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薬物体内動態支配因子のファーマコゲノミクス

に

基づく医薬品開発評価

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研究代表者　鈴木　洋史

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厚生労働科学研究費補助金

（医薬品・医療機器等レギュラトリーサイエンス総合研究事業）

総括研究報告書

薬物体内動態支配因子のファーマコゲノミクスに基づく医薬品開発評価

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Ａ．研究目的

本研究は、個別化医療への応用の期待されるP450代謝酵素（CYP）について、日本人のファーマコゲノミクス（PGx）に必要な情報を、科学的に整理して収集し、動態変化の定量的予測を通じて効果、安全性、薬物間相互作用の予測を可能とすることを目的とする。平成２０年度は、より広範な薬剤に予測を適用するために、*in vitro*の情報を利用する方法論の確立を重点的に検討した。また、薬物動態（PK）の変化を薬効・安全性の評価に読み替える系統的な方法論の構築を行った。

Ｂ．研究方法

薬物動態の予測を個別化医療に積極的に利用するには、方法が単純でしかも精度が十分に高い必要がある。我々はこの観点から薬物動態の理論を再検討し、予測に不可欠な最低限度の情報は、①遺伝子変異や併用薬によるCYPの活性の変化と②基質薬の各CYP分子種への代謝依存度（寄与率）であるとした。前年度まではこれらの情報を臨床試験の成績から得ていたが、今年度は*in vitro*の情報との相関を詳細に見直すことで、精度を保ったままで利用できる情報を選別するとともに、実際に*in vitro*の実験の方法論を検討した。また、PKの変化をランク分けすることで、薬効・安全性の評価に網羅的に結びつけるシステム、PISCSを確立した。本研究では一部で患者より採取した生体試料中の薬物濃度を測定した。実施にあたっては、東京大学医学部倫理委員会による計画の承認を受けた上で行った。

Ｃ．結果および考察

PKの変化をランク分けすることで、薬効・安全性の評価に網羅的に結びつけるシステム、PISCSを確立し、その有用性をベンゾジアゼピン、HMG-CoA阻害剤およびCa拮抗剤を例として示した（資料１：A Proposal for a Pharmacokinetic Interaction Significance Classification System (PISCS) Based on Predicted Drug Exposure Changes and its Potential Application to Alert Classification in Product Labeling. Clinical Pharmacokinetics, 2009, *in press*）。

また、これまでの調査をさらに拡大し、市場の医薬品で特定のCYPの代謝の寄与が大きく、PGxや薬物間相互作用によりPKが変化する薬剤を系統的に調査して発表した（資料２：しくみから理解する薬物間相互作用．PharmaTribune, 2009; 1(3)）。

さらに、薬物間相互作用とPGxについて理論的考察を深め、肝外クリアランスや小腸の代謝の寄与がある場合でも、本研究の予測は精度を保つことを示すとともに、相関解析により、基質の代謝寄与率については肝ミクロソームを用いる*in vitro*実験から精度良く予測することが可能であり、特に発現系酵素を利用するRAF法が比較的優れていることを明らかとした（資料３：Systematic Prediction of Pharmacokinetic Drug-drug Interactions Caused by Changes in Cytochrome P450 Activity）。また、本研究の予測を新薬開発に応用する方法論を提案した。

そこで、LC-MS/MSを利用した高感度分析法と組み合せることで、精度と評価の効率の優れた代謝寄与率の評価法を確立し、多くの組み合わせの薬物間相互作用のPK変化の予測に成功した（資料４：ボリコナゾールおよびフルコナゾールの及ぼすCYP基質に対する薬物間相互作用のIn vitro代謝試験からの予測）。一

方、代謝阻害率については、*in vitro* と *in vivo* の情報の間に齟齬が多く、その原因としては阻害や誘導の機構の複雑さ、代謝物の寄与、あるいは肝臓中への薬物の濃縮などが考えられた。

D．結論

本研究で構築した方法論を積極的に用いることで、現在市場にある多くの薬の CYP の寄与率が判明し、PGx や薬物間相互作用による薬物動態の変化を予測し、さらに PISCS と組み合せることで薬効・安全性の変化の評価が網羅的に可能となった。また、新薬開発においてもこの方法論は適用が可能であり、より安全で有効な薬物治療の実現に貢献できると考えられた。

F．健康危険情報

該当ございません。

別添３　資料１

(Hisaka et al. Clinical Pharmacokinetics, 2009, *in press*)

