In Vitro to In Vivo Predictions of Drug Interactions: Going Beyond the I/Ki Ratio

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Unadkat laboratory: Research Interests

• Elucidating mechanisms of transport and metabolism of antiviral and anticancer drugs in various tissues including the:

  • blood-brain barrier (P-gp transport and PET)

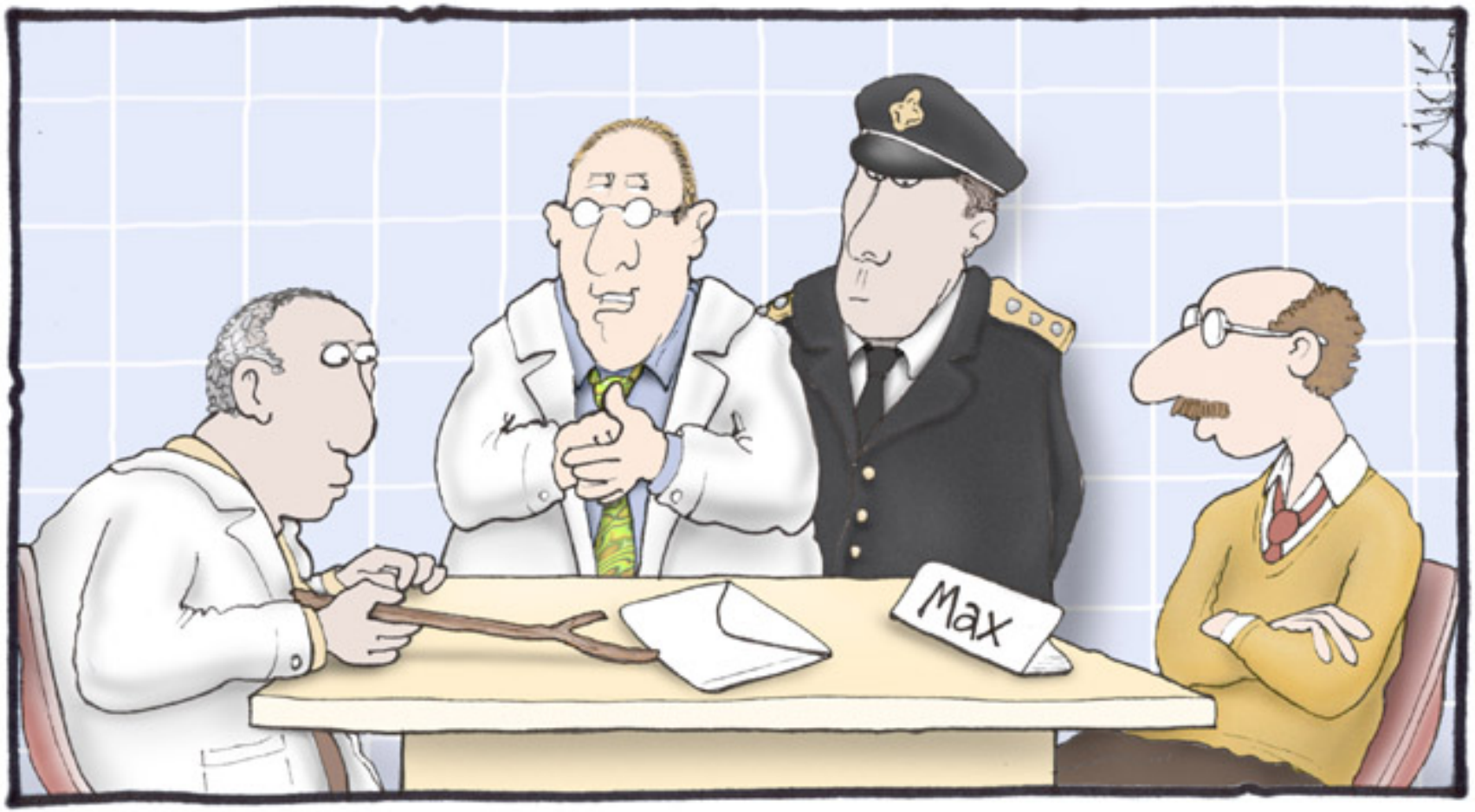
  • blood-placental barrier (P-gp, BCRP, and nucleoside transport)

  • intestinal and hepatic barriers (CYP metabolism, nucleoside, P-gp, and BCRP transport)

• Understanding the *in vivo* consequences of expression of transporters and metabolic enzymes on the PK and PD of antiviral/anticancer drugs including:

  • effect of pregnancy –Specialized **C**enter **O**f **R**esearch or SCOR

  • metabolic and transport-based drug-drug interactions – Program Project grant on drug interactions



"In this laboratory we're always pushing the envelope to the Max."

Predicting Competitive Metabolic In Vivo Drug Interactions

$$AUC_{inhibitor}/AUC = 1 + [I]/Ki \quad (1)$$

Assumptions

1) substrate conc. << Km
2) competitive interaction

e.g. effect of fluconazole
on the *in vivo* formation of sulfamethoxazole or dapsone hydroxylamine

In-vitro to in-vivo correlation of inhibition of SMX hydroxylamine formation by fluconazole

Patient Number	Fluconazole time-averaged concentration (μM)	% Inhibition *in vivo*		Predicted % Inhibition		*In vivo* Ki (μM)	
		AUC	Clf	Ki_{HL142} 19 μM	Ki_{HL123} 46 μM	AUC	Clf
A	20.7	54	49	52	27	17.9	22.1
B	27.5	41	34	59	31	39.9	54.1
C	34.3	51	70	64	36	32.7	15.0
D	20.9	38	48	52	25	34.7	15.0
Mean± SD	25.9± 6.5	46± 8	50± 16	57±9	29± 5	31.3± 9.4	26.6±18.7

In vitro estimates were 19μM for one-enzyme Michaelis-Menten models in human liver (HL) microsomes HL142 (competitive mechanism) and, 46μM for HL123 and 62μM for HL140 (non-competitive mechanism). * Time averaged concentration is the ratio of plasma AUC of fluconazole and Tau 0-12. Winter et al., Clin Pharmacol Ther 2004; 76:313–322

In-vitro to in-vivo correlation of inhibition of Dapsone hydroxylamine formation by fluconazole

Patient Number	Fluconazole time-averaged concentration (μM)	% Inhibition *in vivo*		Predicted % Inhibition		*In vivo* Ki (μM)	
		AUC	Clf	$IC50_{rem}$ 16.8 μM	$IC50_{app}$ 36.1 μM	AUC	Clf
A	26.4	60	62	61	42	17.6	16.2
B	20.5	59	66	55	36	14.1	10.4
C	30.8	34	34	65	46	60.2	60.0
Mean ± SD	25.9±5.2	51±15	54±17	60±5	41±5	30.6±25.7	28.9± 27.1

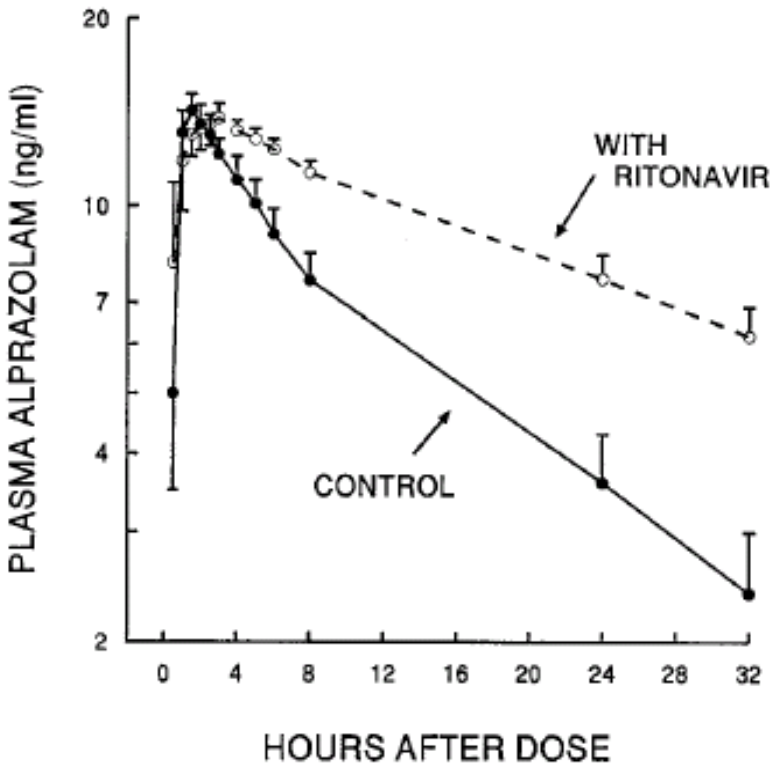
Winter et al, Clin Pharmacol Ther 2004; 76:579–587

The next frontier in predicting in vivo drug interactions

- Enzyme-based interactions
  - More complex interactions problematic –induction, inactivation, allosterism
- Transporter-based interactions
  - which transporters are functionally important in the target tissue (e.g intestine, liver, kidneys, BBB and blood-placental barriers)?
  - which transporters are important in the disposition of the victim drug and capable of being inhibited by the perpetrator?
  - Interspecies difference in expression of transporters
  - Can the I/Ki approach successfully predict *in vivo* interactions?

Induction: in vitro to in vivo

Anti-HIV protease inhibitors



Acute RIT-alprazolam interaction

- Potent CYP3A inhibitors but produce paradoxical interactions

- RIT – alprazolam interaction is significant when administered acutely but is abolished on chronic administration of RIT

- RIT induces CYP1A2 - 43% decrease in the AUC of theophylline.

- RIT induces CYP2C9 - decrease in the anticoagulant effect of warfarin and acenocoumarol.

- NEL induces CYP2C9 and/or CYP2C19 - increase in the oral clearance of phenytoin(17).

