Concentration-dependent effects and intracellular accumulation of HIV protease inhibitors in cultured CD4 T cells and primary human lymphocytes

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Background: The intracellular and plasma concentrations of HIV protease inhibitors (HPIs) vary widely in vivo. It is unclear whether there is a concentration-dependent effect of HPIs such that at increasing concentration they may either block their own efflux (leading to ‘autoboosting’) or influx (leading to saturability/decreased intracellular accumulation).

Method: The effects of various concentrations (0–30 μM) of lopinavir, saquinavir, ritonavir and atazanavir on the accumulation of [14C]lopinavir, [3H]saquinavir, [3H]ritonavir and [3H]atazanavir, respectively, were investigated in CEMparental, CEMVBL (P-glycoprotein (ABCB1) overexpressing), CEME1000 (MRP1 overexpressing) and in peripheral blood mononuclear cells (PBMCs). We also investigated the effects of inhibitors of ABCB1/ABCG2 (tariquidar), ABCC (MK571) and ABCC1/2 (frusemide), singly and in combination with HPIs, on cellular accumulation.

Results: In all the cell lines, with increasing concentration of lopinavir, saquinavir and ritonavir, there was a significant increase in the cellular accumulation of [14C]lopinavir, [3H]saquinavir and [3H]ritonavir. Tariquidar, MK571 and frusemide (alone and in combination with lopinavir, saquinavir and ritonavir) significantly increased the accumulation of [14C]lopinavir, [3H]saquinavir and [3H]ritonavir. Ritonavir (alone or in combination with tariquidar) decreased the intracellular accumulation of [3H]ritonavir in PBMCs. Atazanavir decreased the accumulation of [3H]atazanavir in a concentration-dependent manner in all of the cells tested.

Conclusions: There are complex and variable drug-specific rather than class-specific effects of the HPIs on their own accumulation.

Keywords: lopinavir, saquinavir, ritonavir, atazanavir, transporters

Introduction

Highly active antiretroviral therapy (HAART) has markedly decreased the morbidity and mortality of HIV-infected individuals. However, despite the improvements associated with HAART, the virus continues to evolve in cellular reservoirs and anatomical sanctuary sites during therapy even when below detectable levels of HIV are achieved in plasma. The causes of persistent HIV infection despite undetectable plasma levels remain incompletely understood but probably include multiple factors such as persistence of virus in cellular reservoirs (e.g. CD4+ T cells and cells of the macrophage lineage) and anatomical sanctuary sites (brain and possibly testis), pharmacological and poor compliance. Collectively these sites represent a major impediment to the eradication of HIV. Viral sanctuary sites may result from the overexpression, in sites of HIV replication, of membrane-bound drug efflux transporters, e.g. P-glycoprotein (P-gp; ABCB1), multidrug resistance-associated proteins (MRPs; ABCCs) and breast cancer resistance protein (BCRP; ABCG2).

Some studies have provided evidence that HIV protease inhibitors (HPIs), e.g. saquinavir, ritonavir, lopinavir, atazanavir and darunavir, may be reduced by these drug efflux transporters, which may potentially promote the emergence of...
mutant viruses. Recent studies by others and us have also shown that organic anion transporting polypeptides (OATPs) may also influence the intracellular accumulation of some HPIs.16,17

