \) was between 1% and 100%. Values less than 1% were not observed. Highly protein-bound compounds (ochratoxin A, BHT, BHA, and chlorpyrifos) showed significantly higher plasma protein binding rates (>99.9%) than the in silico-derived values. These differences might affect the prediction of \( V_d \) values. For example, the in silico-derived \( V_d \) of BHT was much higher than the in vitro-based \( V_d \) (5390 L vs. 248 L, respectively).

For predicting CLh, LLC-PK1 cells-based renal tubular secretion and reabsorption assays were used, as previously reported (Kunze et al., 2014). Daidzein, genistein, and caffeic acid were predicted to be the possible renal secreted compounds (CLsecret < CLreabs), whereas others were identified as reabsorptive compounds (CLsecret > CLreabs). Daidzein and genistein have longer half-lives in patients with end-stage renal disease (Fanti et al., 1999). Although renal excretion of caffeic acid was not reported, it can potentially inhibit human organic anion transporter 1 and 3 (Uwai et al., 2011). The limitation of this method is that the expressions and functions of some transporters (e.g., organic anion transporters) were insufficient and contributions of renal secretion and reabsorption were relatively smaller than the glomerular filtration ratio. Therefore, further improvement in in vitro-based prediction methods might be essential. As LLC-PK1 cells are porcine-derived and might not accurately represent the human RPTEC cell line, human renal proximal epithelium tubular cells-derived cell lines, such as RPTEC-TERT1, SA7K-clone, and cPiTEC, might be better choices for improving the predictivity.

Finally, the in silico-predicted \( C_{\text{max}} \) values of 20 food-related compounds were 0.017–187-fold more than the reported human \( C_{\text{max}} \) values. By replacing the in silico-predicted PBK parameters with in vitro-based ones, the prediction accuracy was improved. The predicted \( C_{\text{max}} \) values of 20 food-related compounds were almost within 10-fold as compared to those reported in literature and half of the compounds were within 3-fold. Previously, Terasaka et al. reported that most of the predicted \( C_{\text{max}} \) values were within a 6-fold range against the 150 drugs classified as Class 1a and 2 by the extended clearance classification system. Punt et al. reported that the predicted \( C_{\text{max}} \) values were within the 5-fold range for 34 of 44 drugs and food-related compounds. Therefore, the authors considered that the prediction accuracy of our in vitro-based prediction method was comparable to those with previously reported in vitro and in silico-based prediction methods. The in vitro-based prediction method included in our study has two advantages. The first is its focus on predictive methods for food-related compounds with minimal usage of pharmaceutical datasets, which might broaden the prediction applicable domain than those in drug-based datasets. The second is its transparency by mimicking each ADME process in vitro, which could be more agreeable to safety evaluation assessors emphasizing transparency in the prediction process. However, the limitation of this method is the limited number of compounds (n = 20) as compared with previous reports. Further evaluation of compounds might increase the reliance of our prediction method. Maximum fold error of the prediction is essential because a large prediction difference might lead to the over- or underestimation of the compounds for safety evaluations. Therefore, our in vitro-based prediction method is superior to the in silico-predicted method because the prediction variability was much lower. Although the authors observed that the \( C_{\text{max}} \) values of certain food-related compounds evaluated in this study tended to be overestimated, this might not be a problem in evaluating their safety as previously discussed (Punt et al., 2022). Addition of further ADME-related processes might increase the prediction accuracy of our method. For example, excretion in bile might be an important factor, especially for carboxylic and anionic compounds (Luo et al., 2010). Another possible factor might be the stability of food-related compounds in gastrointestinal fluid. Unlike pharmaceuticals, it is necessary to evaluate their stability in digestive fluid prior to the absorption process. Thus, although the consideration of in vitro-based parameters is important, improved simulation software for analyzing human plasma concentration is also needed. ACD/Percepta is a simplified compartment-based model that does not include the stability of compounds in the gastrointestinal tract and does not consider the different elimination processes, such as metabolism in the liver, renal elimination, and biliary excretion separately. Without modifying the PK Explorer module, its use can the prediction accuracy. The authors experienced this limitation while investigating catechins in the in vitro assays, where catechins were difficult to evaluate because of their instability at physiological pH (data not shown). Out of all the test compounds, ochratoxin A had underpredicted \( C_{\text{max}} \) values (0.092-fold). This compound was reported to have extremely low \( f_s \) values (6 × 10⁻²) and its detection sensitivity was close to the detection limit of UPLC-MS/MS. This experimental variability may lead to a difference in predicted \( V_d \) (11.7 L) compared to reported \( V_d \) (6.9 L), which might lead to lower prediction of \( C_{\text{max}} \) value. Punt et al. (2022) reported that predicted \( C_{\text{max}} \) values of ochratoxin A were lower than the observed values; thus, the underestimation of ochratoxin A was not unique in our prediction method. Further research and refinement would be needed to resolve this issue.

In conclusion, compared with in silico-derived predictions, the authors obtained more accurate and transparent predictions for the \( C_{\text{max}} \) values of food-related compounds by appropriately combining ADME-related in vitro tests and simulation of plasma concentrations. This method can enable accurate safety evaluation of food-related compounds without the need for animal experiments.

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Conflict of interest
The authors have no conflicts of interest.

Data availability statement
The research data described in the manuscript is available within the article and its supplementary data.