Induction: in vitro to in vivo

DRUG METABOLISM AND DISPOSITION Vol. 35, No. 10, 2007

Cytochrome P450 Enzymes and Transporters Induced by Anti-Human Immunodeficiency Virus Protease Inhibitors in Human Hepatocytes: Implications for Predicting Clinical Drug Interactions

Vaishali Dixit, Niresh Hariparsad, Fang Li, Pankaj Desai, Kenneth E. Thummel, and Jashvant D. Unadkat

NOTE:

- Induction by RIT, NEL or RIF
- phenotyping was done with microsomes, not with intact hepatocytes

Induction: in vitro to in vivo

In-Vivo CYP and P-gp activities in Healthy Volunteers after Multiple Dose administration of the anti-HIV protease inhibitors, Nelfinavir, Ritonavir, Rifampin

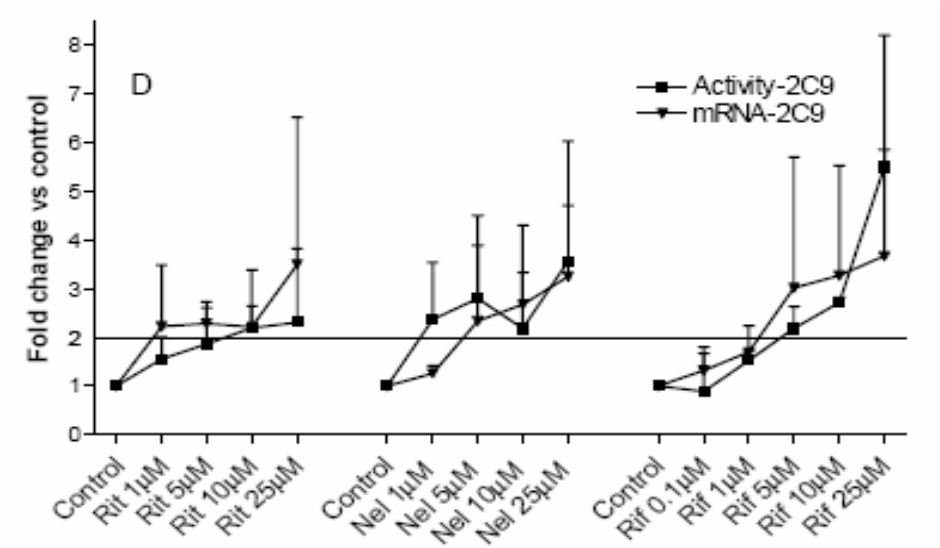
Brian Kirby, Ann C. Collier, Evan D. Kharasch, Dale Whittington, Kenneth E. Thummel, Jashvant D. Unadkat

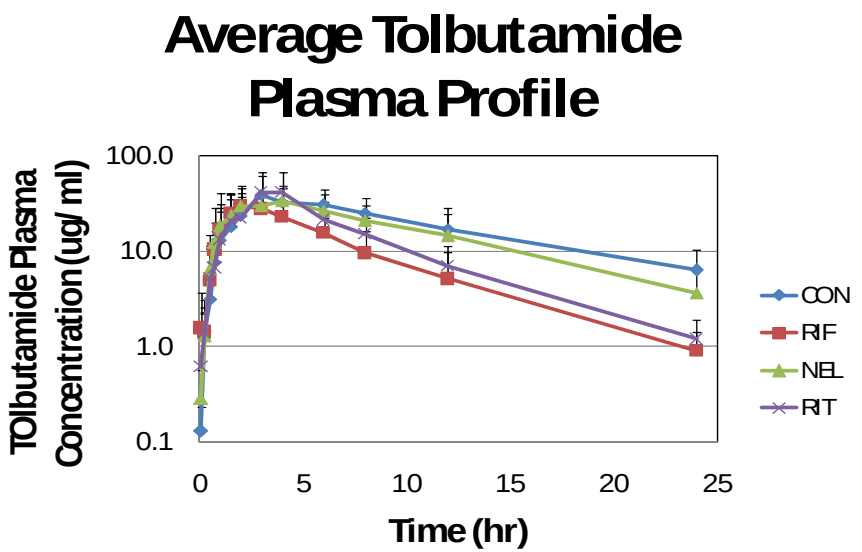
ISSX meeting Puerto Rico, 2007

- Cocktail studies to phenotype CYP1A2, 2D6, 2C9, 3A4 (hepatic and intestinal) and P-gp

- Eliminated acute inhibition by withholding the protease inhibitors during phenotyping study.

Induction in hepatocytes and in vivo: Rifampin, Ritonavir or Nelfinavir



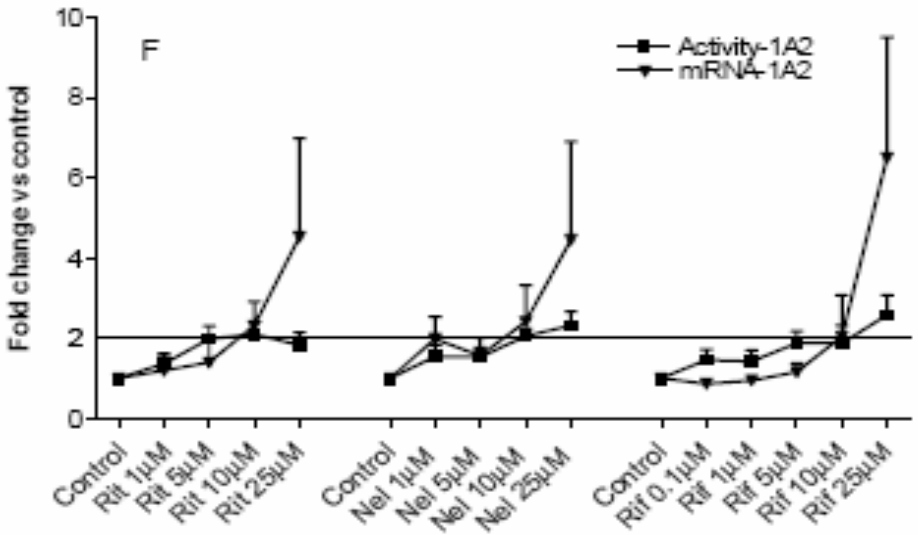


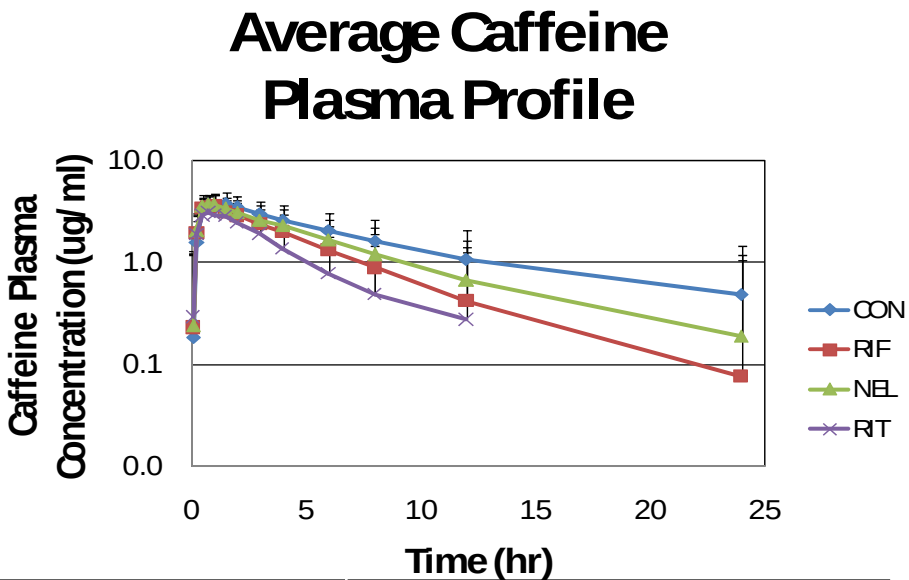
	Fold Increase in CYP2C9 Activity			In Vivo Concentrations			
	Human Hepatocytes	In Vivo		C_{ave} (μM)		C_{max} (μM)	
	10 μM	Tolbutamide CL_{Oral}	OH-Tolbutamide $Cl_{formation}$	Total	Free	Total	Free
Rifampin	3.3 ± 2.3	3.3 ± 2.2	2.9 ± 1.6	2	0.2	10	1.0
Ritonavir	2.2 ± 1.2	2.0 ± 0.4	1.8 ± 0.4	8	0.08	15	0.15
Nelfinavir	2.7 ± 1.6	1.5 ± 0.4	1.3 ± 0.3	4	0.04	7	0.07

Dixit V., *DMD* Epub July 16 2006

Product Labeling, Zwolska Z., *Int J Tuberc Lung Dis* 2 **10**;824-830 1998

Induction in hepatocytes and in vivo: Rifampin, Ritonavir or Nelfinavir



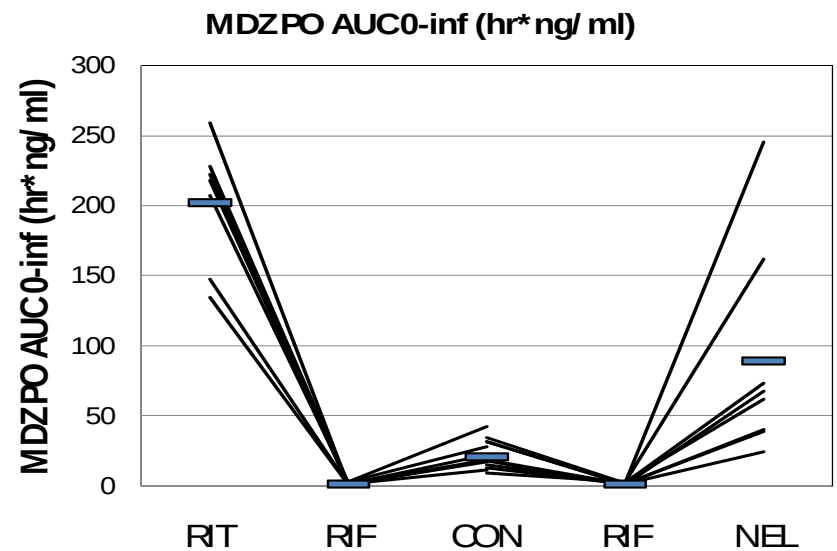


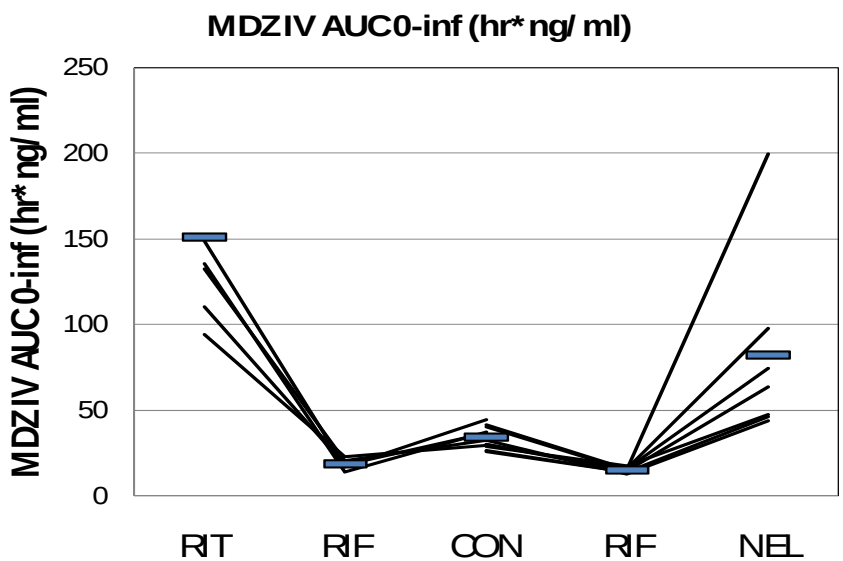
	Fold Increase in CYP1A2 Activity			In Vivo Concentrations			
	Human Hepatocytes	In Vivo		C_{ave} (µM)		C_{max} (µM)	
	10 µM	Caffeine CL_{Oral}	Paraxanthine $Cl_{formation}$	Total	Free	Total	Free
Rifampin	1.9 ± 0.4	2.5 ± 1.5	2.4 ± 1.5	2	0.2	10	1.0
Ritonavir	2.1 ± 0.3	3.6 ± 1.7	3.1 ± 1.2	8	0.08	15	0.15
Nelfinavir	2.1 ± 0.2	2.6 ± 2.3	2.8 ± 2.4	4	0.04	7	0.07

