Building and evaluation of a PBPK model for Felodipine in healthy adults

Version	1.0-OSP12.0
based on *Model Snapshot* and *Evaluation Plan*	https://github.com/Open-Systems-Pharmacology/Felodipine-Model/releases/tag/v1.0
OSP Version	12.0
Qualification Framework Version	3.3

This evaluation report and the corresponding PK-Sim project file are filed at:

https://github.com/Open-Systems-Pharmacology/OSP-PBPK-Model-Library/

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1 Introduction

Felodipine is a calcium-channel blocker, indicated for angina pectoris and arterial hypertension. It is mostly metabolized by CYP3A4 making it a sensitive probe and victim drug for the investigation of CYP3A4 activity *in vivo*. It is a BCS class II compound. Felodipine shows substantial first pass metabolism resulting in a bioavailability of 15%.

The model has been developed and evaluated by comparing observed data to simulations of a large number of clinical studies covering a dose range of 1.5 mg to 10 mg after intravenous and oral administrations. Furthermore, it has been evaluated within a CYP3A4 DDI modeling network as a victim drug.

Model features include:

- metabolism by CYP3A4

- metabolism by an unknown enzyme *via* unspecific hepatic clearance

- a decrease in the permeability between the intracellular and interstitial space (model parameters `P (intracellular->interstitial)` and `P (interstitial->intracellular)`) in intestinal mucosa to optimize quantitatively the extent of gut wall metabolism

2 Methods

2.1 Modeling Strategy

The general concept of building a PBPK model has previously been described by Kuepfer et al. (Kuepfer 2016). Relevant information on anthropometric (height, weight) and physiological parameters (e.g. blood flows, organ volumes, binding protein concentrations, hematocrit, cardiac output) in adults was gathered from the literature and has been previously published (Willmann 2007). The information was incorporated into PK-Sim® and was used as default values for the simulations in adults.

The applied activity and variability of plasma proteins and active processes that are integrated into PK-Sim® are described in the publicly available PK-Sim® Ontogeny Database Version 7.3 (PK-Sim Ontogeny Database Version 7.3) or otherwise referenced for the specific process.

First, a mean model was built using clinical data from single dose and multiple doses studies with intravenous and oral administration of felodipine (Edgar 1987, Bailey 1996, Gelal 2005, Bailey 2003, Goosen 2004, Jalava 1997, Blychert 1990, Lundahl 1998, Bailey 1995, Aberg 1997, Bailey 1993, Edgar 1992, Lundahl 1997). One DDI study (Jalava 1997) was also used in the optimization to help the model describe DDI better. The mean PBPK model was developed using a typical male European individual. The relative tissue-specific expressions of enzymes predominantly being involved in the metabolism of felodipine (CYP3A4) were considered (Meyer 2012).

A specific selected set of parameters (see below) was optimized using the Parameter Identification module provided in PK-Sim®. Structural model selection was mainly guided by visual inspection of the resulting description of data and biological plausibility.

Once the appropriate structural model was identified, dissolution kinetic parameters were optimized for immediate-release tablets.

The model was then evaluated by simulating further clinical studies reporting pharmacokinetic concentration-time profiles of felodipine.

Details about input data (physicochemical, *in vitro* and clinical) can be found in Section 2.2.

Details about the structural model and its parameters can be found in Section 2.3.

2.2 Data

2.2.1 In vitro and physicochemical data

A literature search was performed to collect available information on physicochemical properties of felodipine. The obtained information from literature is summarized in the table below, and is used for model building.

Parameter	Unit	Value	Source	Description
MW	g/mol	384.254	DrugBank DB01023	Molecular weight
pK_{a1}		n.a.	Alskar 2018	Acid dissociation constant of conjugate acid
pK_{a1}		5.07	Pandey 2013	Acid dissociation constant of conjugate acid; compound type: acid
Solubility (pH)	mg/L	14.3 (7.1)	Takano 2016	Aqueous Solubility
		1	Scholz 2002	Aqueous Solubility
		53	Söderlind 2010	Solubility in fasted state simulated intestinal fluid I
		12	Söderlind 2010	Solubility in fasted state simulated intestinal fluid II
		14	Söderlind 2010	Solubility in fasted human intestinal fluid
		15 (7.5)	Persson 2005	Solubility in fasted human intestinal fluid
		413 (6.1)	Persson 2005	Solubility in fed human intestinal fluid
		191	Persson 2005	Solubility in fed state simulated intestinal fluid
		77 (6.35)	Scholz 2002	Solubility in fasted state chyme
		56 (4.93)	Scholz 2002	Solubility in fed state chyme
logP		4.36	DrugBank DB01023	Partition coefficient between octanol and water
		3.44	DrugBank DB01023	Partition coefficient between octanol and water
		3.86	McPherson 2020	Partition coefficient between octanol and water
		4.5	Scholz 2002	Partition coefficient between octanol and water
		4.8	Bu 2006	Partition coefficient between octanol and water
fu	%	0.36	Soons 1993	Fraction unbound in plasma
	%	0.36	Ushimura 2010	Fraction unbound in plasma
V_{max}, K_m CYP3A	pmol/mg/min, µmol/L	1630 2.81	Walsky 2004	CYP3A liver microsomes Michaelis-Menten kinetics
V_{max}, K_m CYP3A	pmol/mg/min, µmol/L	240 6.9	Bu 2006	CYP3A liver microsomes Michaelis-Menten kinetics
V_{max}, K_m CYP3A4	pmol/mg/min, µmol/L	36.8 0.938	Walsky 2004	Recombinant CYP3A4 Michaelis-Menten kinetics
V_{max}, K_m CYP3A5	pmol/mg/min, µmol/L	24.2 1.41	Walsky 2004	Recombinant CYP3A5 Michaelis-Menten kinetics

2.2.2 Clinical data

A literature search was performed to collect available clinical data on felodipine in adults.

The following publications were found in adults for model building:

Publication	Arm / Treatment / Information used for model building
Lundahl 1997	Plasma PK profiles in healthy subjects with single dose administrations of a felodipine 1.5 mg intravenous infusion
Edgar 1987	Plasma PK profiles in healthy subjects with single dose administrations of a felodipine: - 10 mg oral solution - 10 mg extended release tablet - 10 mg immediate release tablet
Blychert 1990	Plasma PK profiles in healthy subjects with multiple dose administrations of a felodipine: - 10 mg oral solution - 10 mg extended release tablet
Goosen 2004	Plasma PK profiles in healthy subjects with single dose administrations of a felodipine 5 mg extended release tablet
Jalava 1997	Plasma PK profiles in healthy subjects with single dose administrations of a felodipine 5 mg extended release tablet - alone (control) - with itraconazole (treatment)
Bailey 1996	Plasma PK profiles in healthy subjects with single dose administrations of a felodipine 10 mg extended release tablet
Gelal 2005	Plasma PK profiles in healthy subjects with single dose administrations of a felodipine 10 mg extended release tablet
Bailey 2003	Plasma PK profiles in healthy subjects with single dose administrations of a felodipine 10 mg extended release tablet
Bailey 1993	Plasma PK profiles in healthy subjects with single dose administrations of a felodipine 5 mg immediate release tablet
Edgar 1992	Plasma PK profiles in healthy subjects with single dose administrations of a felodipine 5 mg immediate release tablet
Blychert 1990	Plasma PK profiles in healthy subjects with multiple dose administrations of a felodipine: - 10 mg oral solution - 10 mg extended release tablet
Lundahl 1998	Plasma PK profiles in healthy subjects with multiple dose administrations of a felodipine 10 mg extended release tablet
Bailey 1995	Plasma PK profiles in healthy subjects with multiple dose administrations of a felodipine 10 mg extended release tablet
Aberg 1997	Plasma PK profiles in healthy subjects with multiple dose administrations of a felodipine 10 mg extended release tablet

The following dosing scenarios were simulated and compared to respective data for model verification:

Scenario	Data reference
po 5 mg single dose (extended release tablet)	Dresser 2000
po 10 mg single dose (extended release tablet)	Dresser 2017
	Dresser 2002
	Bailey 2000
	Bailey 1998
	Lundahl 1997
	Madsen 1996
po 2.5 / 5 mg once daily (extended release tablet)	Dresser 2000
po 10 mg once daily (immediate release tablet)	Blychert 1990
po 10 mg twice daily (immediate release tablet)	Blychert 1990
	Smith 1987
po 10 mg three times daily (immediate release tablet)	Bratel 1989

2.3 Model Parameters and Assumptions

2.3.1 Absorption

The model parameter `Specific intestinal permeability` was was calculated by PK-Sim® and kept to that value since it was insensitive. The default solubility was assumed to be measured value in fasted state simulated intestinal fluid (see Section 2.2.1)

The dissolution of both immediate and extended-release tables was implemented via two Weibull dissolution tablets, and the dissolution kinetic parameters were optimized (see Section 2.3.4).