HPIs exhibit complex interactions with drug transporters, drug metabolizing enzymes (CYPs) and serum proteins. These complex interactions lend support for the discrepancy between the intracellular concentrations of the HPIs measured in vivo and in vitro.18 Although data on association between genetic polymorphisms in drug metabolizing enzymes and transporter proteins are equivocal, they may explain, in part, the variable and complex plasma and cellular concentrations and treatment outcomes of HIV-infected patients. For example, despite some of the HPIs, e.g. lopinavir, being a substrate for ABCB1 and ABC2,12,19 on an earlier retrospective study of HIV-infected patients under antiretroviral therapy found no influence of the ABCB1 C3435T polymorphism on the plasma and peripheral blood mononuclear cell (PBMC) levels of lopinavir (or the non-nucleoside reverse transcriptase inhibitor, efavirenz)20,21 even though polymorphisms at the ABCB1 C3435T and G2677T/A, MRP1 (ABCC1) C218T and G2168A and MRP2 (ABCC2) G1249A have been associated with alterations in ABCB1, ABC1 and ABC2 activity.22–26 However, some studies found no association between the concentrations of saquinavir (alone or when boosted with ritonavir), atazanavir or lopinavir and polymorphisms in ABCB1 C3435T and G2677T/A.27,28 Furthermore, recent studies on three common exonic ABCB1 polymorphisms, C1236T, G2677T/A and C3435T, showed that these are poor predictors of the concentrations of lopinavir and ritonavir in saliva, semen and plasma.29 However, there is evidence of some association between G4544A polymorphism in ABC2C and higher accumulation of lopinavir in PBMCs of HIV-treated patients.30 Similar studies on 74 HIV-infected patients showed significantly higher plasma levels of atazanavir in patients with genotype CC than those with CT or TT for polymorphism at the ABCB1 C3435T.31 Studies in cultured cells showed that the permeability of amprenavir, indinavir, lopinavir and ritonavir was greater in ABCB1 (G1199A) cells than in ABCB1 wt cells, suggesting that ABCB1 G1199A polymorphism may impact on the systemic bioavailability of HPIs.32 Clearly if inter-individual differences in the bioavailability of HPIs is caused by genetic variants of ABCB1, ABCB1 and ABC2C, this may have a profound effect on the pharmacokinetics and pharmacodynamics of substrate drugs.

Inhibition of first-pass metabolism of the HPIs by cytochrome P450 (CYP) enzymes markedly increases the bioavailability of most HPIs and hence their therapeutic efficacy. Thus, ritonavir-boosted HPIs have become part of the standard of care for HIV-infected patients.31–38 Data on the interaction of HPIs are equivocal: we recently showed that amprenavir and atazanavir accumulation of lopinavir in PBMCs of HIV-treated patients.21 Inadequate plasma or intracellular concentrations of anti-retrovirals may lead to treatment failure. In order to adequately manage this, dose modification, guided by therapeutic drug monitoring of plasma concentration, is sometimes used as a strategy to address this problem. As HAART involves the concomitant use of multiple drugs, it appears important to evaluate the concentration-dependent effects of these drugs on intracellular accumulation and this was the aim of the present study.

Materials and methods

Reagents

[14C]lopinavir, [3H]saquinavir, [3H]ritonavir and [3H]atazanavir (specific activities of 1.0 Ci/mmol, 1.0 Ci/mmol, 1.1 Ci/mmol and 3.1 Ci/mmol, respectively) were purchased from Moravek Biochemicals (Brea, CA, USA). Lopinavir and ritonavir were donated by Abbott Laboratories (North Chicago, IL, USA). Saquinavir was donated by Roche (Welwyn Garden City, UK) and atazanavir was a gift from Bristol Myers Squibb (Hounslow, UK). Tenovir was a gift from Xenova Group Plc, (Slough, UK) and MK571 from Alexis Biochemicals (San Diego, CA, USA). CEM, CEMVBL and CEME1000 Cell lines were from Dr R. Davey (Bill Walsh Cancer Research Laboratories, Royal North Shore Hospital, Sydney, Australia). PBMCs were from blood Buffy coats obtained from the regional blood transfusion centre (Liverpool, UK). All other chemicals were supplied by Sigma Chemical Co. (Poole, UK).

Cell culture

The parental cell line was CEM (a CD4 T cell line). CEMVBL (VBL, P-gp overexpressing) cells were selected using vinblastine. CEME1000 (E1000, MRPI overexpressing) cells were selected with epirubicin. Cell volume (range 0.8–1.0 pL) and cell density were measured using a CASY Cell Counter (Sedna Scientific Ltd, Dronfield, Derbyshire, UK). We have previously validated the expression of the transporters in our laboratory.10 CEM cells were maintained at 37°C and 5% CO2 in RPMI 1640 medium supplemented with 10% fetal calf serum (FCS).

Isolation of PBMCs

PBMCs were isolated from blood Buffy coats using Lymphoprep, following the manufacturer’s instructions. Cell volume (0.3–0.4 pL) and cell density were measured using a CASY Cell Counter.