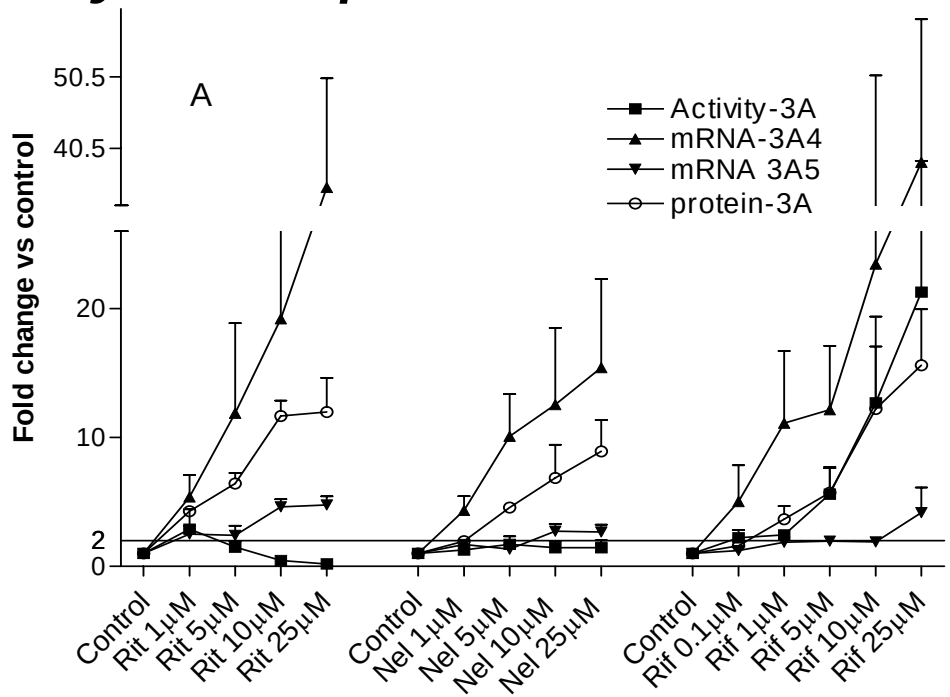
Dixit V., *DMD* Epub July 16 2006

Product Labeling, Zwolska Z., *Int J Tuberc Lung Dis* 1998

CYP3A Induction by Rifampin







- Rifampin ↑midazolam GI intrinsic CL ~ 3.3-fold
- In hepatocytes rifampin (10 μM) induces CYP3A4 activity and mRNA by ~12 and 25-fold respectively.
- Are induction studies in hepatocytes representative of induction in the intestine? Tissue specific induction likely!

Brandin H., *Phytother. Res.* **21**, 239-244 2007

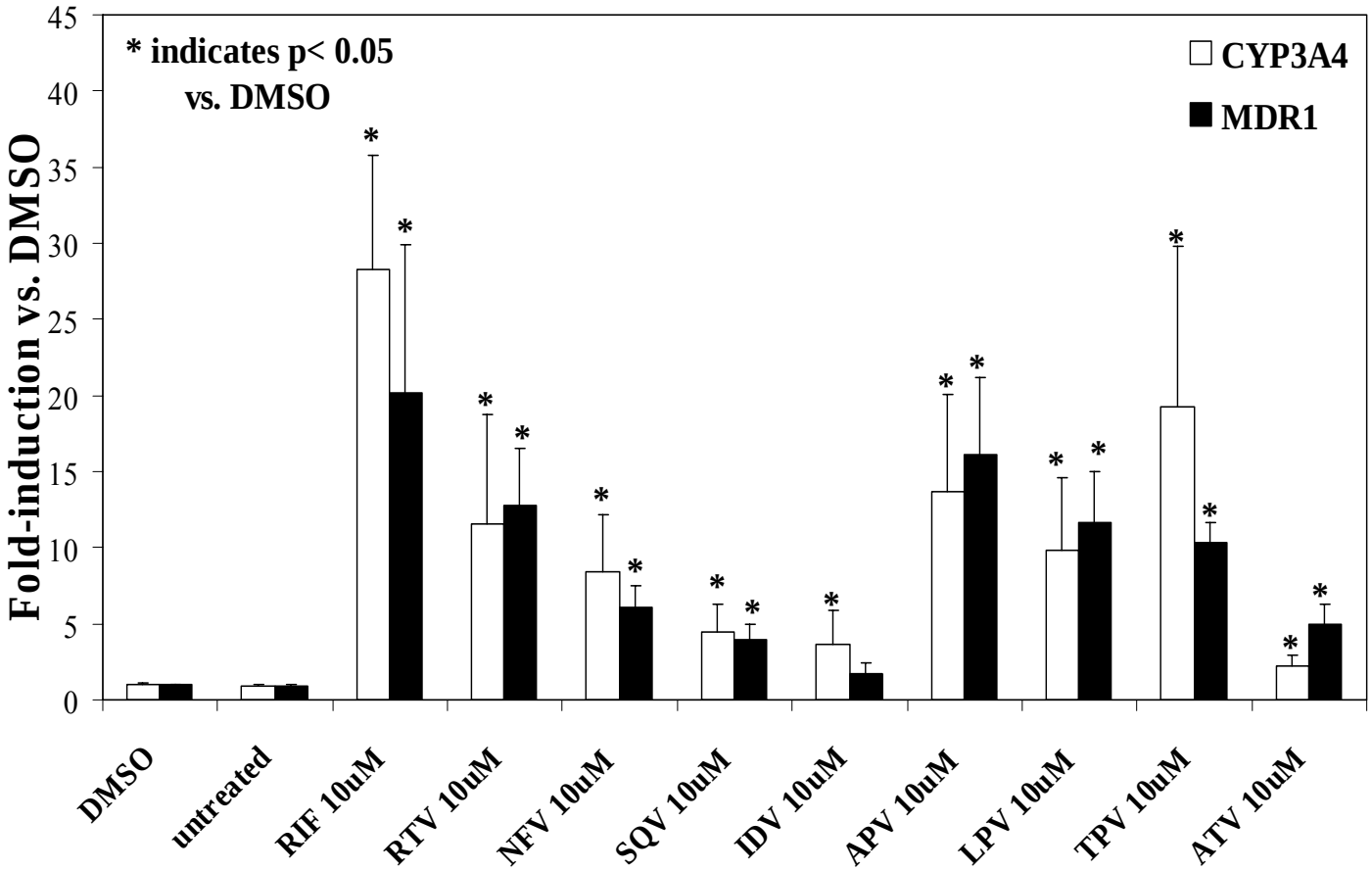
Induction in Intestinal Cells

Intestinal human colon adenocarcinoma cell line, LS180, is an excellent model to study PXR- but not CAR-mediated CYP3A4 and MDR1 induction: studies with Anti-HIV Protease Inhibitors

Anshul Gupta, Ganesh Mugundu, Pankaj B. Desai, Kenneth E. Thummel, Jashvant D. Unadkat

DMD: Manuscript In Revision

Induction in LS180 cells



- This induction can be knocked down by PXRsi
- Induction is PXR-mediated
- CAR is not expressed in LS180 cells
- Protease inhibitors do not activate CAR3.

Induction – Future Challenges

- Which *in vitro* systems are predictive of *in vivo* induction
- Quantitative Correlation
  - EC_{50} , E_{max} , I_u
- Is the steady state inducer concentration approach sufficient?
- Best model system to study intestinal CYP3A induction
  - LS180 cells?
- Inducer washout (*in vitro* and *in vivo*)
- Nuclear receptors involved

Inactivation: in vitro to in vivo correlation?

Model #1

$$\frac{AUC'_{IV}}{AUC_{IV}} = \frac{1}{\dfrac{f_m}{1+\dfrac{k_{inact} \times I_u}{k_{deg} \times (K_I + I_u)}} + (1 - f_m)}$$

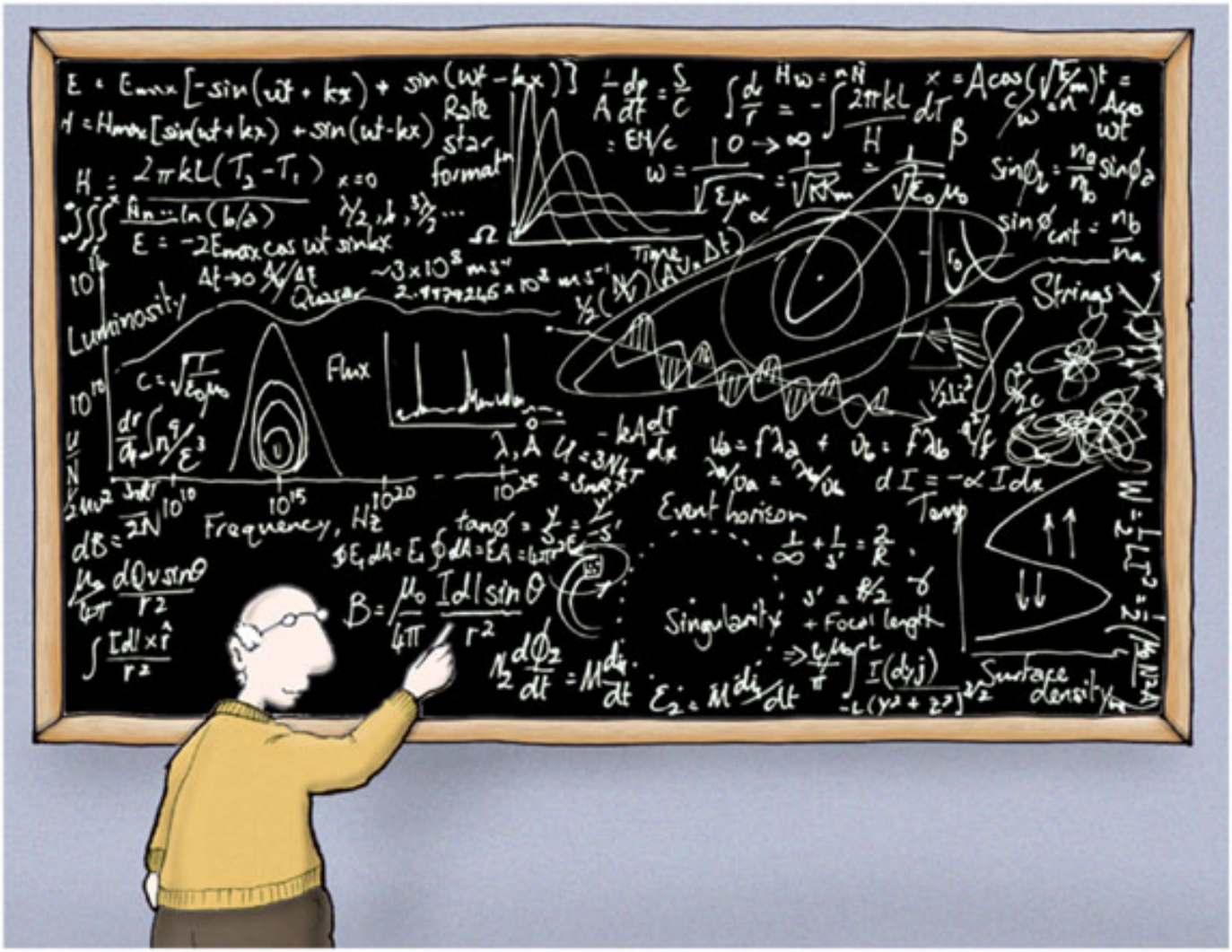
λ

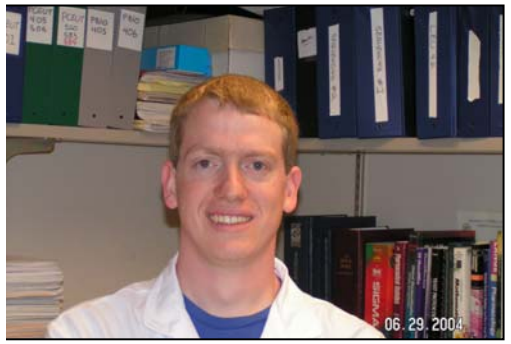
Ernest C.S., *JPET* **312**;583-591 2005