A Proposal for a Pharmacokinetic Interaction Significance Classification System (PISCS) Based on Predicted Drug Exposure Changes and Its Potential Application to Alert Classifications in Product Labeling

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ABSTRACT

Background and Objective: Pharmacokinetic drug-drug interactions (DDIs) are one of the major causes of adverse events in pharmacotherapy, and systematic prediction of the clinical relevance of DDIs is an issue of significant clinical importance. In a previous study, total exposure changes of many substrate drugs of cytochrome P450 (CYP) 3A4 caused by co-administration of inhibitor drugs were successfully predicted by using *in vivo* information. In order to exploit these predictions in daily pharmacotherapy, the clinical significance of the pharmacokinetic changes needs to be carefully evaluated. The aim of the present study was to construct a pharmacokinetic interaction significance classification system (PISCS) in which the clinical significance of DDIs was considered with pharmacokinetic changes in a systematic manner. Furthermore, the classifications proposed by PISCS were compared in a detailed manner with current alert classifications in the product labeling or the summary of product characteristics used in Japan, the United States of America (USA), and the United Kingdom (UK).

Methods: A matrix table was composed by stratifying two basic parameters of the prediction: CR, the contribution ratio of CYP3A4 to the oral clearance of substrates, and IR, the inhibition ratio of inhibitors. The total exposure increase was estimated for each cell in the table by associating CR and IR values, and the cells were categorized into nine zones according to the magnitude of the exposure increase. Then, correspondences between the DDI significance and the zones were determined for each drug group considering the observed exposure changes and the current classification in the product labeling. Substrate drugs of CYP3A4 selected from three therapeutic groups, i.e. HMG-CoA reductase inhibitors (statins), calcium-channel blockers (Ca blockers) and benzodiazepines (BZPs), were analyzed as representative examples. The

product labeling descriptions of drugs in Japan, USA, and UK were obtained from the websites of each regulatory body.

Results: Among 220 combinations of drugs investigated, estimated exposure changes were more than five-fold for 41 combinations in which ten combinations were not alerted in the product labeling at least in one country; these involved buspirone, nisoldipine and felodipine as substrates, and ketoconazole, voriconazole, telithromycin, clarithromycin and nefazodone as inhibitors. For those drug combinations, the alert classifications were anticipated as potentially inappropriate. In the current product labeling, many inter-country differences were also noted. Considering the relationships between previously observed exposure changes and the current alert classifications, the boundaries between "contraindication" and "warning/caution" were determined as a seven-fold exposure increase for statins and Ca blockers, and as a four-fold increase for BZPs. PISCS clearly discriminated these drug combinations in accordance with the determined boundaries. Classifications by PISCS were expected to be valid even for future drugs because the classifications were made by zones, not by designating individual drugs.

Conclusion: The present analysis suggested that many current alert classifications were potentially inappropriate especially for drug combinations where pharmacokinetics had not been evaluated. It is expected that PISCS would contribute to constructing a leak-less alerting system for a broad range of pharmacokinetic DDIs. Further validation of PISCS is required in clinical studies with key drug combinations, and its extension to other CYPs and metabolizing enzymes remains to be achieved.

INTRODUCTION

Many patients suffer from excessive or impaired drug effects because of drug–drug interactions (DDIs)[1] and some drugs have even been withdrawn because of fatal adverse events[2-5], which may have been potentiated by DDIs. Prediction of DDIs is an issue of clinical significance and has been extensively investigated in the literature by *in vitro* experiments[6-10]. However, these have met with limited success because of insufficient accuracy and limited applicability when used in clinical settings for dose adjustment[2]. Considering the huge number of drugs used commercially, a complete conception change will be required to allow the prediction of many DDIs occurring in daily pharmacotherapeutic situations.

Recently, a systematic method has been reported for predicting DDI-mediated total drug exposure (or the area under the drug plasma or serum concentration-time curve, AUC) changes caused by inhibition or induction of cytochrome P450 (CYP) 3A4 activity[11, 12]. CYP3A4 is the most abundant metabolic enzyme in the human liver and the intestine and is involved in the metabolism of approximately 50% of currently available therapeutic agents[2, 13-15]. CYP3A5 is another important metabolizing enzyme in human CYP3A family, and it shares similar substrate specificities with CYP3A4[16-18]. Therefore, the contributions of CYP3A5 to most DDIs are difficult to differentiate from those of CYP3A4. Nevertheless, CYP3A5 is not completely equal to CYP3A4, and it has been reported that some inhibitors of CYP3A4 inhibit CYP3A5 significantly less potently than CYP3A4 both *in vitro*[19-21] and *in vivo*[22].