Ethics

No ethical approval was required in the collection and use of the blood products from the blood transfusion services.

Effects of various concentrations of unlabelled HPIs on the accumulation of radiolabelled equivalents

CEM and its variant cells (2.5×10⁶ cells/mL) and isolated PBMCs (5×10⁶ cells/mL) were pre-incubated with various concentrations (0–30 µM) of unlabelled lopinavir, ritonavir, saquinavir and atazanavir for 5 min before the addition of 0.5 µM [14C]lopinavir or 0.1 µM [3H]ritonavir or [3H]saquinavir or [3H]atazanavir in RPMI medium supplemented with 10% FCS. Given that HPIs are inhibitors of drug efflux transporters,34,47,52,53 we introduced the pre-incubation step to allow the inhibition of transporter activity by the unlabelled HPIs before the addition of their labelled equivalents. At the end of the initial pre-incubation...
Effects of tariquidar, MK571 and frusemide (alone and in combination with unlabelled lopinavir) on the accumulation of \([^{14}C]\)lopinavir

As inhibitors of drug efflux transporters such as tariquidar (inhibits ABCB1/ABCG2\(^{24–26}\)), MK571 (inhibits \(ABCB^{10,17,57–59}\)) and frusemide (inhibits \(ABCC1/2\)) increased the intracellular accumulation of HPIs,\(^{3,19}\) these agents were employed in the current studies, at the indicated concentrations, to characterize HPI-mediated activity against the cells. Here, CEM and its variant cells were initially pre-treated for 5 min with 1 \(\mu\)M tariquidar (CEM and CEM\(_{E1000}\)) cells) or 50 \(\mu\)M MK571 (CEM and CEM\(_{E1000}\)) cells) to inhibit ABCB1 and ABCC, respectively. Thereafter, the cells were incubated without or with 10 \(\mu\)M unlabelled lopinavir. In separate experiments, PBMCs were pre-treated for 5 min without or with 1 \(\mu\)M tariquidar or 50 \(\mu\)M frusemide (previously shown to increase the accumulation of lopinavir in PBMCs\(^{20}\)), followed by a further incubation treatment of the cells in the absence or presence of 10 and 30 \(\mu\)M lopinavir for 5 min. Thereafter, 0.5 \(\mu\)M \([^{14}C]\)lopinavir in RPMI medium supplemented with 10% FCS was added and the samples incubated for 15 min before the assay samples were processed as described above.

**Results**

Unlabelled lopinavir increased the accumulation of \([^{14}C]\)lopinavir in both cultured cells and PBMCs

\([^{14}C]\)lopinavir accumulated differentially in CEM and its variant cells, with the following rank order: CEM\(_{E1000}\) \(\geq\) CEM\(_{E1000}\) \(\geq\) CEM\(_{VBL}\) (Figure 1a and b and see Figure 3a). Pre-incubation of the cultured cells with unlabelled lopinavir (1–30 \(\mu\)M) followed by the addition of 0.5 \(\mu\)M \([^{14}C]\)lopinavir significantly (\(P<0.001\)) increased the CAR of \([^{14}C]\)lopinavir in CEM cells, with a concentration-dependent increase observed in CEM\(_{VBL}\) cells (Figure 1a). This self-stimulation could be due to inhibition of efflux transporters by unlabelled compound or alternatively could be a true trans-acceleration phenomenon, in which the
observed that in PBMCs there was a significant increase in the CAR of \( ^{14}\text{C}\)lopinavir alone (Figure 3a). Overall, co-incubation of MK571 or tariquidar with unlabelled lopinavir (at 10 \(\mu\)M) did not enhance the accumulation of \( ^{14}\text{C}\)lopinavir over that observed with unlabelled lopinavir alone.