- f_m - fraction metabolized
- k_{inact} – maximal inativation rate
- k_{deg} – degradation rate of the enzyme
- K_I – conc. of the inactivator at 50% of k_{inact}

- Model does not incorporate
  - induction
  - blood flow
  - competitive interaction

How does this model perform when the drugs (e.g. anti-HIV protease inhibitors) inactivate, induce and competitively inhibit CYP3A and other enzymes



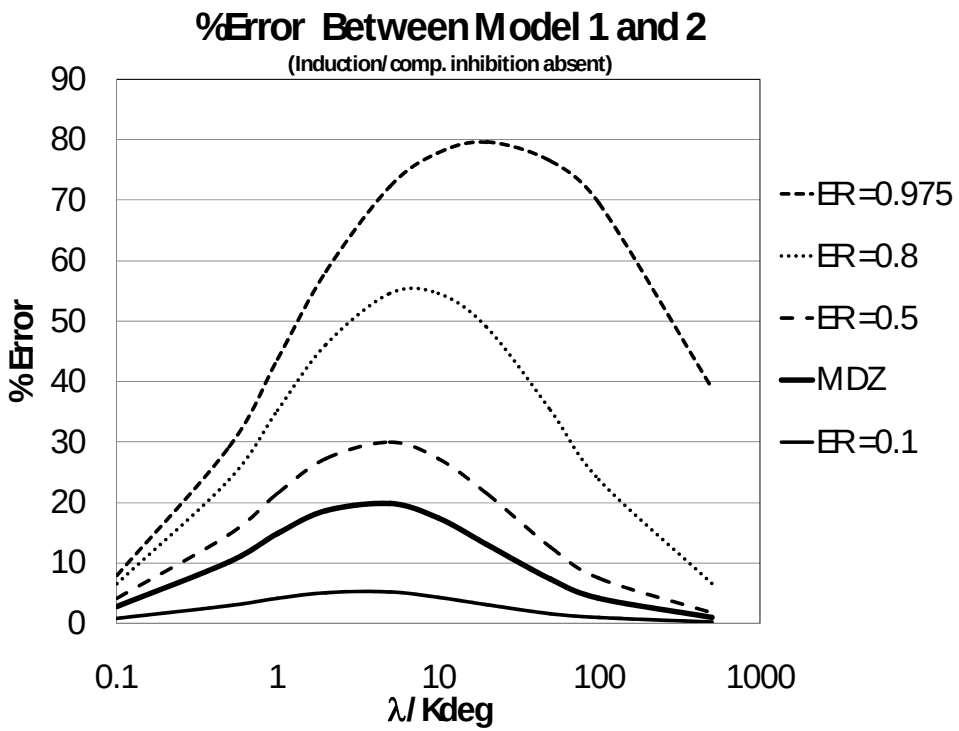


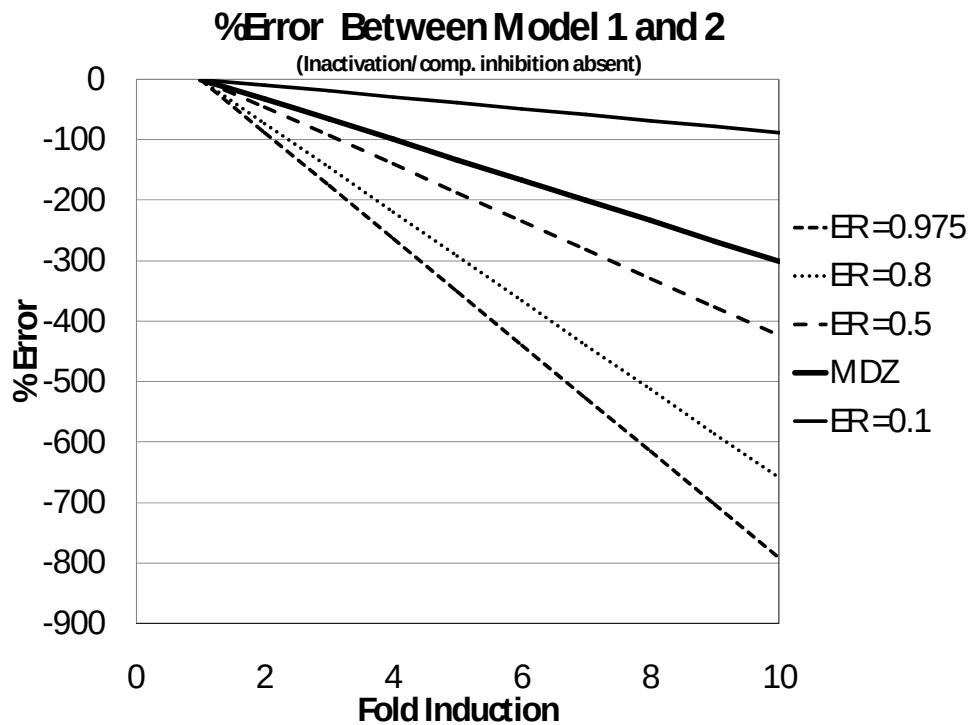
Pharmacokinetics made simple

In vitro- in vivo prediction Model for IV administration (incorporating hepatic blood flow)

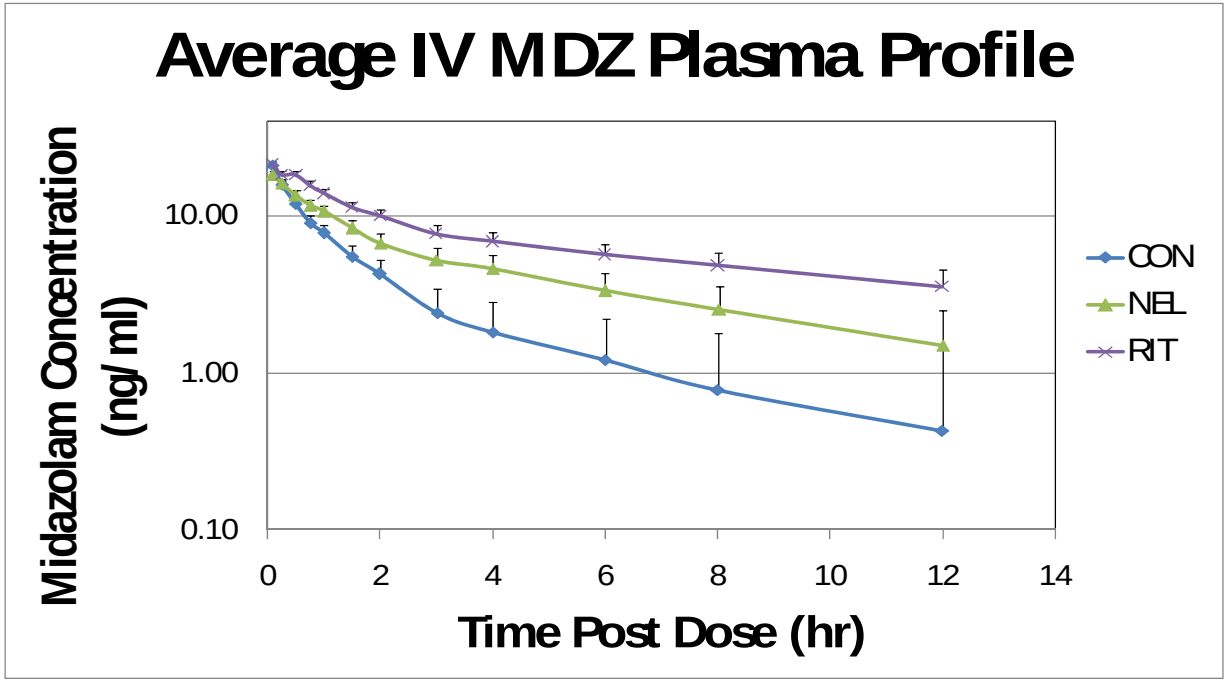
Model #2

$$\frac{AUC'_{IV}}{AUC_{IV}} = \frac{1}{f_{hep}\left(\frac{1/ER}{\left(\frac{1}{ER}-1\right)\left(\frac{Comp}{Induc}\right)\left(1+\frac{\lambda}{K_{deg}}\right)+1}\right)+\left(1-f_{hep}\right)}$$





Inactivation - HIV Protease Inhibitors Ritonavir or Nelfinavir



Protease Inhibitor	Object	Observed AUC ratio in our study	Predicted AUC ratio (Model 1)#	Predicted AUC ratio Model 2	
				No induction	+ induction
Ritonavir	IV Midazolam	**3.7** (95% CI: 3.0, 4.7)	9.2-9.8*	6.5 -6.6*	**5.5-6.3***
Nelfinavir	IV Midazolam	**2.2** (95% CI: 1.5, 3.3)	4.6-7.9	3.3 -5.4	**1.1-2.7**

#Ernest C.S., *JPET* **312**;583-591 2005

** Assuming t1/2 of CYP3A degradation of 9 and 44 h respectively*

Allosterisim: R-Lansoprazole activation of Phenytoin hydroxylation (In-Vitro)

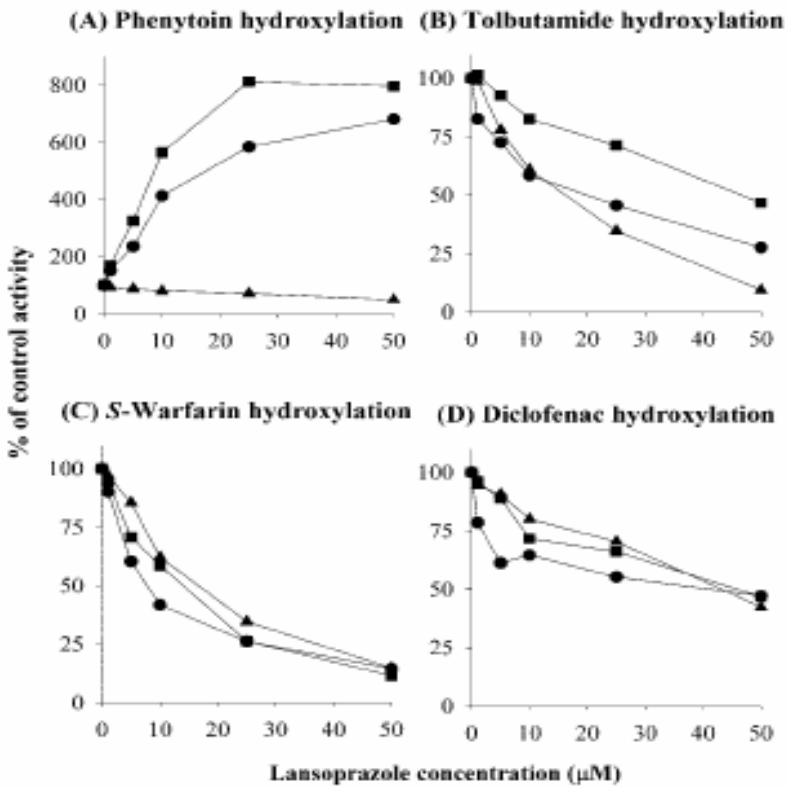


FIG. 2. Effect of racemic lansoprazole (●), *R*-lansoprazole (■), and *S*-lansoprazole (▲) on CYP2C9-catalyzed phenytoin 4-hydroxylation