For inhibitory DDIs, the prediction method is based on two parameters obtained from drug exposure changes derived from clinical studies in which drugs were orally co-administered with typical CYP3A4 substrates (i.e., midazolam or simvastatin) or inhibitors (i.e., ketoconazole or itraconazole)[11]. Theoretically, these two parameters can be estimated from *in vitro* experiments. However, in these studies, the source of information was limited to *in vivo* studies because the accuracy of prediction has not been fully analyzed when these parameters are estimated *in vitro*. Once the two parameters have been calculated, total exposure changes for any oral combination of drugs can be predicted. The accuracy of prediction was satisfactory and the estimated exposure increases were within a range of 0.5- to 2.0-fold of the observed increases in 62 out of 65 drug combinations (95%) involving inhibition of CYP3A4[11].

Considering the broad applicability and precision of the prediction method, it can be regarded as useful in clinical settings. However, for practical application to pharmacotherapy, the clinical significance of DDIs needs to be estimated rather than simple pharmacokinetic changes. Therefore, the aim of the present study was to develop a pharmacokinetic interaction significance classification system (PISCS) which is capable of estimating the clinical significance of DDIs by considering both pharmacokinetic changes and therapeutic aspects. It should be noted that drugs with a broad therapeutic window are less sensitive to clinical significant adverse consequences due to pharmacokinetic DDIs and *vice versa*. However, the therapeutic window of a drug is often difficult to characterize. Moreover, on occasion, a drug needs to be used when an alternative therapy is unavailable, even though the therapeutic window is narrow and the predicted DDI is significant. Hence, the relationships between pharmacokinetic changes and clinical significance are complicated and not

apparent for many clinical personnel. For this reason, having a systematic classification of the clinical significance of DDIs based on pharmacokinetic changes is advantageous. This will aid in constructing a DDI alerting system for various risks associated with numerous pharmacotherapies used in the current market.

The Food and Drug Administration (FDA) of the USA announced a draft guidance with regard to DDI in 2006[23]. In this draft guidance, inhibitors and substrates of CYP enzymes were classified according to the magnitude of the drug exposure increase caused by typical co-administered drugs. Although the proposal is effective for classification of new drug candidates, it provides no means for predicting the significance of DDI for a specific drug combination. PISCS has some similarities to the draft guidance in the classification criteria of drugs, but possesses a unique function which allows prediction of clinical significance of DDI.

In many countries, the drug prescriptions are legally required to be checked for agreement with the product labeling (or the summary of product characteristics in European countries). The product labeling is developed by pharmaceutical manufacturers under the supervision of regulatory bodies. In the product labeling, a DDI is traditionally described as one of three categories, viz., contraindication, warning or caution, or nonalerted. In some situations, dose-adjustment recommendations are provided as a useful part of warning label. The criteria for these alert categories are not always definitive. In this study, the classifications proposed by PISCS were compared with current alert classifications in the product labeling or the summary of product characteristics used in Japan, the United States of America (USA), and the United Kingdom (UK). We examined whether drug exposure changes predicted by PISCS are in agreement with information provided by the product labeling. Furthermore, the alert classifications were compared in detail among countries for many drug combinations in which a significant exposure increase was anticipated.

In the present study, the target DDIs are limited to pharmacokinetic ones caused mainly by inhibition of CYP3A4, although it is well known that a series of metabolizing enzymes and transporters other than CYP3A4 are involved in pharmacokinetic DDIs. Furthermore, the interactions with some drugs, such as protease inhibitors for treatment of HIV, were excluded because those drugs exhibited a marked potential to induce and inhibit CYP3A4 simultaneously[24-26] . In spite of these limitations, the present study is the first attempt to predict the significance of pharmacokinetic DDIs for many combinations of drugs in a systematic manner.