2.3.2 Distribution

Felodipine is highly bound to proteins in plasma (see Section 2.2.1). A value of 0.36% was used in this PBPK model for `Fraction unbound (plasma, reference value)`.

An important parameter influencing the resulting volume of distribution is lipophilicity. The reported experimental logP values are in the range of 4 (see Section 2.2.1) which served as a starting value. Finally, the model parameter `Lipophilicity` was optimized to match best clinical data (see also Section 2.3.4).

After testing the available organ-plasma partition coefficient and cell permeability calculation methods built in PK-Sim, observed clinical data was best described by choosing the partition coefficient calculation by `Rodgers and Rowland` and cellular permeability calculation by `PK-Sim Standard`.

2.3.3 Metabolism and Elimination

Two metabolic pathways were implement into the model via Michaelis-Menten kinetics

- CYP3A4
- unknown hepatic enzyme *via* unspecific hepatic clearance

The latter was preferred over renal clearance, since there is evidence that felodipine is fully metabolized and not found in urine (Edgar 1987).
CYP3A5 was not implemented since the fraction metabolized appeared to be minor compared to CYP3A4.

The CYP3A4 expression profiles is based on high-sensitive real-time RT-PCR (Nishimura 2003). Absolute tissue-specific expressions were obtained by considering the respective absolute concentration in the liver. The PK-Sim database provides a default value for CYP3A4 (compare Rodrigues 1999 and assume 40 mg protein per gram liver).

The first model simulations showed that gut wall metabolism was underrepresented in the PBPK model. In order to increase gut wall metabolism, the "mucosa permeability on basolateral side" (jointly the model parameters in the mucosa: `P (interstitial->intracellular)` and `P (intracellular->interstitial)`) was estimated. A decrease in this permeability may lead to higher gut wall concentrations and, in turn, to a higher gut wall elimination. This parameter was preferred over other parameters such as relative CYP3A4 expression or fraction unbound (fu) in the gut wall as it is technically not limited to a maximum value of 100%.

2.3.4 Automated Parameter Identification

This is the result of the final parameter identification for the base model:

Model Parameter	Optimized Value	Unit
`Lipophilicity`	4.51	Log Units
Basolateral mucosa permeability (`P (interstitial->intracellular)`, `P (intracellular->interstitial)`)	0.09	cm/min
`kcat` (CYP3A4)	204.70	1/min
`Dissolution time` (extended release tablet)	286.95	min
`Dissolution shape` (extended release tablet)	0.76	
`Lag time` (extended release tablet)	18.68	min
`Tablet time delay factor` (extended release tablet)	0.07	
`Dissolution time` (immediate release tablet)	46.50	min
`Dissolution shape` (immediate release tablet)	0.89	

3 Results and Discussion

The PBPK model for felodipine was developed and verified with clinical pharmacokinetic data.

The model was built and evaluated covering data from studies including in particular

- intravenous (infusions) and oral administrations (solutions, immediate release and extended release tablets).
- a dose range of 1.5 to 10 mg.

The model quantifies metabolism via CYP3A4, and a second unknown hepatic enzyme.

The next sections show:

1. the final model input parameters for the building blocks: Section 3.1.
2. the overall goodness of fit: Section 3.2.
3. simulated vs. observed concentration-time profiles for the clinical studies used for model building and for model verification: Section 3.3.

3.1 Final input parameters

The compound parameter values of the final PBPK model are illustrated below.

Compound: Felodipine

Parameters

Name	Value	Value Origin	Alternative	Default
Solubility at reference pH	12 µg/ml	Publication-Soderlind, 2010	FaSSIF II	True
Reference pH	6.5	Publication-Soderlind, 2010	FaSSIF II	True
Lipophilicity	4.5085714616 Log Units	Parameter Identification-Parameter Identification-Value updated from 'PI_IV+Solution+ER+DDI_additionalCL_3' on 2022-08-10 10:40	Measurement	True
Fraction unbound (plasma, reference value)	0.0036	Publication-Ushimura, 2010	Measurement	True
Cl	2	Internet-DrugBank DB01023		
Is small molecule	Yes			
Molecular weight	384.254 g/mol	Internet-DrugBank DB01023		
Plasma protein binding partner	Unknown			

Calculation methods

Name	Value
Partition coefficients	Rodgers and Rowland
Cellular permeabilities	PK-Sim Standard

Processes

Metabolizing Enzyme: CYP3A4-Walsky 2004

Molecule: CYP3A4

Parameters

Name	Value	Value Origin
In vitro Vmax for liver microsomes	1630 pmol/min/mg mic. protein	Publication-Walsky 2004
Km	2.81 µmol/l	Publication-Walsky 2004
kcat	204.6995652687 1/min	Parameter Identification-Parameter Identification-Value updated from 'PI_IV+Solution+ER+DDI_additionalCL_3' on 2022-08-10 10:40

Systemic Process: Total Hepatic Clearance-Unspecific hepatic clearance

Species: Human

Parameters

Name	Value	Value Origin
Fraction unbound (experiment)	0.0036	
Lipophilicity (experiment)	4.3407865958 Log Units	
Plasma clearance	0 ml/min/kg	
Specific clearance	12.8042083376 1/min	Parameter Identification-Parameter Identification-Value updated from 'PI_IV+Solution+ER+DDI_additionalCL_3' on 2022-08-10 10:41

Formulation: Felodipine_ER tablet

Type: Weibull

Parameters

Name	Value	Value Origin
Dissolution time (50% dissolved)	286.9463213309 min	Parameter Identification-Parameter Identification-Value updated from 'PI_IV+Solution+ER+DDI_additionalCL_3' on 2022-08-10 10:41
Lag time	18.6758448616 min	Parameter Identification-Parameter Identification-Value updated from 'PI_IV+Solution+ER+DDI_additionalCL_3' on 2022-08-10 10:41
Dissolution shape	0.7639975313	Parameter Identification-Parameter Identification-Value updated from 'PI_IV+Solution+ER+DDI_additionalCL_3' on 2022-08-10 10:41
Use as suspension	Yes	

Formulation: Felodipine_IR tablet

Type: Weibull

Parameters

| Name	Value	Value Origin
Dissolution time (50% dissolved)	46.5005948338 min	Parameter Identification-Parameter Identification-Value updated from 'PI IR Tablet alone' on 2022-08-10 11:29
Lag time	0 min	
Dissolution shape	0.8876005929	Parameter Identification-Parameter Identification-Value updated from 'PI IR Tablet alone' on 2022-08-10 11:29
Use as suspension	Yes	

3.2 Diagnostics Plots

Below you find the goodness-of-fit visual diagnostic plots for the PBPK model performance of all data used presented in Section 2.2.2.