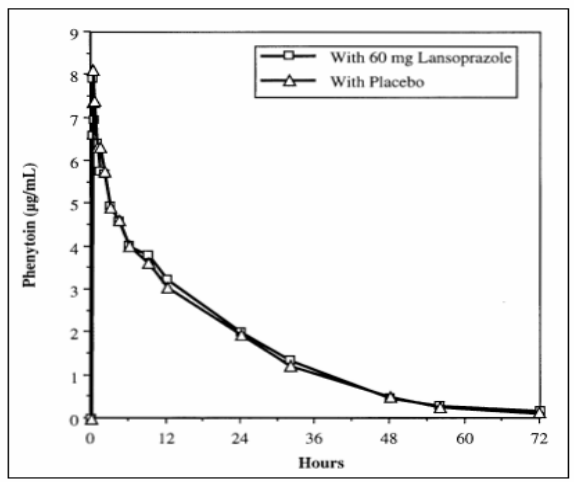


Figure 1. Mean phenytoin concentrations.

Table 1
Mean flurbiprofen kinetic parameter estimates

Variable	Units	Visit A	Visit B	Visit C
$AUC_{0-\infty}$	μg/l·h	43.8±13.8	39.3±9.4	38.3±8.5
Cl/F	l/h	1.23±0.32	1.33±0.29	1.37±0.30*
C_{max}	μg/ml	10.5±2.9	9.9±4.2	10.0±3.4
$T_{1/2}$	h	3.7±1.0	3.6±1.3	3.3±0.6
T_{max}	h	1.5±0.9	1.8±1.0	1.4±0.8
V_d/F	l	6.2±1.2	6.9±3.2	6.5±2.2
4'-OH FCl	l/h	0.38±0.14	0.39±0.13	0.40±0.16

Data are mean values±S.D.
Visit A, flurbiprofen 50 mg alone; Visit B, flurbiprofen 50 mg + dapsone 100 mg; and Visit C, flurbiprofen 50 mg after 7 days of dapsone 100 mg daily.

Liu K-H., *DMD* **33**;209-213, 2005 , Karol M. D., *J Clin Pharmacol.* **39**;1283-1289, 1999

Hutzler et al. Eu J Pharm. Sci., 14, 2001, 47-52

Allosterism – Future Challenges

- Is allosterism consequential *in vivo*?
- *In vitro* methods to determine constants
- Quantitative prediction models yet to be developed

What are the challenges?

- Enzyme-based interactions
  - I/K_i ratio for predicting *in vivo* competitive inhibition interactions has been largely successful
  - More complex interactions problematic – inactivation, induction, allosteric
- Transporter-based interactions
  - which transporters are functionally important in the tissue of interest (e.g intestine, liver, kidneys, BBB and blood-placental barriers)?
  - Identifying the transporters important in the disposition of the victim drug and capable of being inhibited by the perpetrator
  - Can the I/Ki approach successfully predict *in vivo* interactions?

Can in vivo transporter-based interactions be predicted?

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Review

The role of transporters in drug interactions

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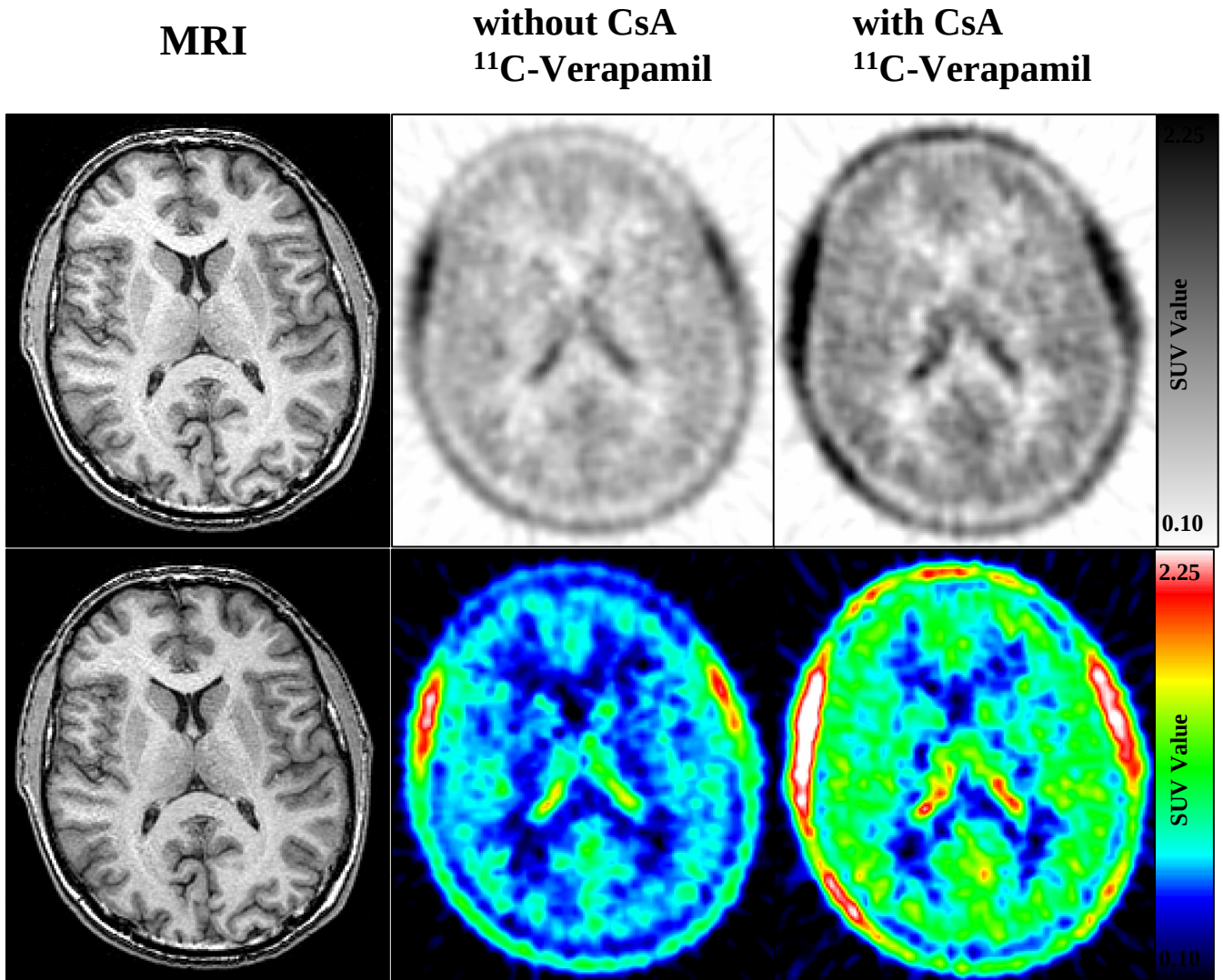
Quantitative Predictions of In Vivo P-gp Drug Interactions Based on In Vitro Data and Comparison With the Magnitude of Interaction Observed In Vivo

						Prediction		Observed
			f_u	K_i or IC_{50} (µM)	[I] (µM)	Unbound Drug (f_u×[I])	Total Drug [I]	$\frac{Cl_{inhibit}}{Cl}$
Verapamil	**CsA**	**brain distribution**	**0.02[a]**	**0.46[b]**	**2.9[c]**	**0.88**	**0.14**	**0.56[c]**
Digoxin	**Itraconazole**	**oral Cl**	**0.002[d]**	**0.5[e]**	**0.3[f]**	**1.0**	**0.63**	**0.67[f]**
Digoxin	**Quinidine**	**biliary Cl**	**0.13[d]**	**2.2[g]**	**4.5[h]**	**0.79**	**0.33**	**0.65[h]**
Digoxin	**Verapamil**	**biliary Cl**	**0.1[d]**	**2.2[l]**	**0.13[m]**	**0.98**	**0.94**	**0.57[m]**
Digoxin	**Itraconazole**	**biliary Cl**	**0.002[d]**	**0.5[e]**	**0.3[f]**	**1.0**	**0.63**	**0.8[f]**
Digoxin	**Ritonavir**	**oral Cl**	**0.01[d]**	**3.8[i]**	**6.2[j]**	**0.98**	**0.38**	**0.70[j]**
Digoxin	**Ritonavir**	**oral Cl**	**0.01[d]**	**3.8[i]**	**8.2[k]**	**0.98**	**0.32**	**0.58[k]**
Digoxin	**Quinidine**	**renal Cl**	**0.13[d]**	**2.2[g]**	**4.5[h]**	**0.79**	**0.33**	**0.71[h]**
Digoxin	**Ritonavir**	**renal Cl**	**0.01[d]**	**3.8[i]**	**8.2[k]**	**0.98**	**0.32**	**0.65[k]**

Endres et al, Eu J Pharm. Sci 27:2006 501-07

P-glycoprotein based drug interaction at the BBB: CsA-verapamil



Sasongko et al (2005) *Clin Pharmacol Ther.* 77:503-514.