In the PBMCs, the effects of fixed concentrations (10 and 30 \(\mu\)M) of lopinavir were investigated alone and in combination with 1 \(\mu\)M tariquidar or 50 \(\mu\)M frusemide (Figure 3b). Tariquidar and frusemide also significantly (\(P<0.001\)) increased the CAR of \( ^{14}\text{C}\)lopinavir, but not as much as that observed with unlabelled lopinavir alone. Tariquidar (at 1 \(\mu\)M) or 50 \(\mu\)M frusemide in combination with unlabelled lopinavir (at 10 and 30 \(\mu\)M) significantly (\(P<0.001\)) increased the accumulation of \( ^{14}\text{C}\)lopinavir over and above the increases measured for tariquidar and frusemide alone. However, the levels were identical to those observed in samples treated with unlabelled lopinavir alone (Figure 3b).

To further understand lopinavir-mediated increase in its own accumulation, we investigated its effects on other known substrates of ABCB1 and ABCC. To this end we evaluated the effects of various concentrations (0–30 \(\mu\)M) of unlabelled lopinavir on the accumulation of \( ^{3}\text{H}\)saquinavir and \( ^{3}\text{H}\)ritonavir in CEM, CEM\(_{E1000}\) (ABCC1 overexpressing) and CEM\(_{VBL}\) (ABCC1 overexpressing) cells. Data obtained from these manipulations showed that unlabelled lopinavir significantly (\(P<0.01\)) increased the accumulation of \( ^{14}\text{C}\)lopinavir in all of the cells in a concentration-dependent manner (Figure 3c and d).

**Ritonavir increased the accumulation of \( ^{3}\text{H}\)ritonavir in cultured cells**

\( ^{3}\text{H}\)ritonavir accumulated differentially in CEM cells with the following rank order: CEM > CEM\(_{E1000}\) > CEM\(_{VBL}\) (Figure 4a and b), indicating that ritonavir is a substrate for ABCB1 and ABCC1. Pre-treatment of the cultured cells with unlabelled ritonavir followed by the addition of \( ^{3}\text{H}\)ritonavir significantly (\(P<0.001\)) increased the accumulation of \( ^{3}\text{H}\)ritonavir in CEM\(_{E1000}\) cells in a concentration-dependent manner. In contrast, unlabelled ritonavir (at 10 and 30 \(\mu\)M) significantly (\(P<0.01\)) increased the CAR of \( ^{3}\text{H}\)ritonavir in parental CEM cells at 10 and 30 \(\mu\)M unlabelled ritonavir, whilst only ritonavir (at 30 \(\mu\)M) produced a significant (\(P<0.001\)) increase in the accumulation of \( ^{3}\text{H}\)ritonavir in CEM\(_{VBL}\) cells (Figure 4a). The differences between CEM cells and CEM\(_{E1000}\) cells are significant at concentrations of ritonavir >3 \(\mu\)M (\(P<0.01\)).

**Tariquidar, MK571 and frusemide (alone and in combination with unlabelled ritonavir) demonstrated variable effects on the accumulation of \( ^{3}\text{H}\)ritonavir**

Unlabelled ritonavir (at 30 \(\mu\)M) significantly (\(P<0.001\)) increased the CAR of \( ^{3}\text{H}\)ritonavir in CEM, CEM\(_{VBL}\) and CEM\(_{E1000}\) cells compared with their respective controls (Figure 4b). Tariquidar (at 1 \(\mu\)M) significantly (\(P<0.001\)) increased the accumulation of \( ^{3}\text{H}\)ritonavir in CEM\(_{VBL}\), but not in parental CEM cells. In contrast, 50 \(\mu\)M MK571 significantly (\(P<0.001\)) increased the accumulation of \( ^{3}\text{H}\)ritonavir in both CEM and CEM\(_{E1000}\) cells. Pre-treatment of the cells with 1 \(\mu\)M tariquidar followed by unlabelled ritonavir (at 30 \(\mu\)M) significantly (\(P<0.001\)) increased the CAR of \( ^{3}\text{H}\)ritonavir compared with that observed for tariquidar-treated samples alone. However, the levels were significantly different from those observed in samples treated with unlabelled ritonavir alone (Figure 4b).