The first plot shows observed versus simulated plasma concentration, the second weighted residuals versus time.
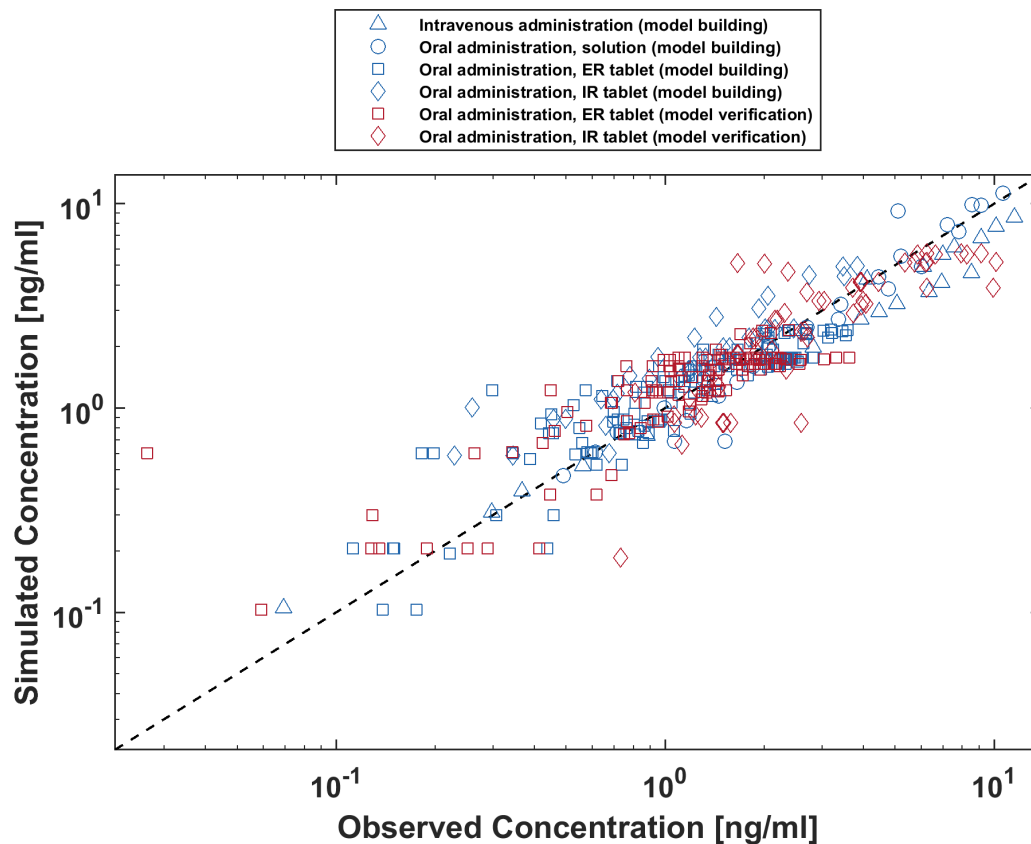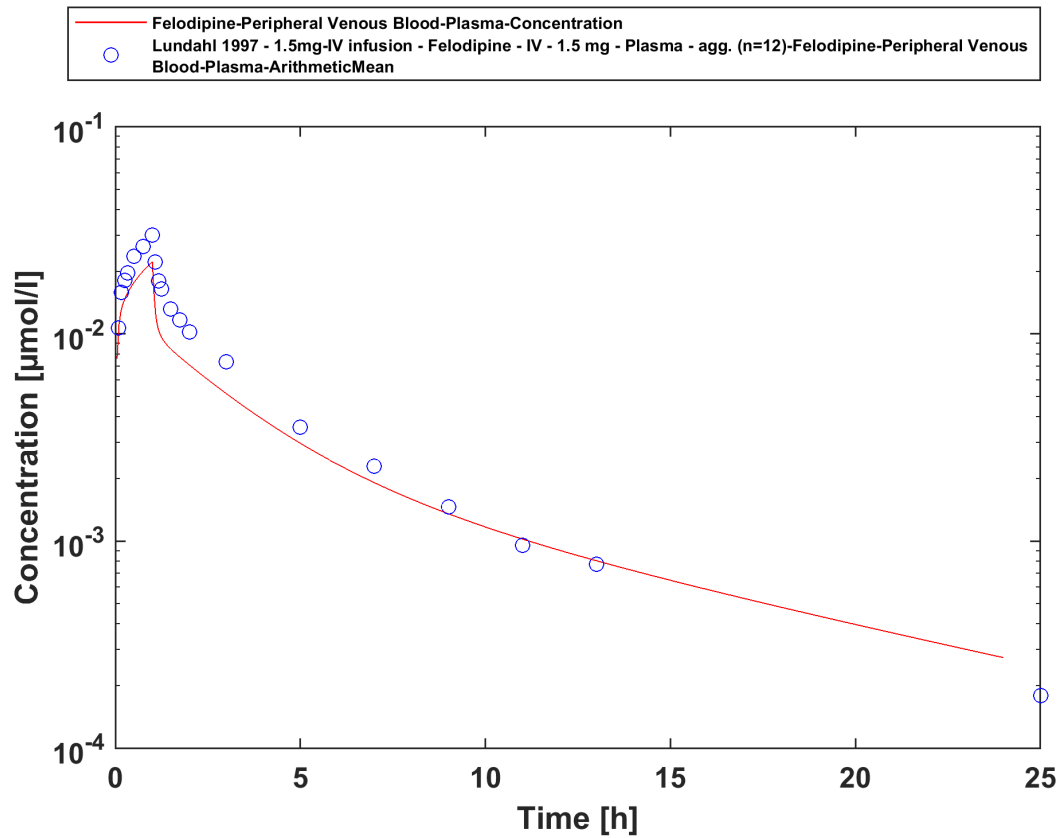

Felodipine concentration in plasma
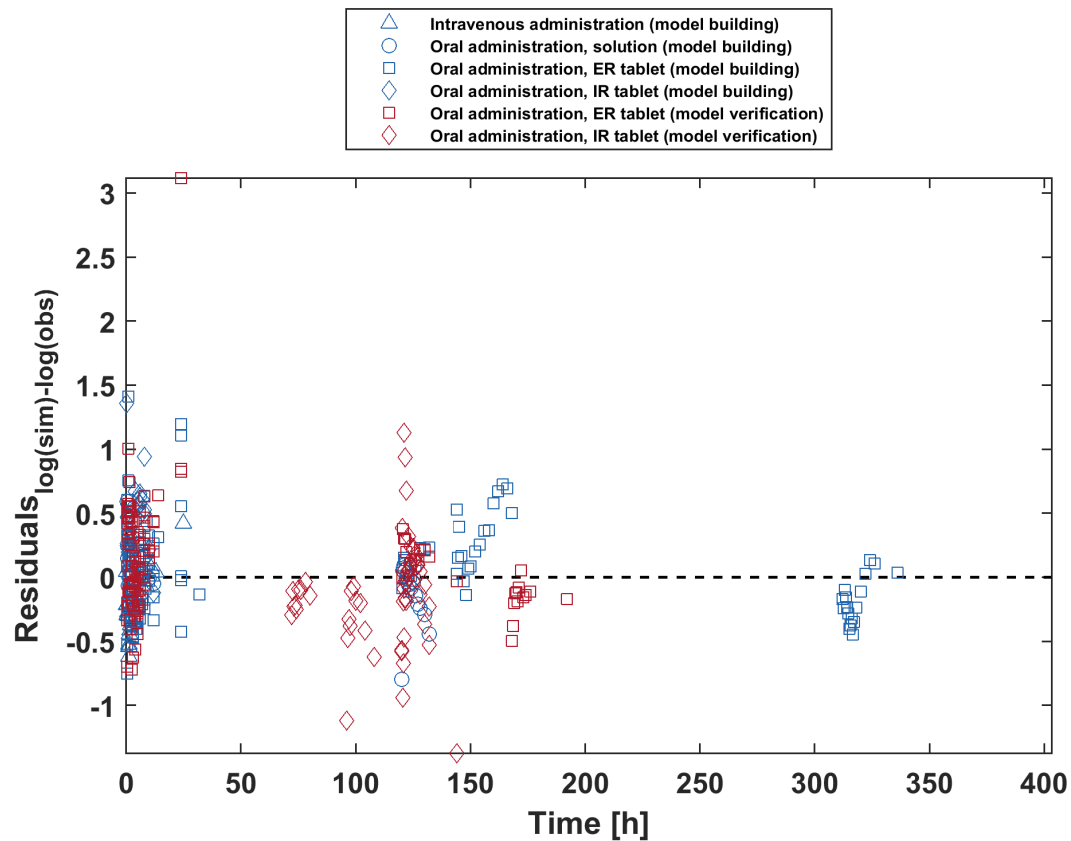
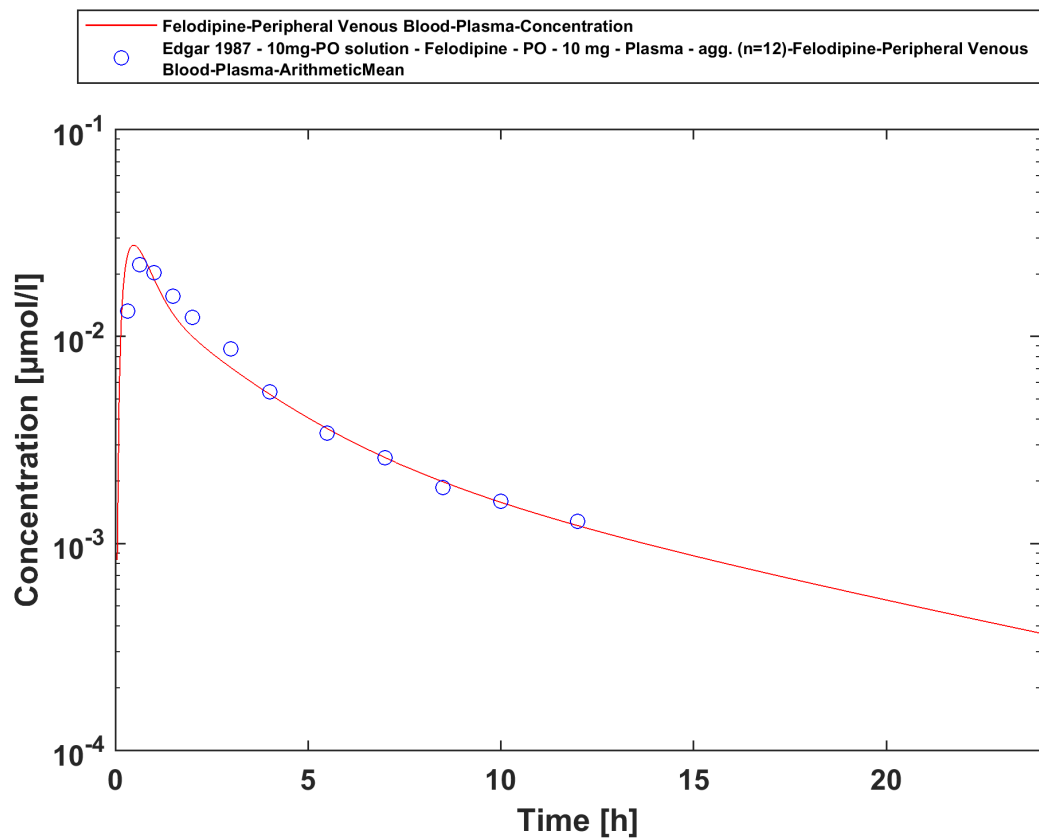Felodipine concentration in plasma