P-gp drug interactions at the human BBB

In vivo imaging protocol

- Healthy volunteers: [^{11}C]-verapamil infused over 1 min (~ 0.2 mCi/kg, < 0.12 μg/kg) -- brain PET images captured over 45 minutes
- P-gp inhibitor, cyclosporine (2.5 mg/kg/h), infused IV
- After ~60 min of cyclosporine infusion, [^{11}C]-verapamil (~0.2 mCi/kg, <0.12 μg/kg) administered again, PET images captured for ~45 min.
- Arterial blood samples collected before and for 45 min after each [^{11}C]-verapamil administration

In vivo imaging protocol

- Tissue blood flow measured before ***<u>each</u>*** [^{11}C]-verapamil study by IV administration of [^{15}O] H_2O ($\leq$ 0.5 mCi/kg or up to a maximum of 40 mCi).
- Tissue intravascular volume measured at the end of the study by [^{11}C]-CO (0.2 mCi/kg) inhalation.
- MRI images of the brain were taken for co-registration of PET data
- Blood and plasma samples counted and metabolite content determined by a rapid SPE/HPLC assay
- The ratios of AUC tissue : AUC blood were calculated. Compartmental modeling also conducted. Metabolism or plasma protein binding of verapamil or cerebral blood flow (0.31 $\pm$ 0.16 vs. 0.29 $\pm$ 0.16 mL/min/g; *P* = 0.10) was not affected by CsA

P-glycoprotein based drug interaction at the BBB: CsA-verapamil

Increase in ^{11}C-radioactivity brain distribution in the presence of CsA

	Blood CsA	Ratio of AUC_{brain}:AUC_{blood} (20 min)			Ratio of AUC_{brain}:AUC_{blood} (45 min)		
N=12*	μM	- CsA	+ CsA	% increase	- CsA	+ CsA	% increase
Mean	2.8	0.42	0.78	87	0.55	1.02	88
St. Dev.	0.4	0.04	0.10	19	0.10	0.18	20
Max.	3.2	0.55	0.98	148	0.68	1.31	128
Min.	2.1	0.30	0.56	62	0.38	0.75	65

* 6 males, 6 females – no sig. difference between males and females

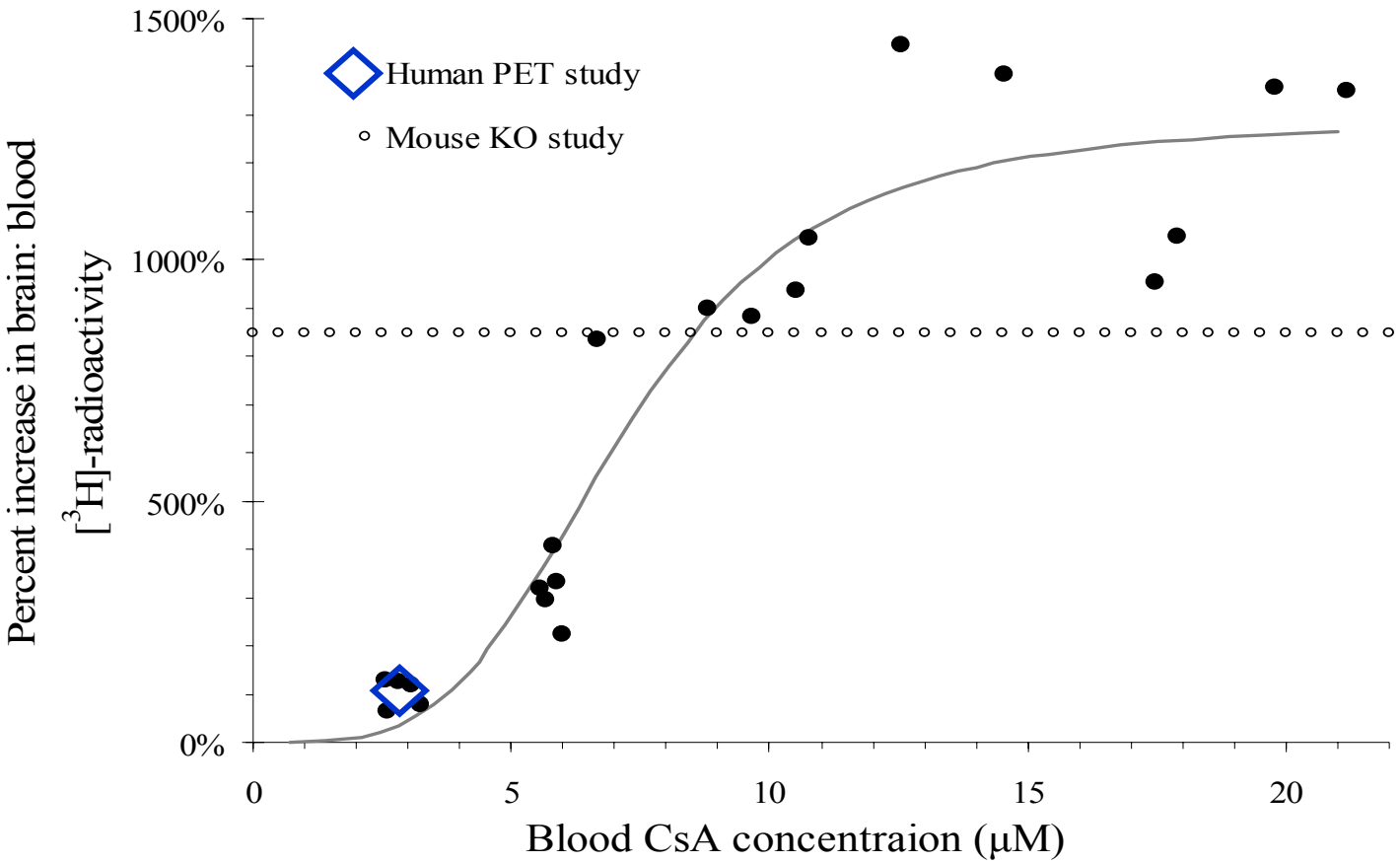
Sasongko et al., Clin Pharmacol. Ther. 2005 77:503-14.

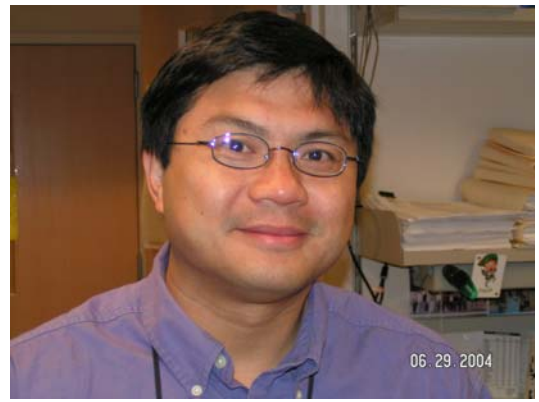
Do the rodent models grossly overestimate P-gp based drug interactions at the human BBB?

Rodent PET study At 1 hour post ^{11}C-verapamil	
Mdr1a(-/-) mice	Sprague Dawley Rat+50 mg/Kg CsA IV bolus
950% ↑	1,060% ↑

Human PET +2.5 mg/kg/h CsA	20 Minutes post ^{11}C-Verapamil	45 Minutes post ^{11}C-Verapamil
Brain : Blood (single point)	100% ↑	79% ↑
Brain : Blood (AUC)	87% ↑	88% ↑

Concentration-dependent inhibition of P-gp at the rat BBB



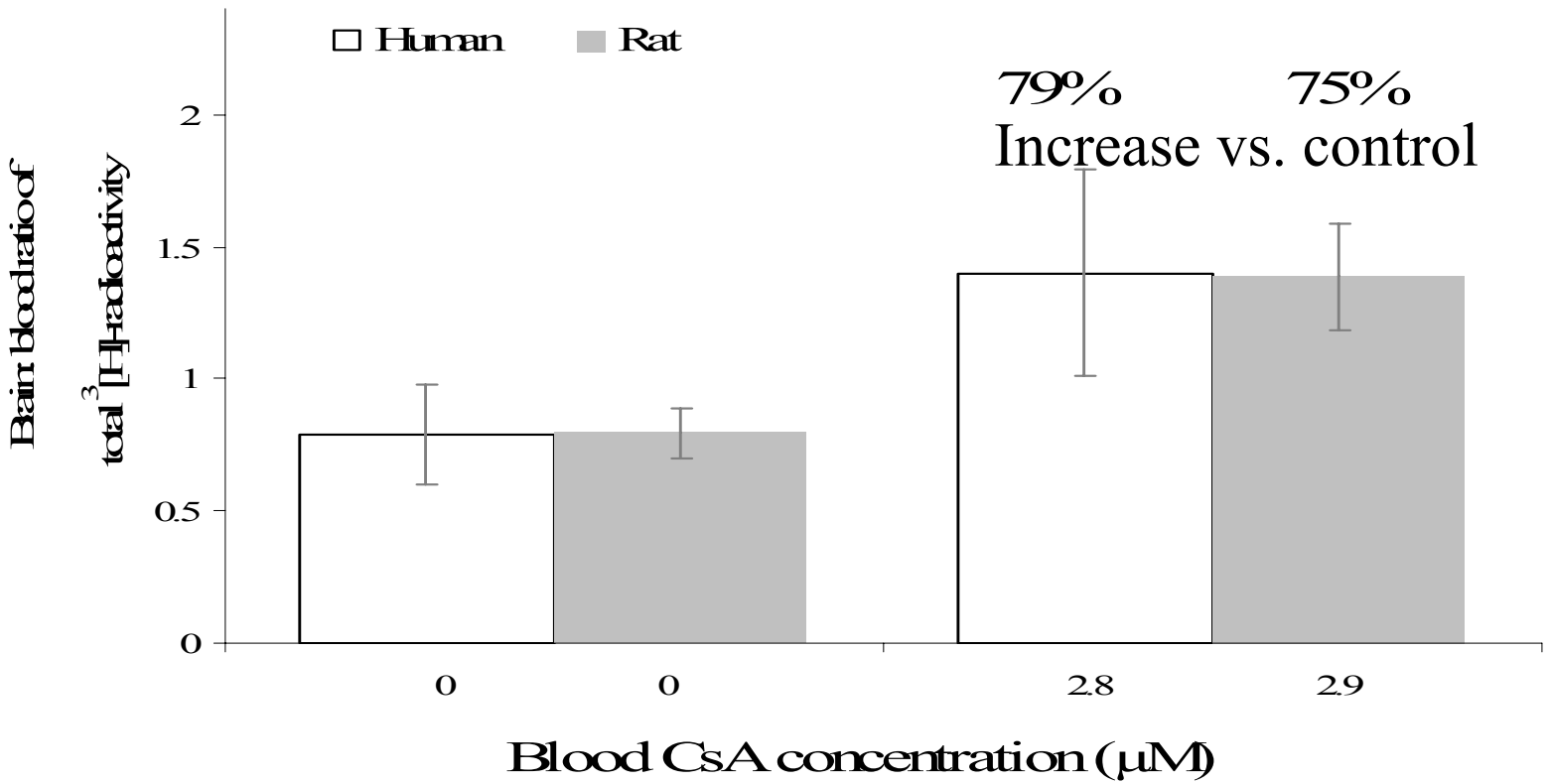


EC50=7.2 μM (7%)
Emax=1290% (7%)
γ=3.8 (22%).