METHODS

Prediction of DDI-mediated total exposure changes

DDI-mediated total drug exposure changes were estimated using the *in vivo*-based method previously described[11]. Briefly, based on pharmacokinetic considerations, it was hypothesized that total exposure changes are determined by two parameters: CR_{CYP3A4}, the apparent contribution ratio of CYP3A4 to oral clearance of the substrate drug, and IR_{CYP3A4}, the apparent inhibition ratio of CYP3A4 caused by an inhibitor drug[11]. The values of these two parameters were calculated from reported changes in total exposures of substrates produced by inhibitory DDIs with CYP3A4. For any DDI

that results in inhibition of CYP3A4, the change in the AUC may be estimated using Eq. 1[11]:

$$AUC(change) = \frac{1}{1 - CR_{CYP3A4} \cdot IR_{CYP3A4}} \quad \text{Eq. 1}$$

Eq. 1 is compatible with previous pharmacokinetic theories[6, 7, 10, 27-29] as described below. Under assumptions of reversible inhibition and of negligible non-CYP clearance, the following equations are maintained where I, K_i and f_m are the concentration of an inhibitor, the inhibition constant and the fraction of metabolism, respectively.

$$IR = \frac{I}{I + K_i} \quad \text{Eq. 2}$$

$$CR = f_m \quad \text{Eq. 3}$$

Using these relationships, Eq. 1 can be rewritten as Eq. 4 which is frequently presented in the literature of DDI research for competitive and non-competitive inhibitions [6, 7, 10, 27-29].

$$AUC(change) = \frac{1}{(\frac{f_m}{1 + \frac{I}{K_i}}) + (1 - f_m)} \quad \text{Eq. 4}$$

When metabolites of a parent drug also contribute to DDI *via* inhibition of the CYP enzyme, the IR is calculated using Eq. 5:

$$IR = 1 - \frac{1}{1 + \sum_{i=0}^{n} \frac{I_i}{K_{i,i}}} \quad \text{Eq. 5}$$

where I_0 and $K_{i,0}$ are the concentration and inhibition constant of a given parent drug, I_1, I_2, I_3..., and $K_{i,1}$, $K_{i,2}$, $K_{i,3}$... are those of metabolites, respectively. The drug exposure changes by mechanism-based inhibition were explained mathematically using a degeneration constant (k_{deg}) and an inactivation rate constant (k_{inact}) [30, 31]. Eq. 1 becomes equivalent to the equation reported when IR is related with k_{deg} and with k_{inact} as in Eq. 6.

$$IR = \frac{I}{I + \frac{k_{inact}}{k_{deg}}(I + K_i)} \quad \text{Eq. 6}$$

Therefore, Eq. 1 covers various DDI situations, including reversible (competitive and non-competitive) and irreversible (mechanism-based) inhibitions, and inhibition by metabolites.

Oral formulations for 13 substrates and 17 inhibitors of CYP3A4 were analyzed in this study (Tables 1 and 2). In this study, predicted drug exposure increases were restricted to equal or less than 25-fold considering preciseness of the CR and IR values. Predicted exposure increases were compared with reported exposure increases in humans, which were retrieved from the PubMed database using the key words, CYP3A4, drug interaction, and clinical trial.

Classification of substrates and inhibitors of CYP3A4

To demonstrate the applicability of PISCS, substrate drugs of CYP3A4 selected from three therapeutic groups were analyzed: HMG-CoA reductase inhibitors (statins), calcium-channel blockers (Ca blockers) and benzodiazepines (BZPs). These groups were selected because many CYP3A4 substrates were included (Table 1). However, a series of clinically important drugs in these groups were excluded from the analysis because there is no or only minor contribution of CYP3A4 to their clearances. Although zolpidem is not a BZP, it was included in the BZP group in this analysis because of its therapeutic similarity to BZPs.

In the first step of the analysis, all substrates and inhibitors were stratified into six categories: (1) very selective/strong (VS), (2) selective/strong (S), (3) slightly selective/strong (SS), (4) moderate (M), (5) weak (W), and (6) very weak (VW) those correspond to CR_{CYP3A4} and IR_{CYP3A4} values of ≥ 0.9, 0.8~0.89, 0.7~0.79, 0.5~0.69, 0.3~0.49, and 0.1~0.29, respectively. 'Very weak' categories were introduced in a PISCS table for consistency with the prediction of inductive DDIs, which will be described in a future study. For the purpose of estimating significant drug exposure changes caused by inhibition of a single metabolizing enzyme, 'very weak' categories would not be informative. Next, a 6 × 6 matrix table was constructed using these categories (Fig. 1). The estimated average exposure increase in each cell of the matrix was calculated by the double integral of Eq. 1 as follows.

$$\iint_{c\ a}^{d\ b} \frac{1}{1-CR\cdot IR} dCR\cdot dIR / S$$
$$= \frac{Li_2(a\cdot d) - Li_2(a\cdot c) + Li_2(b\cdot c) - Li_2(b\cdot d)}{(b-a)(d-c)} + 1 \qquad \text{Eq. 7}$$

where variables a and b represent boundaries for CR, and variables c and d represent boundaries for IR. S is an area defined by boundaries a, b, c and d. Li_s is a polylogarithm function ($Li_s(z) = \sum_{k=1}^{\infty} \frac{z^k}{k^s}$). The table was divided into nine zones by grouping the cells of similar estimated average exposure increase. The final decision for grouping was made based on the profiles of the distribution of predicted increases, which were calculated as follows.