### Interaction of HIV protease inhibitors

**Figure 2.** Effects of pre-incubating PBMCs with various concentrations (0–30 \(\mu\)M) of unlabelled lopinavir (LPV) followed by the addition of \( ^{14}\text{C}\)LPV and co-incubating the cells with \( ^{14}\text{C}\)LPV followed by various concentrations (0–30 \(\mu\)M) of unlabelled LPV (trans-stimulation) on the accumulation of \( ^{14}\text{C}\)LPV. Bars indicate mean±SD (n=6, with four independent observations from each buffy coat PBMC sample). P values of \(P<0.05\), **\(P<0.01\) and ***\(P<0.001\) indicate statistically significant differences in the CAR of \( ^{14}\text{C}\)LPV between control and LPV-treated samples.

**Tariquidar, MK571 and frusemide (alone and in combination with unlabelled lopinavir) increased the accumulation of \( ^{14}\text{C}\)lopinavir**

Given that 10 \(\mu\)M unlabelled lopinavir maximally increased the CAR of \( ^{14}\text{C}\)lopinavir in the CEM cells (Figure 1), we compared the inhibitory profile of 10 \(\mu\)M unlabelled lopinavir or in combination with known inhibitors of the two drug efflux transporters (tariquidar and MK571, inhibitors of ABCB1/ABCG2 and ABCC, respectively) expressed by the CEM cells. Tariquidar (at 1 \(\mu\)M) significantly (\(P<0.001\)) increased the CAR of \( ^{14}\text{C}\)lopinavir in a concentration-dependent manner, suggesting that the mechanism is an inhibition of efflux transporters rather than true trans-acceleration (Figure 1b). We also observed that in PBMCs there was a significant increase (\(P<0.001\)) in the CAR of \( ^{14}\text{C}\)lopinavir in a concentration-dependent fashion (Figure 2).

**Ritonavir increased the accumulation of \( ^{3}\text{H}\)ritonavir in cultured cells**

\( ^{3}\text{H}\)ritonavir accumulated differentially in CEM cells with the following rank order: CEM > CEM\(_{E1000}\) > CEM\(_{VBL}\) (Figure 4a and b), indicating that ritonavir is a substrate for ABCB1 and ABCC1. Pre-treatment of the cultured cells with unlabelled ritonavir followed by the addition of \( ^{3}\text{H}\)ritonavir significantly (\(P<0.001\)) increased the accumulation of \( ^{3}\text{H}\)ritonavir in CEM\(_{E1000}\) cells in a concentration-dependent manner. In contrast, unlabelled ritonavir (at 10 and 30 \(\mu\)M) significantly (\(P<0.01\)) increased the CAR of \( ^{3}\text{H}\)ritonavir in parental CEM cells at 10 and 30 \(\mu\)M unlabelled ritonavir, whilst only ritonavir (at 30 \(\mu\)M) produced a significant (\(P<0.001\)) increase in the accumulation of \( ^{3}\text{H}\)ritonavir in CEM\(_{VBL}\) cells (Figure 4a). The differences between CEM cells and CEM\(_{E1000}\) cells are significant at concentrations of ritonavir >3 \(\mu\)M (\(P<0.01\)).

**Tariquidar, MK571 and frusemide (alone and in combination with unlabelled ritonavir) demonstrated variable effects on the accumulation of \( ^{3}\text{H}\)ritonavir**