Hsiao et al J Pharmacol Exp Ther. 2006

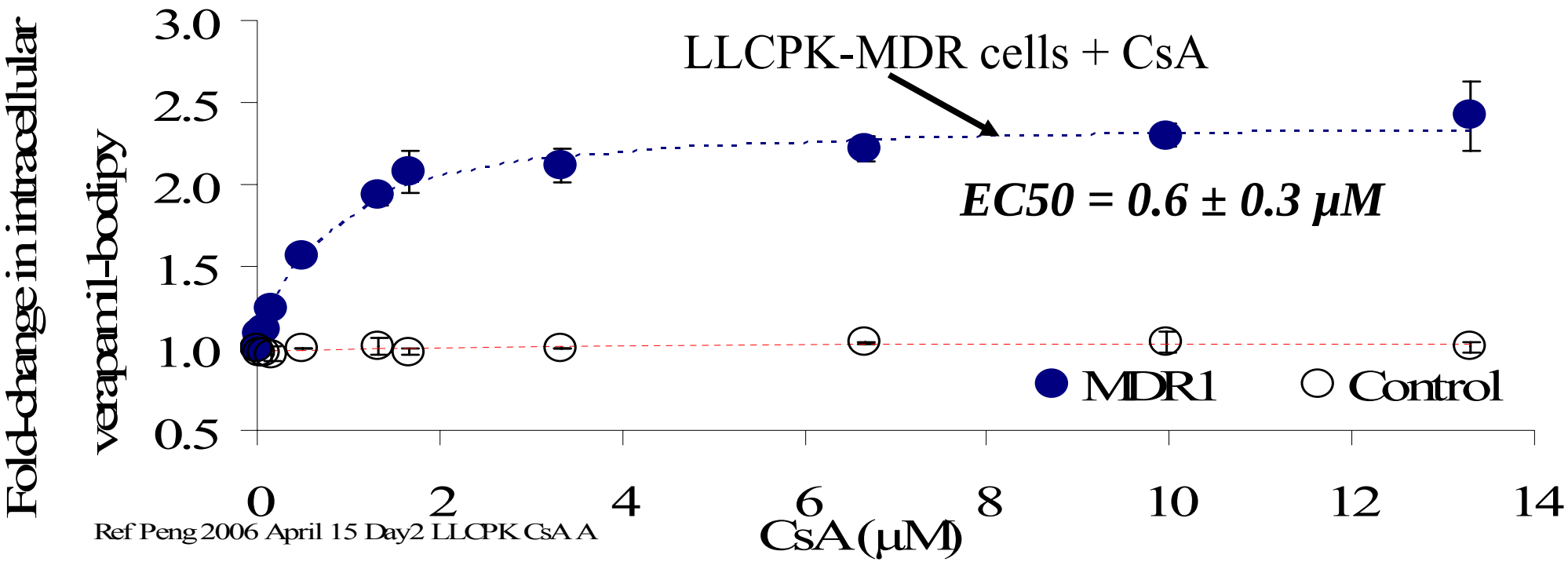
P-glycoprotein based drug interaction at the BBB: CsA-verapamil

Comparison of human and rat data



Hsiao et al J Pharmacol Exp Ther. 2006

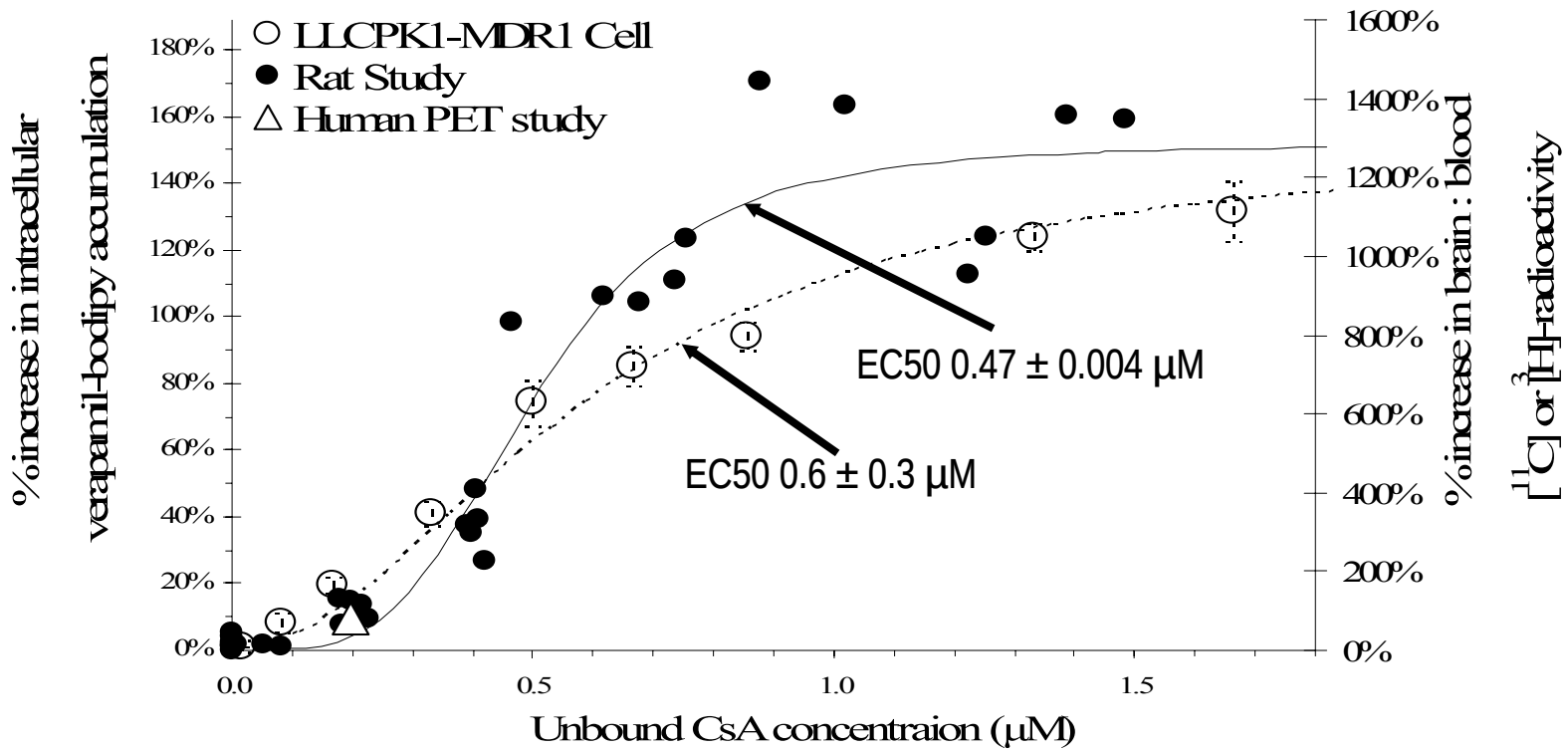
Can such In Vivo P-gp-based drug interactions be Predicted from In Vitro Studies?



In vivo unbound EC50 at the rat BBB 0.47 ± 0.004 µM

P-glycoprotein based drug interaction at the BBB: CsA-verapamil

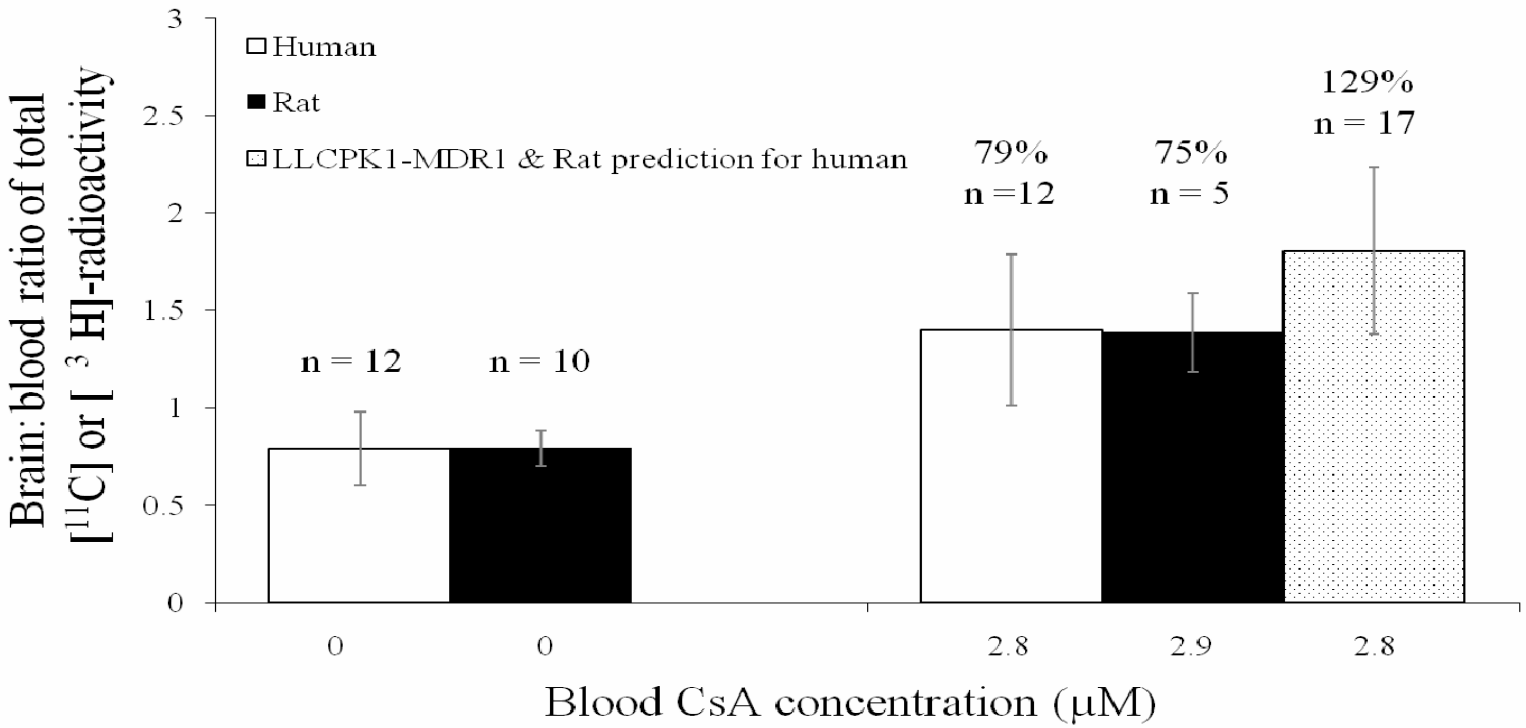
Comparison of *in vitro* cell culture data and *in vivo* data in humans and rats