The distribution of predicted drug exposure increases in each zone were simulated numerically by generating CR and IR values. In each cell in the PISCS table (Fig. 1),

1600 total exposure predictions were calculated with an arithmetical series of CR and IR values (40 × 40). The distribution of prediction was analyzed by making a histogram with Microsoft Office Excel 2007. Distribution curves were normalized so that the area under the curve was equivalent between zones.

In the FDA draft guidance "Drug interaction studies- study design, data analysis, and implications for dosing and labeling" announced in 2006[23], inhibitors and substrates of CYP3A were classified into three (strong, moderate and weak) and two (sensitive and nonsensitive) categories, respectively. Exposure increases of these substrates with co-administration of the inhibitor were simulated assuming the boundaries of the inhibitors correspond to IR values of 0.87, 0.54 and 0.22, and the boundary for substrates corresponds to CR values of 0.8 and 0.3. The lower boundary of nonsensitive substrates was not specified in the guidance but determined provisionally as a CR value of 0.3 which is equal to the lower boundary of Zone VII.

The boundaries for classification of the significance of a given DDI were determined for statins, Ca blockers and BZPs as representative examples. Theoretically, the boundaries were adjustable with regard to any pharmacological measure, such as the margin of the therapeutic window. In this study, the boundaries were determined in a more pragmatic manner, considering relationships between the observed exposure changes and the current classification of alerts in each product labeling. The boundary between areas corresponding to "contraindication" and "warning/caution" was defined as an total exposure increase of seven-fold for statins and Ca blockers, and four-fold for BZPs. These values were chosen because observed total exposure increases greater than seven-fold for statins and Ca blockers, and four-fold for BZPs are categorized as contraindications in many cases in the current product labeling. AUC boundaries between "warning/caution" and "nonalerted" were defined as two-fold for statins and Ca blockers, and 1.5-fold for BZPs based on similar consideration. For statins and Ca blockers, Zone I corresponds to contraindication and Zones II~V correspond to caution (Fig. 1). For BZPs, Zones I~II and Zones III~VI correspond to contraindication and caution, respectively.

Survey of product labeling descriptions of drugs

The product labeling descriptions of drugs in Japan, the United States of America (USA), and the United Kingdom (UK) were obtained from the website of the Pharmaceuticals and Medical Device Agency (http://www.pmda.go.jp), the FDA website (http://www.fda.gov), and the electronic Medicines Compendium (http://emc.medicines.org.uk), respectively. The websites were accessed in April 2008. These descriptions of DDIs, which were categorized as contraindication, warning or caution, and nonalerted, were compared with predicted changes in AUCs. When an inconsistency existed between the alert classifications of the substrate drug and the inhibitor drug, a higher level alert was used for analysis. If DDIs were alerted for a group of drugs with example names (for example, azole antifungals such as ketoconazole and itraconazole), the description was interpreted as limited to the example drugs. Observed total exposure changes for DDIs were obtained from published data[11].

RESULTS

Implementation of the pharmacokinetic interaction significance classification system (PISCS)

The substrates and inhibitors of CYP3A4 analyzed in this study are listed in Tables 1 and 2, respectively. Fig. 1 shows the PISCS table in which substrates and inhibitors are stratified into six categories according to the contribution ratio of CYP clearance (CR) and the inhibition ratio (IR), respectively. The table was then divided into nine zones according to the estimated drug exposure increase.

To explore the classification performance of the zones (from I to VII) in the PISCS table, the distributions of total exposure increase were carefully simulated with the arithmetical series of CR and IR values in Fig. 2A. The zones discriminated the magnitude of exposure increases efficiently. According to our numerical simulation presented in Fig. 2B, the classifications of CYP3A inhibitors and substrates made by the FDA draft guidance[23] failed to predict exposure increases quantitatively. The magnitudes of the predicted exposure increases overlapped considerably between combinations of sensitive substrate · moderate inhibitor and of nonsensitive substrate · strong inhibitor. The combination of nonsensitive substrate · strong inhibitor also overlapped with the combinations of nonsensitive substrate · moderate inhibitor and sensitive substrate · weak inhibitor.