GMFE = 1.325173

3.3 Concentration-Time Profiles

Simulated versus observed concentration-time profiles of all data listed in Section 2.2.2 are presented below.
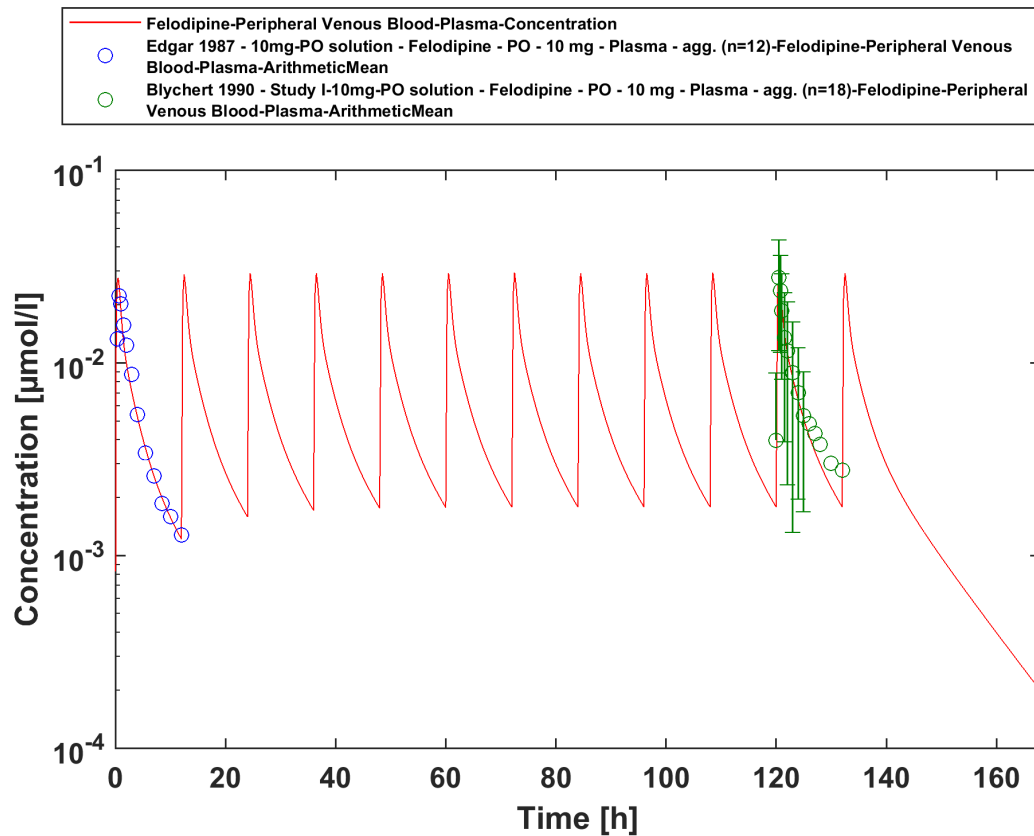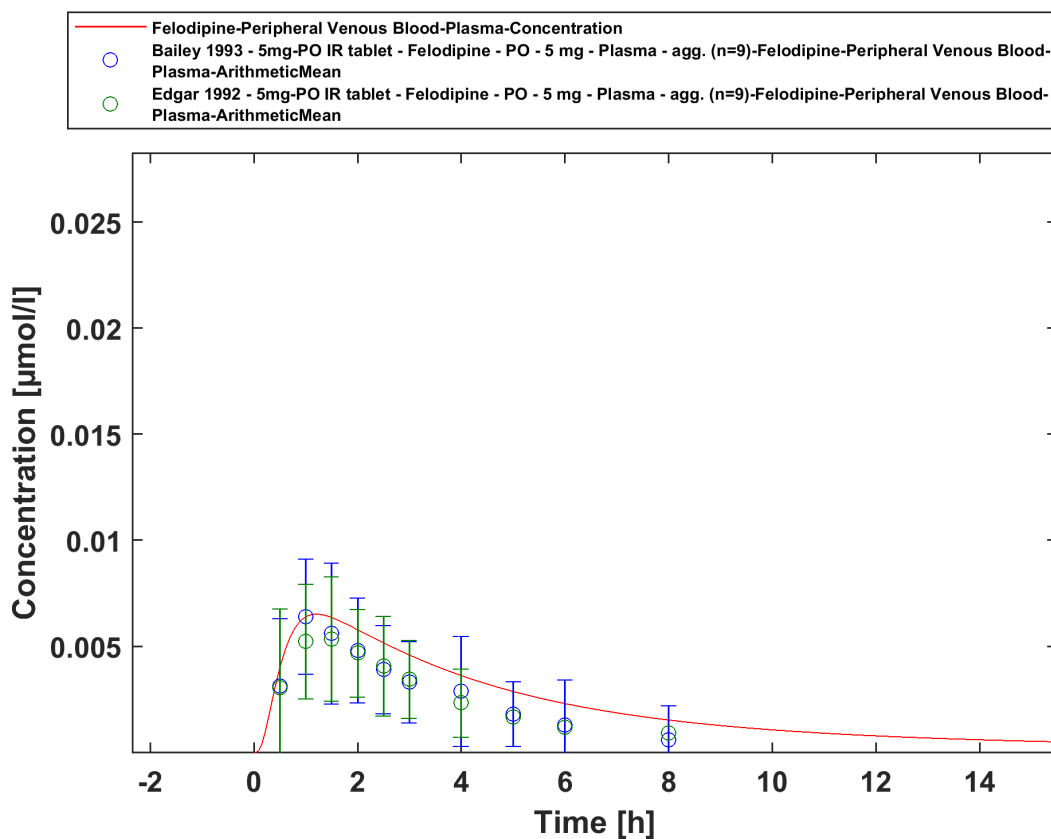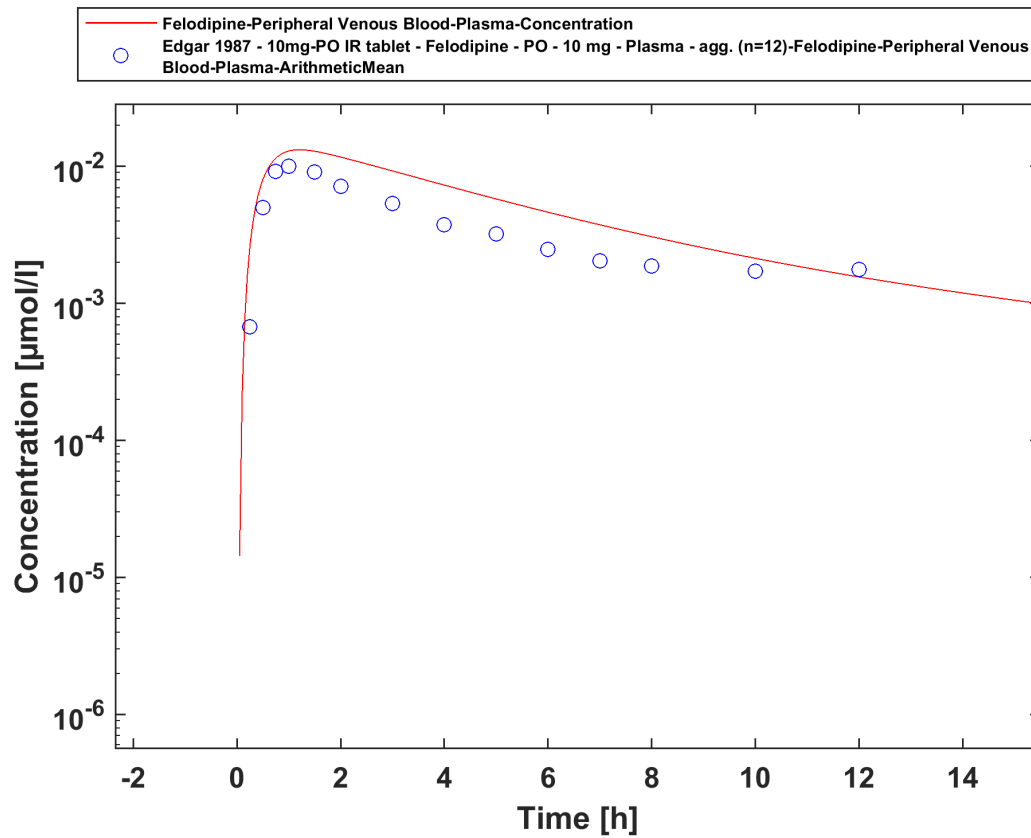
3.3.1 Model Building