Hsiao et al DMD 2007
In Press

P-glycoprotein based drug interaction at the BBB: CsA-verapamil

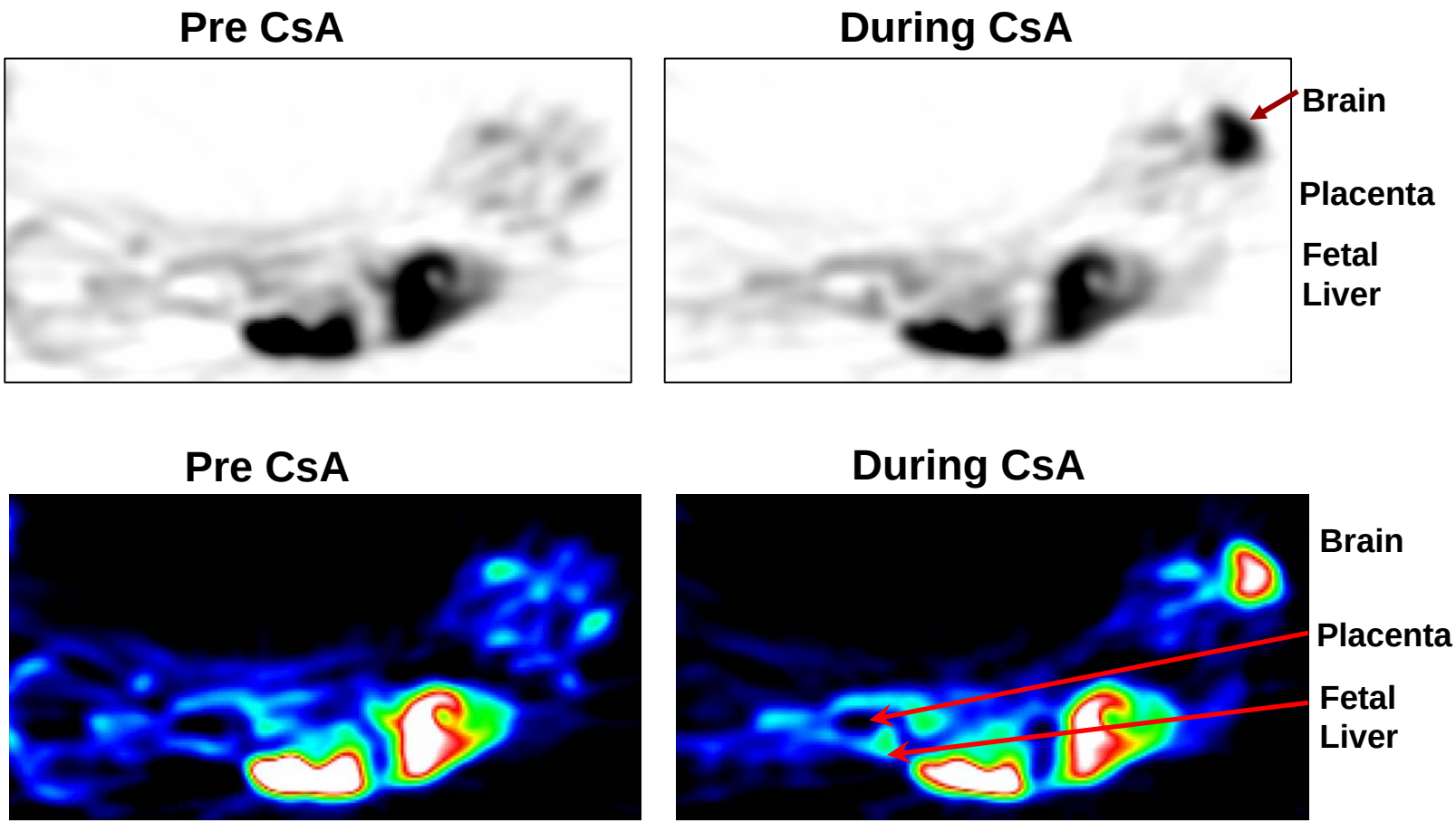
Prediction from in vitro cell culture and in vivo rodent data



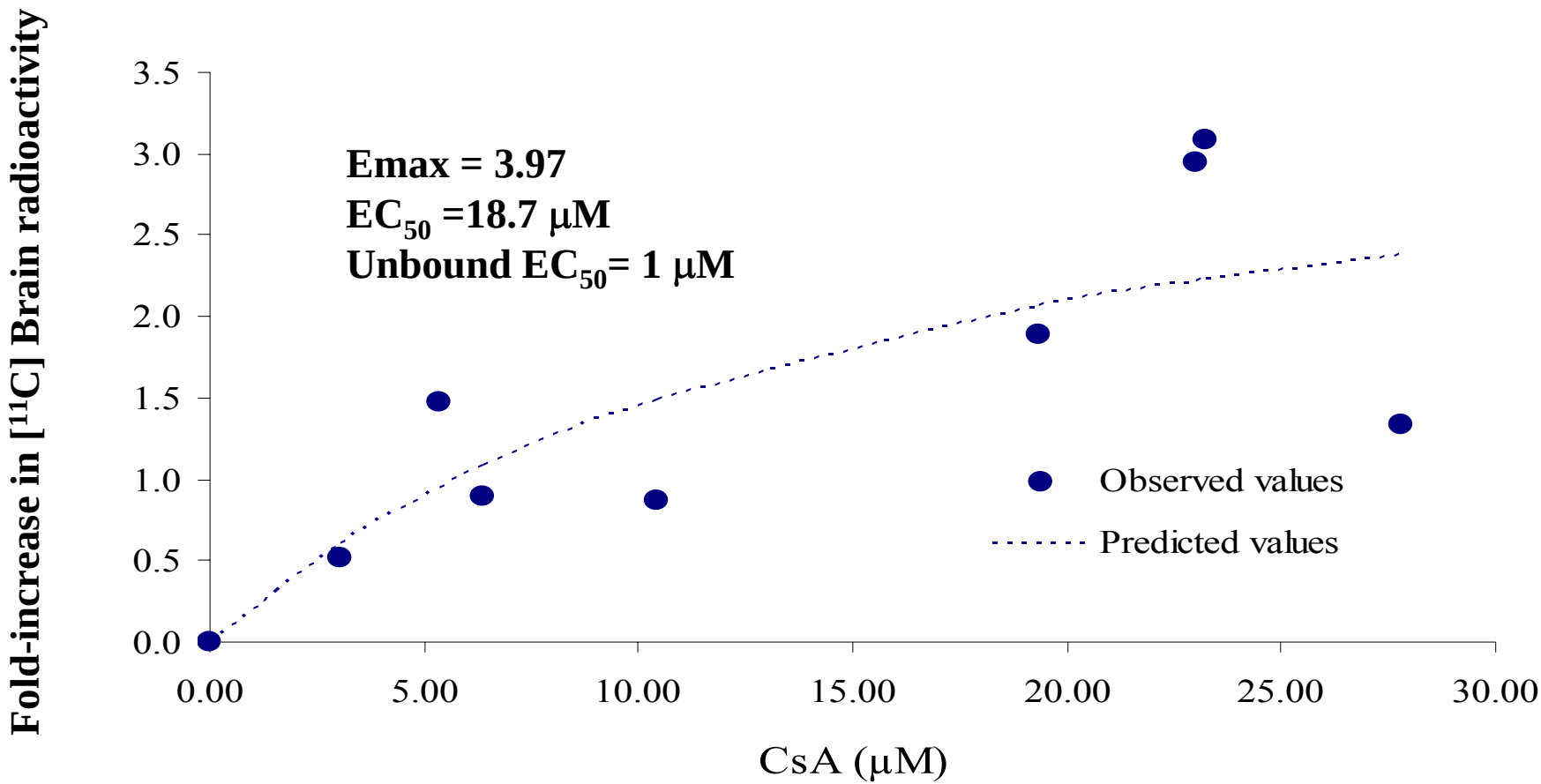
Hsiao et al DMD In Press 2007

P-glycoprotein based drug interaction at the BBB and BPB: CsA-verapamil

Is Emax in the rodents and humans the same?

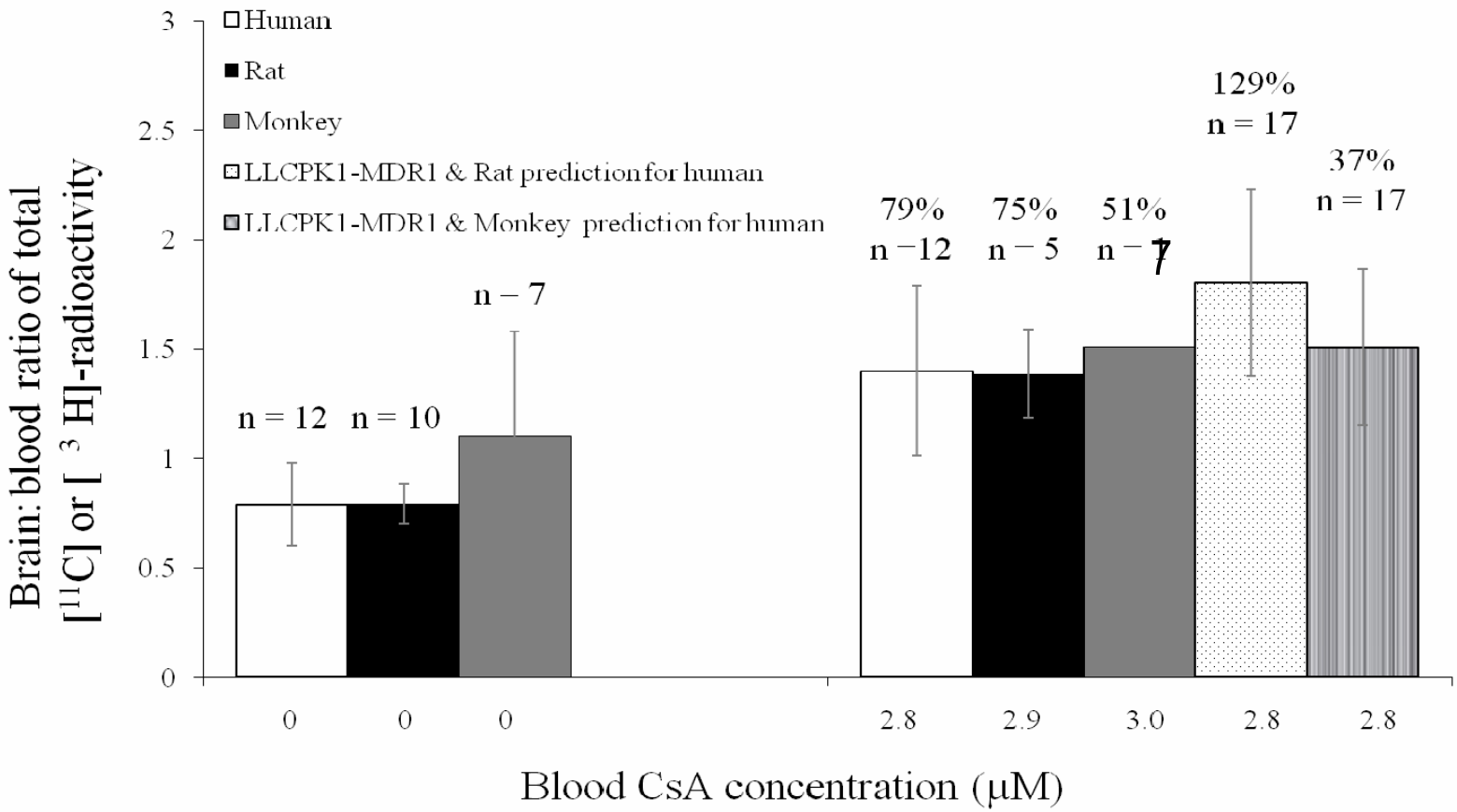


Inhibition of P-gp activity by CsA at the Non-Human-Primate BBB



Inhibition of P-gp activity by CsA at the Human BBB

Prediction from in vitro cell culture and in vivo data in rodents and non-human primates



Predicting drug-drug interactions from in vitro to in vivo: challenges of the future

Summary

- Metabolic competitive interactions relatively well predicted – issue of which concentration of the inhibitor to use (transporter related?) remains – total or unbound?

- Induction – progress made in prediction, but models need to be refined to identify the inducer concentration to use in the intestine and liver. Need to take into consideration the dynamics of induction in intestine and liver.

- Models exist for predicting inactivation interaction, but validity needs to be widely tested and may need to be refined to incorporate induction.

- Cautious optimism in prediction of transporter-related competitive interactions. Many unanswered questions remain – which transporters are functionally important in various human tissues, the Ki of the inhibitors, the conc. of the inhibitor to use (total or unbound) etc.

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BBB studies

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