Unlabelled ritonavir (at 30 \(\mu\)M) significantly (\(P<0.001\)) increased the CAR of \( ^{3}\text{H}\)ritonavir in CEM, CEM\(_{VBL}\) and CEM\(_{E1000}\) cells compared with their respective controls (Figure 4b). Tariquidar (at 1 \(\mu\)M) significantly (\(P<0.001\)) increased the accumulation of \( ^{3}\text{H}\)ritonavir in CEM\(_{VBL}\), but not in parental CEM cells. In contrast, 50 \(\mu\)M MK571 significantly (\(P<0.001\)) increased the accumulation of \( ^{3}\text{H}\)ritonavir in both CEM and CEM\(_{E1000}\) cells. Pre-treatment of the cells with 1 \(\mu\)M tariquidar followed by unlabelled ritonavir (at 30 \(\mu\)M) significantly (\(P<0.001\)) increased the CAR of \( ^{3}\text{H}\)ritonavir compared with that observed for tariquidar-treated samples alone. However, the levels were significantly higher than those observed in samples treated with unlabelled ritonavir alone (Figure 4b).
Effects of (a) pre-incubating CEM, CEME1000 (E1000) and CEMVBL (VBL) cells with fixed concentrations (30 µM) of unlabelled lopinavir (LPV) (alone and in combination with 1 µM tariquidar or 50 µM MK571), (b) co-incubating the PBMCs with 10 and 30 µM unlabelled LPV (alone and in combination with 1 µM tariquidar or 50 µM frusemide) on the accumulation of [14C]LPV, (c) pre-incubating CEM, E1000 and VBL cells with various concentrations (0–30 µM) of unlabelled LPV followed by the addition of [3H]saquinavir (SQV) and (d) pre-incubating CEM, VBL and E1000 cells with various concentrations (0–30 µM) of unlabelled LPV on the accumulation of [3H]ritonavir (RTV). Bars indicate mean±SD (n=4, with four independent observations from cultured CEM and its variant cells and n=4 with four independent observations from each buffy coat PBMC sample). P values of *P<0.05, **P<0.01 and ***P<0.001 indicate statistically significant differences in the CAR of [14C]LPV or [3H]SQV between controls and drug-treated samples. Note that tariquidar/LPV combinations were compared with samples treated with tariquidar alone.

Identical to those measured for samples treated with unlabelled ritonavir (at 30 µM) alone. Compared with MK571-treated cells, pre-treatment of CEM and CEME1000 cells with 50 µM MK571 in the presence of 30 µM unlabelled ritonavir significantly (P<0.001) increased the CAR of [3H]ritonavir in CEME1000 cells, but not in the parental CEM line—identical levels of accumulation of [3H]ritonavir were measured in MK571-treated CEM cells compared with samples treated with MK571 in the presence of 30 µM unlabelled ritonavir (Figure 4b).

Unexpectedly, unlabelled ritonavir (at 10 and 30 µM) significantly (P<0.001) decreased the accumulation of [3H]ritonavir in the PBMCs tested (Figure 4c). Tariquidar did not alter the CAR of [3H]ritonavir, but frusemide significantly (P<0.001) increased accumulation. Compared with cells treated with 10 or 30 µM unlabelled ritonavir alone, pre-treatment of the cells with 1 µM tariquidar in combination with 10 µM or 30 µM unlabelled ritonavir significantly decreased the CAR of [3H]ritonavir (P<0.001 for 1 µM tariquidar+10 µM ritonavir and P<0.05 for 1 µM tariquidar+30 µM ritonavir). Pre-treatment of the cells with frusemide in combination with unlabelled ritonavir significantly reduced the CAR of [3H]ritonavir; at both 10 (P<0.01) and 30 µM (P<0.001) of unlabelled ritonavir (Figure 4c). Both reductions were identical to that observed with unlabelled ritonavir alone.
Unlabelled saquinavir increased the accumulation of [3H]saquinavir in both cultured cells and PBMCs

As can be seen in Figure 5(a), saquinavir accumulated differentially in the CEM and its variant cells with the following rank order: CEM ≫ CEM_E1000 ≫ CEM_VBL. Baseline levels of [3H]saquinavir were also variable in the PBMC samples tested (Figure 5b). Unlabelled saquinavir significantly (P<0.001) increased the CAR of [3H]saquinavir in CEM, CEM_E1000 cells (Figure 5a) and in PBMCs (Figure 5b) in a concentration-dependent manner. However, the accumulation of [3H]saquinavir was only significantly (P<0.001) increased in CEM_VBL cells by 30 µM unlabelled saquinavir (Figure 5b).

Atazanavir decreased the accumulation of [3H]atazanavir in both cultured cells and PBMCs

[3H]atazanavir accumulated differentially in CEM cells with the following rank order: CEM > CEM_E1000 ≥ CEM_VBL (Figure 6a). Unlabelled atazanavir significantly (P≤0.05) decreased the
accumulation of [3H]atazanavir in a concentration-dependent manner in these cells, with the decreases being more marked in the parental CEM line than in its variants. Similarly, unlabelled atazanavir significantly \((P<0.05)\) decreased the CAR of [3H]atazanavir in PBMCs in a concentration-dependent manner.