Relationship between predicted drug exposure increases and alert classifications

Fig. 3 shows the predicted drug exposure increases for 220 DDIs and product labeling alert classifications in Japan, the USA, and the UK. In general, drug combinations with large predicted exposure increases were associated with high-level alerts in all three countries. However, there was considerable irregularity in all three countries in which the alert classification was at variance with the predicted exposure increase. For example, combinations of nisoldipine and inhibitors of CYP3A4, such as voriconazole, telithromycin, clarithromycin, and erythromycin, are not alerted in the UK despite an approximately five-fold total exposure increase of nisoldipine being estimated for these combinations. On the other hand, a combination of nisoldipine and cimetidine is alerted as a caution but this only raised the plasma exposure of nisoldipine 1.5-fold[32]. Similar irregularities were also found for the alert classifications in Japan and the USA (Fig. 2).

Among 220 combinations of various substrates and inhibitors investigated, the drug exposure was anticipated to increase more than five-fold for 41 combinations in which ten combinations were nonalerted by the product labeling at least in one country; these involved buspirone, nisoldipine and felodipine as substrates, and ketoconazole, voriconazole, telithromycin, clarithromycin and nefazodone as inhibitors (Table 3). For only one of these combinations, the exposure change had been measured in humans. The number of combinations increased to 27 when a more than three-fold total exposure increase was considered (Table 3).

Comparison of product labeling alerts in Japan, the USA, and the UK

According to the prediction, drug exposures increased by more than two-fold for 109 of 220 drug combinations. In total, 71.4% of these combinations were associated with alerts and the percentage of alerts was similar among countries (Table 4). Clinically documented exposure increases were available for 40.4% (44/109) of these combinations.

In all three countries, most combinations in which the observed total exposure increase was greater than two-fold in humans were associated with product labeling alerts (94.1% in total, Table 4). In contrast, only 56.3% of combinations for which human pharmacokinetics were unavailable were accompanied by product labeling alerts (Table 4).

Inconsistencies were also noted among the three countries. Of 109 combinations with a two-fold or greater predicted total exposure increase, 49.5% of combinations involved drugs unapproved in more than one country. Only 20.2% of combinations had identical alerts in all three countries. Of the remaining 30.3%, 24.8% of combinations had warning/caution alerts in one or two countries.

Analysis of alerts for statins, Ca blockers, and benzodiazepines

In Fig. 4, the consistency between drug exposure increases and significance classification of DDI was compared between the current product labeling and PISCS for CYP3A4 substrate drugs categorized in statins, Ca blockers and BZPs. It was apparent that PISCS provided more discriminatory alerts. In Table 5, alert classifications of the current product labeling were compared with proposals by PISCS for azole antifungals. In the present analysis, approximately 50% of classifications by PISCS disagree with the current classifications. For instance, a combination of simvastatin is contraindicated with erythromycin in the UK with a 6.2-fold increase in the reported AUC of simvastatin[33]. A combination of simvastatin and telithromycin is labeled as a warning in the USA with an eleven-fold increase in the reported AUC of simvastatin[34]. On the other hand, PISCS suggested that simvastatin would be classified as a caution and contraindication with erythromycin and telithromycin, respectively.

DISCUSSION

Alerts for DDIs can be classified according to the exposure increases because the pharmacological actions or adverse reactions to drugs that have common pharmacological or toxicological target molecules, such as receptors and enzymes, depend on the degree of occupation of the target molecules[35-37]. Other than total exposure, the maximum plasma concentration (C_{max}, peak exposure) and the time above a certain plasma concentration (such as the minimum inhibitory concentration, MIC) have been used as indexes of drug efficacy and toxicity. However, since the correlation between the total exposure and these parameters is generally high, it is not easy to prove the advantages of using these parameters other than the drug total exposure (AUC). Therefore, the total exposure was adopted as a representative index of drug blood concentrations in this study. Correlation between plasma or serum concentrations of BZPs and the incidence of adverse events, such as postural sway, have been reported[38]. For Ca blockers and BZPs, the severity of dizziness and other adverse events increase concomitantly with the increase in the blood concentration of the drug after coadministration of inhibitors of CYP3A4[39-41]. For statins, rhabdomyolysis have been associated with coadministration of CYP3A4 inhibitors[42]. These pieces of evidence support the development of DDI alerts based on predicted total exposure increases.