Time Profile Analysis

Time Profile Analysis

Time Profile Analysis

Time Profile Analysis

Felodipine-Peripheral Venous Blood-Plasma-Concentration
○ Edgar 1987 - 10mg-PO IR tablet - Felodipine - PO - 10 mg - Plasma - agg. (n=12)-Felodipine-Peripheral Venous Blood-Plasma-ArithmeticMean

Time Profile Analysis

Felodipine-Peripheral Venous Blood-Plasma-Concentration
○ Goosen 2004 - 5mg-PO ER tablet - Felodipine - PO - 5 mg - Plasma - agg. (n=11)-Felodipine-Peripheral Venous Blood-Plasma-ArithmeticMean
○ Jalava 1997 - 5mg-PO ER tablet - Felodipine - PO - 5 mg - Plasma - agg. (n=9)-Felodipine-Peripheral Venous Blood-Plasma-ArithmeticMean

Time Profile Analysis

Time Profile Analysis

Time Profile Analysis

3.3.2 Model Verification
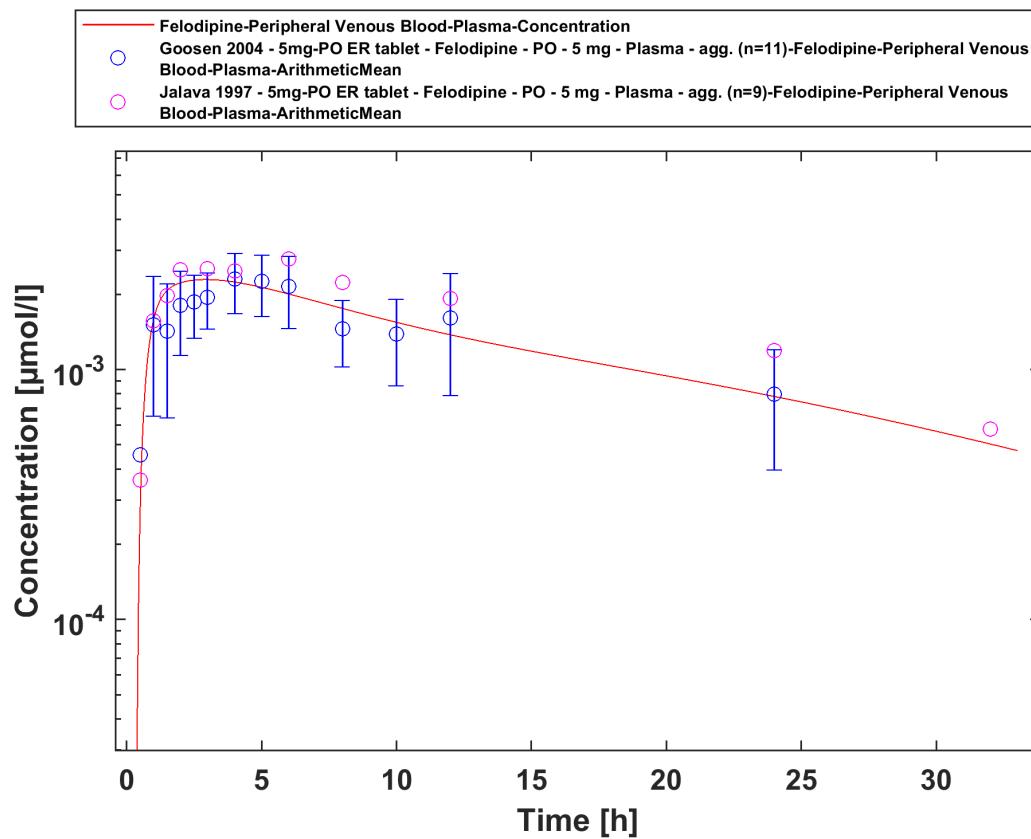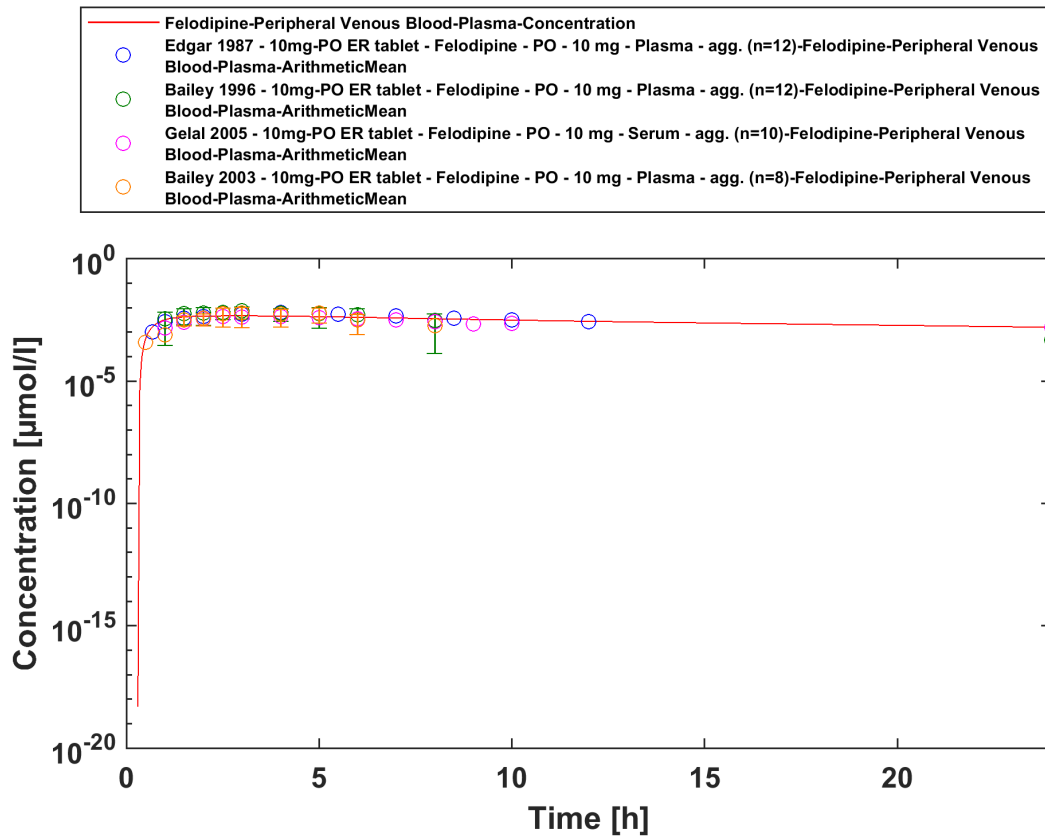

Time Profile Analysis