**Discussion**

Given the wide variability in plasma concentrations of HPIs achieved with standard dosing, it is important to understand how the variable plasma concentration impacts on intracellular drug accumulation. This is because being efficient inhibitors, substrates and inducers of some drug efflux proteins and drug metabolizing enzymes, there is a complex interaction between HPIs and drug efflux/influx transporters and enzymes, especially if the patients are on other medications. Indeed alterations in ABCB1 and ABCC2 activity have been associated with single nucleotide polymorphisms in ABCB1 (C3435T and G2677T/A), ABCC1 and ABCC2 (G1249A, G1199A).

While some studies showed no association between the exposure of HPIs and polymorphisms in ABCB1 C3435T, ABCC1 and ABCC2, some in vitro and in vivo studies found some association between G4544A and G1199A polymorphisms in ABCB2 and ABCB1, respectively and higher accumulation of some HPIs, suggesting that these polymorphisms may impact on the systemic bioavailability of various HPIs that are substrates of ABCB1 and ABCC2.

Clearly, the effect of modifying extracellular drug concentrations on intracellular accumulation requires careful consideration. Here we demonstrate that unlabelled lopinavir pharmaco-enhances its own accumulation in both cultured and primary human cells. The ‘self-enhancement’ measured in CEM, CEM\(_{E1000}\) (ABCC1
overexpressing) and CEMVBL (ABCB1 overexpressing) (Figure 1) suggests that lopinavir inhibits various efflux proteins, possibly including ABCB1 and ABCC1. However, since the effects are quite similar in CEM and CEME1000 it is possible that MRP1 is only minimally affected and that other efflux transporters might be involved. Given that PBMCs express ABCB1, ABCG2, ABCC1 and ABCC2,13,19 ‘the self-enhancement’ of the accumulation of [14C]lopinavir by unlabelled lopinavir in these cells (Figure 2) also suggests inhibition of one or more of these efflux proteins. However, there is also evidence that HPIs inhibit ABCG2, but are not substrates of this protein.52

If lopinavir is an inhibitor of ABCB1 and ABCC1 activity, how does its inhibitory profile compare with relatively specific inhibitors of these proteins (e.g. tariquidar and MK571)? To address this question, we compared (i) the inhibitory profiles of unlabelled lopinavir alone with those of tariquidar and MK571 and (ii) the inhibitory effects of unlabelled lopinavir (alone and in combination with tariquidar or MK571). As shown previously,19 we observed that tariquidar and MK571 significantly increased the CAR of [3H]ritonavir in cell lines and primary cells. However, the increase in the CAR of [14C]lopinavir by unlabelled lopinavir alone was markedly higher than that measured for tariquidar- or MK571-treated samples alone (Figure 3a). This is consistent with unlabelled lopinavir having a greater effect at increasing its own accumulation in cells overexpressing ABCB1 and ABCC1 than tariquidar and MK571, respectively, although this needs to be tested over a wider range of inhibitor concentrations.

Inhibition of efflux proteins leads to an increase in the intracellular accumulation of lopinavir.17,19,70 Here the CAR of [14C]lopinavir increased in cells pre-treated with tariquidar or MK571 in the presence of unlabelled lopinavir and the observed increases were identical to that measured in cells treated with unlabelled lopinavir alone (Figure 3a), suggesting no additional ‘boosting’ of the accumulation of [14C]lopinavir by tariquidar or MK571. In the PBMCs, pre-treatment of the cells with tariquidar or frusemide increased the accumulation of [14C]lopinavir. However, a similar profile of inhibition to that observed in CEM and its variant cells was measured when PBMCs were pre-treated with tariquidar or frusemide in the presence of unlabelled lopinavir (Figure 3a versus b). The observed effects of lopinavir on its own accumulation are consistent with inhibition of ABCB1 and ABCC1 activity, and supports previous observations that HPIs inhibit drug transporters.19,53 Indeed, the observation that unlabelled lopinavir increased the CAR of [3H]saquinavir and [3H]ritonavir in CEM, CEME1000 (ABCB1 overexpressing) and CEMVBL (ABCB1 overexpressing) cells (Figure 3c and d) provides additional evidence that the observed effects are mediated via ABCB1 and ABCC1 inhibition.