For many drug combinations investigated in this study, exposure was anticipated to be markedly elevated according to our prediction, yet nonalerted by the current product labeling. For most of these combinations, pharmacokinetic alternations had not been evaluated in the literature. Therefore, it is meaningful to evaluate their exposure changes in actual clinical studies. Even so, from the therapeutic standpoint of view, the significance of these clinical studies would not be always high since some of these combinations include drugs that are rather old and now infrequently prescribed. For example, the alert classification of nisoldipine was at variance with the predicted total exposure increase and was inconsistent among countries (Fig. 2). This is probably a reflection of both insufficient DDI data and slow updates of the product labeling on nisoldipine. Concerning the disposition of nisoldipine, DDI clinical studies have only been conducted with ketoconazole and cimetidine[32, 40] and our analysis suggested it is possible to classify nisoldipine as a very selective substrate of CYP3A4 from these clinical studies. Consequently, exposure changes of nisoldipine were made to be predictable for various combinations. In contrast, it should be emphasized that we could not even determine CR values of the third generation Ca blockers such as amlodipine and azelnidipine which are frequently prescribed in the current pharmacotherapy. This is because of lack of appropriate *in vivo* DDI data on these drugs. Further DDI clinical studies are obviously required with key drug combinations considering therapeutic needs very carefully.

PISCS would also facilitate safer pharmacotherapy of newer drugs with limited clinical information, such as the effective antifungal agent, voriconazole[43]. Although its inhibition of CYP3A4 was reported to be insubstantial in an *in vitro* experiment as indicated by an IC_{50} value of 10.5μM[44], *in vivo* data indicated that voriconazole is a strong inhibitor of CYP3A4 because the plasma AUC of coadministered midazolam and sirolimus increased to approximately ten-fold[45, 46]. In PISCS, voriconazole is classified as a very strong inhibitor of CYP3A4 comparable with ketoconazole and itraconazole (Table 2), and it should be prescribed with great care for use concomitantly with very selective or selective substrates of CYP3A4, such as lovastatin, simvastatin, nisoldipine, or midazolam (Table 1). As Table 5 shows, DDIs for voriconazole are possibly underestimated relative to DDIs for other antifungal agents of similar inhibitory activity in the current product labeling. As PISCS is a prediction-based method, it would be possible to simply overestimate the DDI potential of voriconazole, i.e. a false positive. However, caution should be warranted in using voriconazole until a series of clinical studies clearly identifies the *in vivo* inhibitory potential of voriconazole.

In this study, significant between-country differences were also revealed in DDI alert classifications of the product labeling (Fig. 3). Theoretically, these differences may reflect intrinsic (genetic) and extrinsic (environmental or cultural) ethnic differences. In the present analysis, however, no clear evidence was found for ethnic differences in drug responses. Rather, these differences may appear to have arisen from the heterogeneity that has resulted historically from approvals that might have been granted over a time range of several decades in each region. It is probable that the description of any product labeling was restricted by proven evidence available at the time of submission and could not refer to hypothetical theories. In the future, however, it seems reasonable to accept that proven evidence for all possible DDIs cannot be

collected as the number of substrate drug for CYP is in the thousands. Therefore, predictive descriptions may need to be used more explicitly with regard to alerts on DDIs in the product labeling. In addition, achieving international harmonization on the criteria for alerting on DDIs could be very helpful.

Concerning the regulatory aspects of DDI at present, the FDA announced a draft guidance titled "Drug interaction studies- study design, data analysis, and implications for dosing and labeling" in 2006[23] which should have substantial impacts on international drug development and also on the product labeling in the world. One of new features of the draft guidance was that the inhibitor and substrate drugs of CYPs were categorized by potential of DDIs. In the draft guidance, drugs which increase the AUC of sensitive CYP3A substrates, such as midazolam, by five-fold or higher, from two- to five-fold, and from 1.25- to two-fold were defined as strong, moderate and weak CYP3A inhibitors, respectively. The basic concept of PISCS is the same as the draft guidance in that the total exposure increase of a concomitantly given selective substrate is the best index for evaluating the inhibitory potential. In fact, increases of midazolam exposure of 1.25-, two- and five-fold correspond to IR values of 0.22, 0.54 and 0.87, respectively. Regarding the classification of substrates of CYP3A, "sensitive substrate" was defined as drugs which exhibit total exposure increases of more than five-fold with co-administration of potent inhibitors in the draft guidance. This criterion corresponds to CR values of more than 0.8 in PISCS. In spite of these similarities, the draft guidance provides no means of quantitative prediction for exposure changes caused by DDI. As simulated in Fig. 2B, the classifications proposed by the draft guidance would be insufficient to predict the magnitude of drug exposure changes caused by inhibition of CYP enzymes.