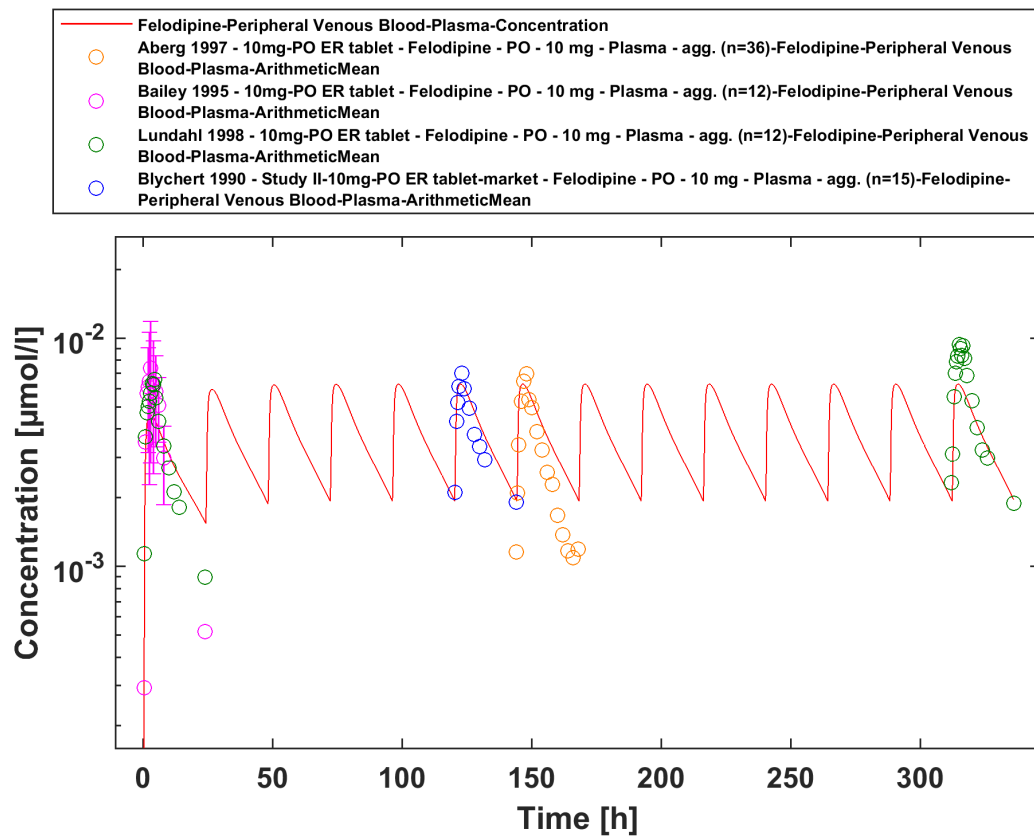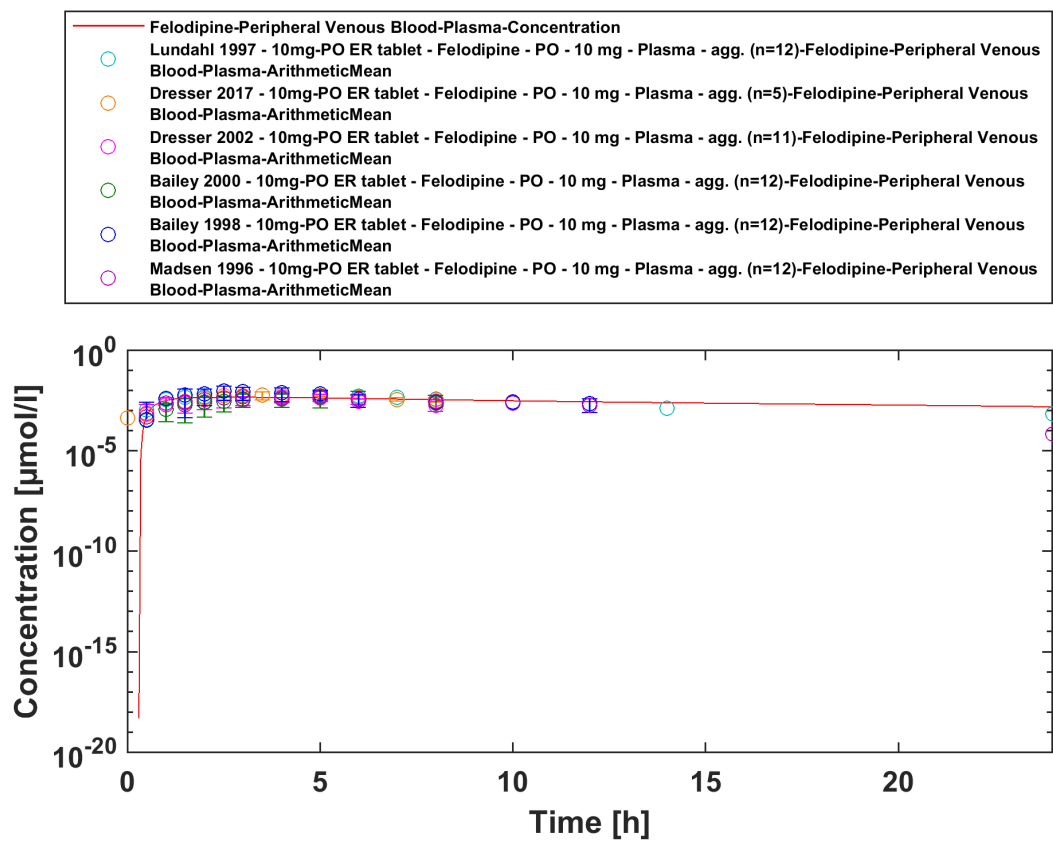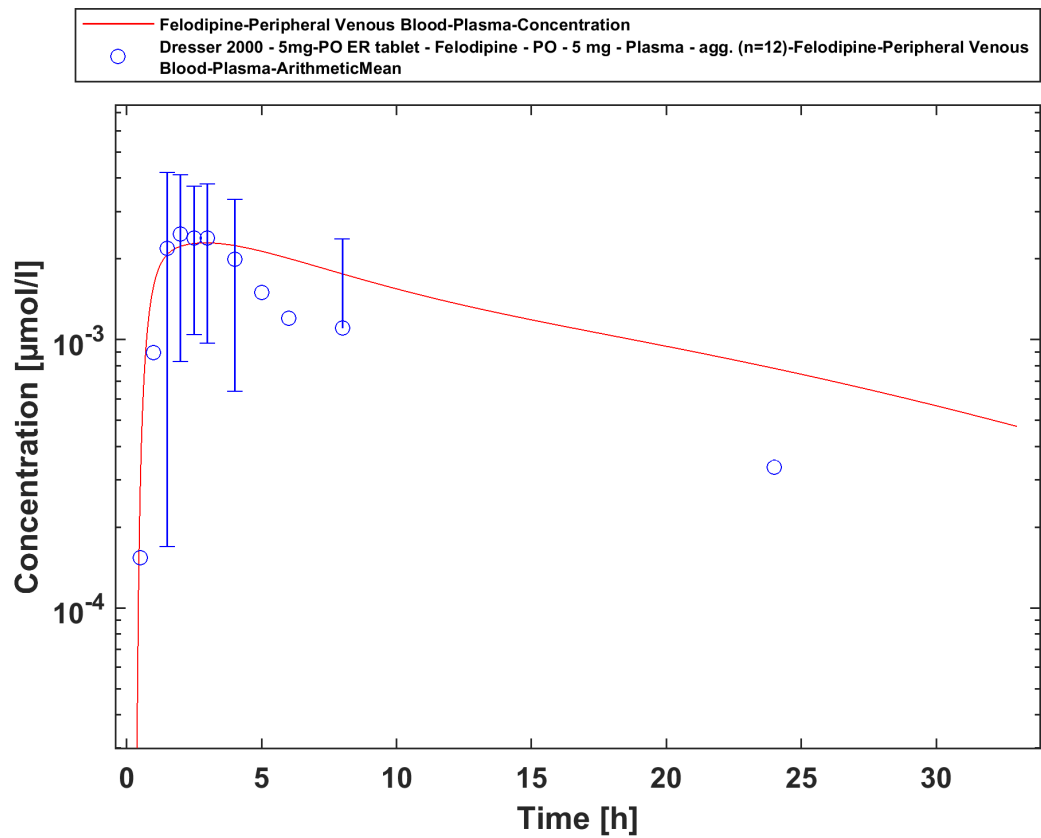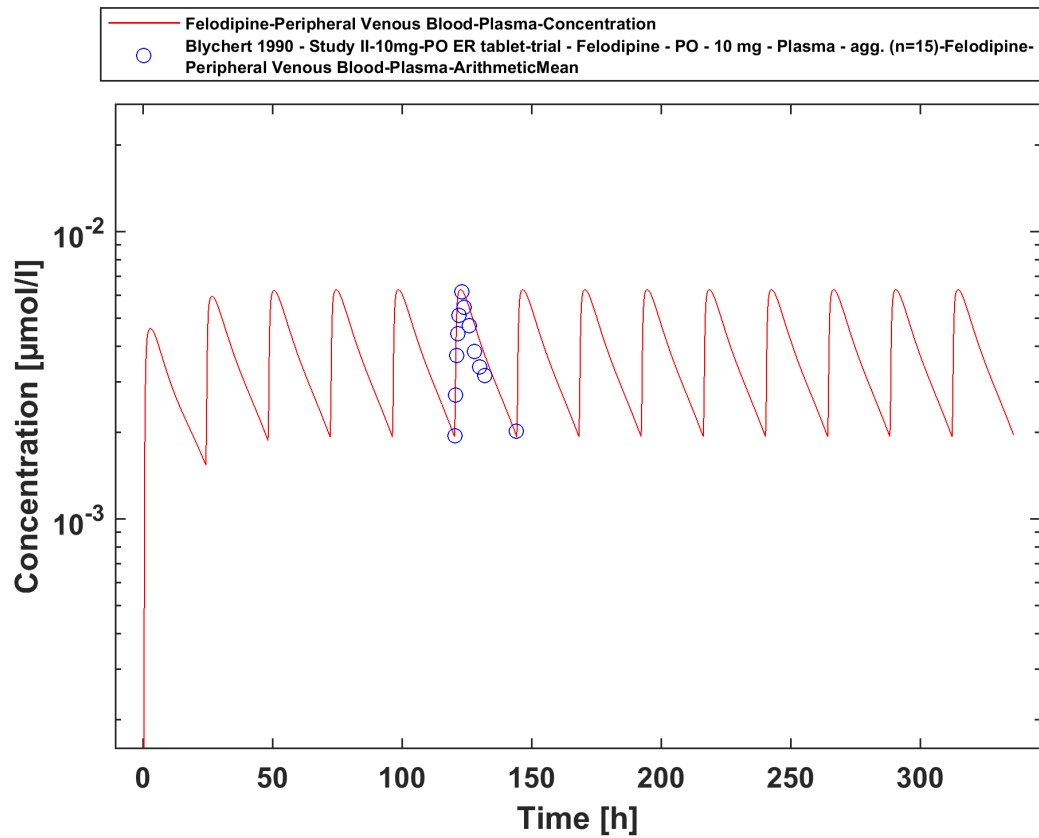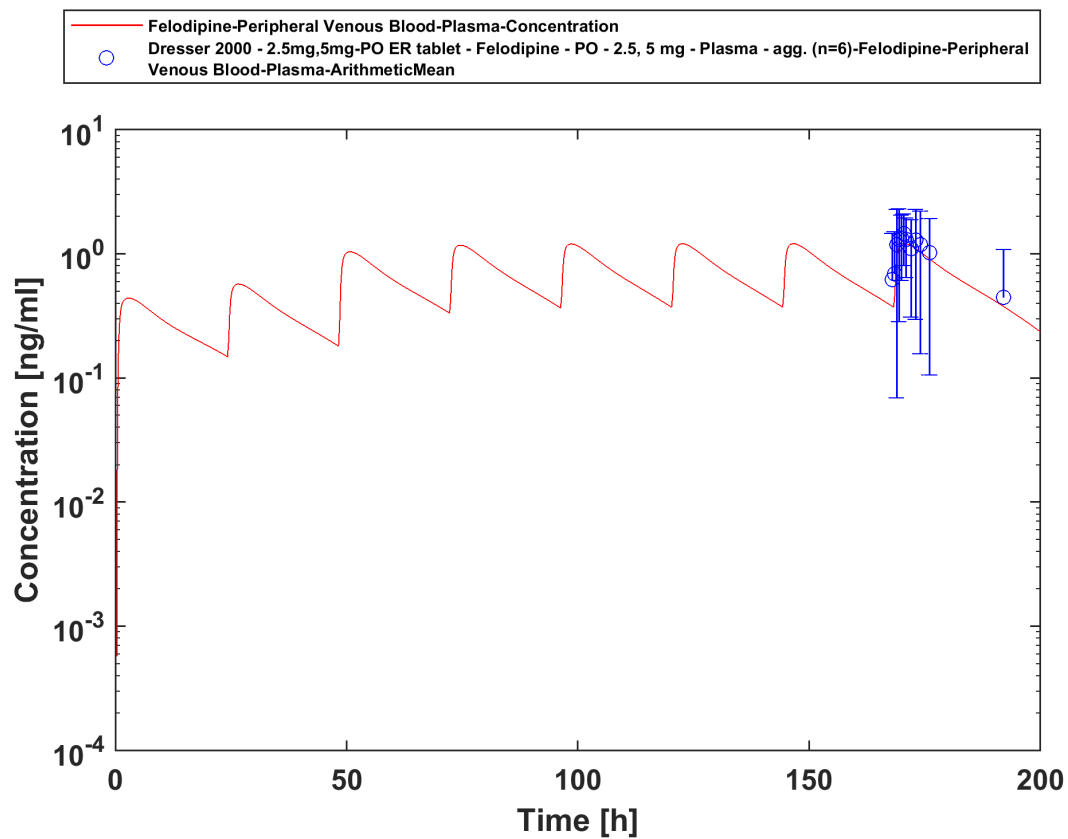Time Profile Analysis
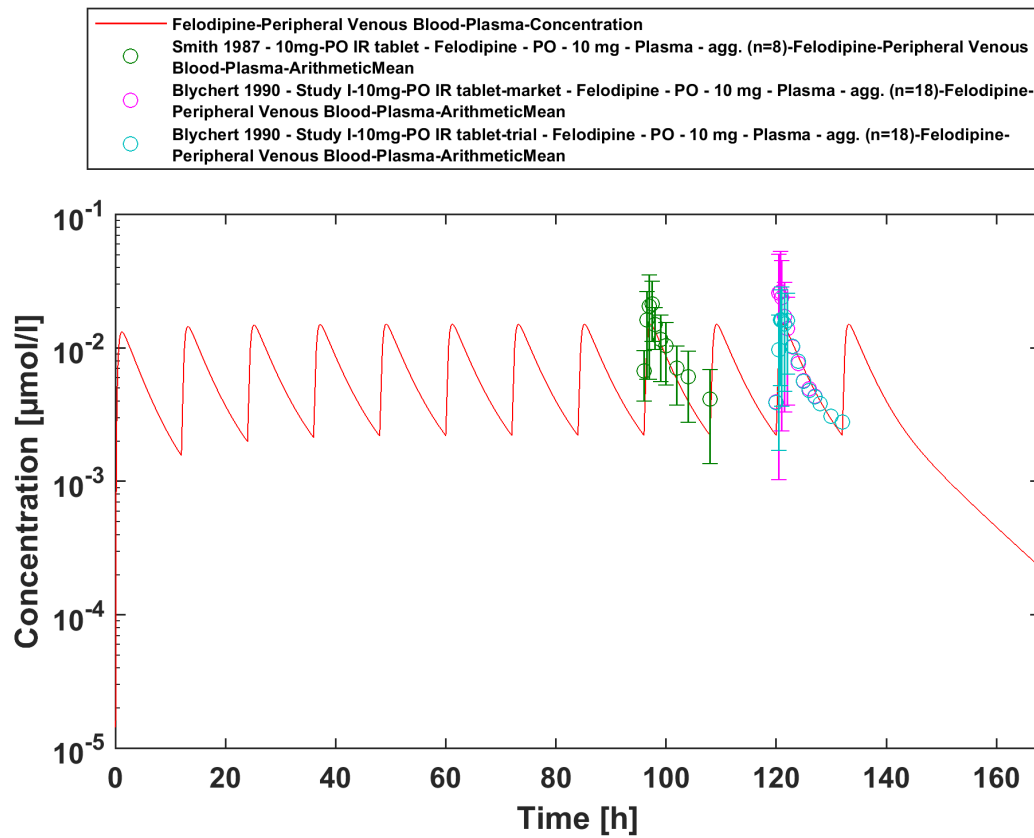
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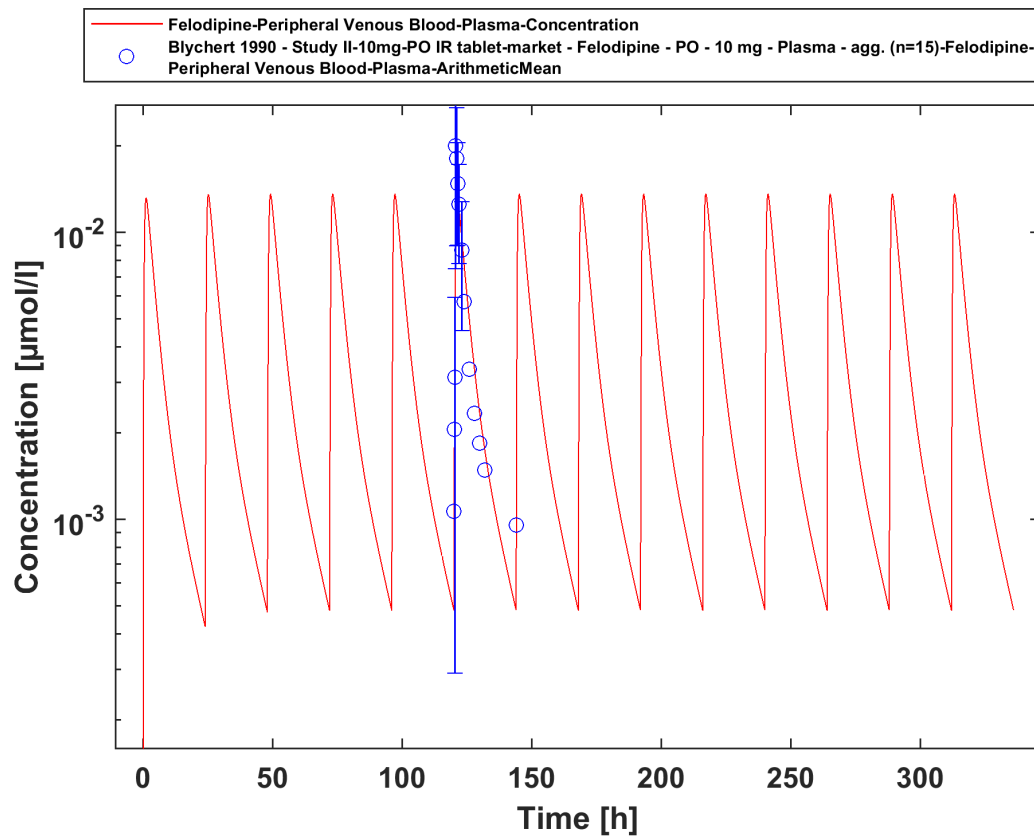
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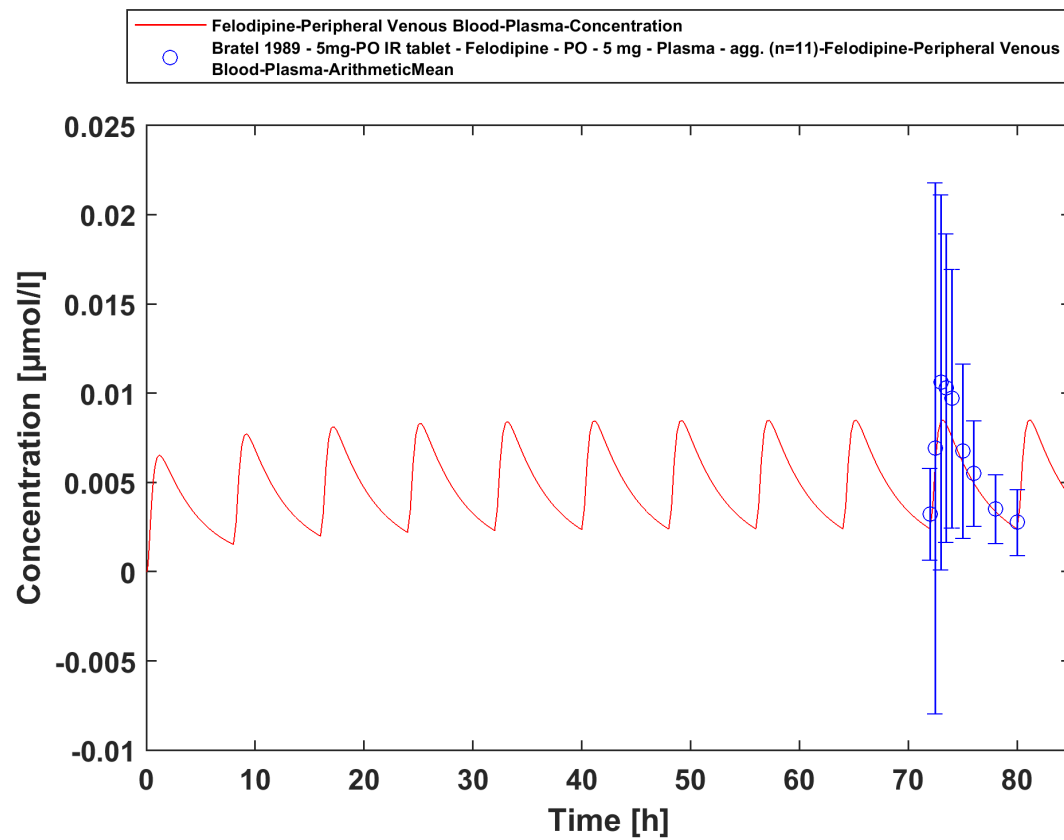
Time Profile Analysis

4 Conclusion

The herein presented PBPK model adequately describes the pharmacokinetics of felodipine in adults.

In particular, it applies quantitative metabolism by CYP3A4, and a second unknown hepatic enzyme. Thus, the model is fit for purpose to be applied for the investigation of drug-drug interactions with regard to its CYP3A4 metabolism.

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