To extend these observations, we evaluated the effects of unlabelled ritonavir, saquinavir and atazanavir on the accumulation of [3H]ritonavir, [3H]saquinavir and [3H]atazanavir in CEM, its variant cells and PBMCs. The data presented in Figure 4 confirms that ritonavir is a substrate of both ABCB1 and ABCC1.19,71,72 (i) there is differential accumulation of the drug in the ABCB1 (CEM1000) and ABCB1 overexpressing (CEMVBL) cells compared with parental CEM cells (Figure 4a and b); and (ii) both tariquidar and MK571 increased the CAR of [3H]ritonavir in CEMVBL and CEM1000 cells, respectively (Figure 4b). It is also clear that ritonavir inhibits ABCB1 and ABCC1, with unlabelled ritonavir causing an enhancement in the intracellular accumulation of [3H]ritonavir in the cultured cells (Figure 4a). Although cells pre-treated with tariquidar, followed by the addition of unlabelled ritonavir (at 30 µM) to the bathing medium showed a significantly increased CAR of [3H]ritonavir compared with those treated with tariquidar alone, the observed increase was identical to that measured for unlabelled ritonavir alone, suggesting that pre-treatment with tariquidar did not cause a further enhancement in the accumulation of [3H]ritonavir. Similarly, although pre-treatment of the cells with MK571, followed by the addition of unlabelled ritonavir, significantly increased the CAR of [3H]ritonavir (in the CEM1000 cells above that observed for the MK571-treated cells), the overall effect of this manipulation, when compared with samples treated with unlabelled ritonavir alone, was that of an attenuated response (Figure 4b). Investigations using PBMCs showed that unlabelled ritonavir (at 10 and 30 µM) significantly decreased the CAR of [3H]ritonavir (Figure 4c). Overall, tariquidar did not alter the CAR of [3H]ritonavir in the samples tested, but frusemide significantly increased the CAR of [3H]ritonavir. However, co-incubation of the cells pre-treated with tariquidar or frusemide, followed by unlabelled ritonavir (at 10 and 30 µM) resulted in a decrease in the CAR of [3H]ritonavir. However, combination of unlabelled ritonavir (at 10 µM) with frusemide abrogated the increase in CAR of [3H]ritonavir previously measured with frusemide alone. This is possibly due to saturation of intracellular binding sites by high concentrations of unlabelled ritonavir such that inhibition of ABCB1 is unable to increase the intracellular concentration of radio-labelled ritonavir high enough to displace the unlabelled compound. We provide evidence for differential accumulation of atazanavir in the cultured cells and in PBMCs (Figure 6), supporting previous studies that atazanavir is a substrate of ABCB148,73 and ABC. Although there is evidence that atazanavir inhibits ABCB1 activity,74 unlabelled atazanavir did not enhance the accumulation of [3H]atazanavir in cells overexpressing ABCB1 (CEMVBL and PBMCs) and ABCC1 (CEM1000 and PBMCs), but caused a concentration-dependent decrease in accumulation. Possible explanations are saturation of accumulation, inhibition/competition for intracellular influx, or activation of efflux. Differences between the HPIs indicate that influx/efflux mechanisms are drug specific rather than class specific.

In summary, we have demonstrated that unlabelled lopinavir and saquinavir enhanced the intracellular accumulation of [14C]lopinavir and [3H]saquinavir, respectively, in cultured cells and in PBMCs, but unlabelled atazanavir decreased the accumulation of [3H]atazanavir in both cell types. Unlabelled ritonavir increased the accumulation of [3H]ritonavir in cultured cells, but decreased accumulation in PBMCs. These observations clearly demonstrate a complex relationship between the extracellular and intracellular concentrations of the HPIs, which are drug specific rather than class specific. A better understanding of the relationship between plasma concentration and intracellular concentration in vivo is important when focusing on factors impacting on efficacy or toxicity of HPIs.

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