Likewise, "substrates with narrow therapeutic range" were exemplified as drugs which potentially cause serious safety concerns, such as Torsades de Pointes, in the draft guidance. This is an important factor to be considered to estimate the significance of DDIs, however, an actual procedure to incorporate the therapeutic range in the alert classification was not documented. Advantages of PISCS would be that the total exposure increases can be quantitatively predicted and, in addition, the alert classification is systematically adjustable considering the therapeutic range and other requirements. These characteristics may contribute to constructing a leak-less alerting system.

Similar to the FDA guidance, PISCS categorized the substrate and the inhibitor drugs by explanatory names such as "selective inhibitor" rather than using the CR and IR values directly (Fig. 1). This system would enable alerts to be more descriptive, e.g., "This drug is a selective substrate of CYP3A4 and a moderate inhibitor of CYP2D6" or "This drug is contraindicated with very strong inhibitors of CYP3A4." It would be impractical to include the names of all relevant generic drugs or therapeutic drug groups in product labeling. An advantage of the proposed system is that such alerts would also be appropriate for future drugs. With the current method, updating the product labeling is slow and often occurs after adverse events have been experienced by patients[47].

Interindividual variability is an issue that needs great cares in any method used for predicting biological events[48, 49]. In PISCS, the pharmacokinetic alternations are

accounted for primarily in average fold-changes in drug exposure. The significance of any interindividual variability caused by factors such as age, gender, disease state, ethnicity, and genetics needs to be considered additionally for the output of the system in some situations. In the PISCS table (Fig. 1), a given pharmacokinetic change is translated into a clinical significance. Conceptually, interindividual variability should be accounted for in this translation. For most drugs, when selecting zones in the PISCS table, a therapeutic window might need to be regarded as narrower than actual when considering interindividual variability in pharmacokinetics and/or pharmacodynamics. In addition, clarifying, and if necessary, differentiating target populations of each alert is recommended to reduce potential risks associated with interindividual variability. For example, for BZPs, defining the zones for the elderly population differently from the young would be better because of the higher sensitivity of the elderly for adverse events with these drugs[50, 51].

Finally, current limitations of PISCS should be discussed from the pharmacokinetic viewpoint. Theoretically, PISCS can be applied to DDIs caused by inhibition of any hepatic metabolizing enzymes. However, use of PISCS should be limited to inhibitory DDIs of CYP3A4 at present because prediction for the total exposure changes have been validated only for CYP3A4[47]. The interactions with some drugs, such as protease inhibitors for treatment of HIV, were not predictable with the current method because those drugs exhibited a marked potential to induce and inhibit CYP3A4 simultaneously[47]. Furthermore, the current system cannot manage DDIs caused by an inhibition of transporter activity. Cyclosporin is a typical inhibitor of transporters including OATP1B1(SLCO1B1) that plays a significant role in the hepatic uptake of several statins[52]. For this reason, cyclosporin as an inhibitor was excluded from the current analysis. It should be noted that cyclosporin increased the exposure of some statins which could not be explained by inhibition of CYP3A4[52, 53]. In the future, to apply PISCS to DDIs caused by alternations in transporter activity, theoretical extensions would be necessary since drug transport is a reversible process in principle and different from usual irreversible metabolism. Further studies are underway in our laboratory to apply PISCS to metabolizing enzymes other than CYP3A4.

CONCLUSION

Our analysis of current label classifications and predicted total drug exposure increases for DDIs involving CYP3A4 inhibition revealed current inconsistencies and shows that a comprehensive, and quantitative framework for determining criteria for alert classifications would be plausible. The PISCS table was proposed to categorize substrates and inhibitors, and to relate pharmacokinetic changes and clinical significance of DDIs in a systematic manner. Our proposal may facilitate safer and more reliable pharmacotherapy. Further validation of PISCS should be necessary from various viewpoints, and extensions to other CYPs and metabolizing enzymes remain to be achieved.

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