

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

| | |
|---|---|
| Version | 2.0-OSP12.1 |
| based on <i>Model Snapshot</i> and <i>Evaluation Plan</i> | https://github.com/Open-Systems-Pharmacology/Felodipine-Model/releases/tag/v2.0 |
| OSP Version | 12.1 |
| 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 $P_{(intracellular \rightarrow interstitial)}$ and $P_{(interstitial \rightarrow intracellular)}$) 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 |

| Parameter | Unit | Value | Source | Description |
|--------------------------|------------------------|---------------|-----------------------------|--|
| 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 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 tablets 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 implemented 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: $P_{(interstitial \rightarrow intracellular)}$ and $P_{(intracellular \rightarrow interstitial)}$) 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 ($P_{(interstitial \rightarrow intracellular)}$, $P_{(intracellular \rightarrow interstitial)}$) | 0.09 | cm/min |
| k_{cat} (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_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 | |

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 | |

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.

Table 3-1: GMFE for Felodipine concentration in plasma

| Group | GMFE |
|---|-------------|
| Intravenous administration (model building) | 1.33 |
| Oral administration, ER tablet (model building) | 1.30 |
| Oral administration, ER tablet (model verification) | 1.35 |
| Oral administration, IR tablet (model building) | 1.51 |
| Oral administration, IR tablet (model verification) | 1.35 |
| Oral administration, solution (model building) | 1.17 |
| All | 1.33 |

- ▲ Intravenous administration (model building)
- Oral administration, ER tablet (model building)
- Oral administration, ER tablet (model verification)
- ◆ Oral administration, IR tablet (model building)
- ◆ Oral administration, IR tablet (model verification)
- Oral administration, solution (model building)

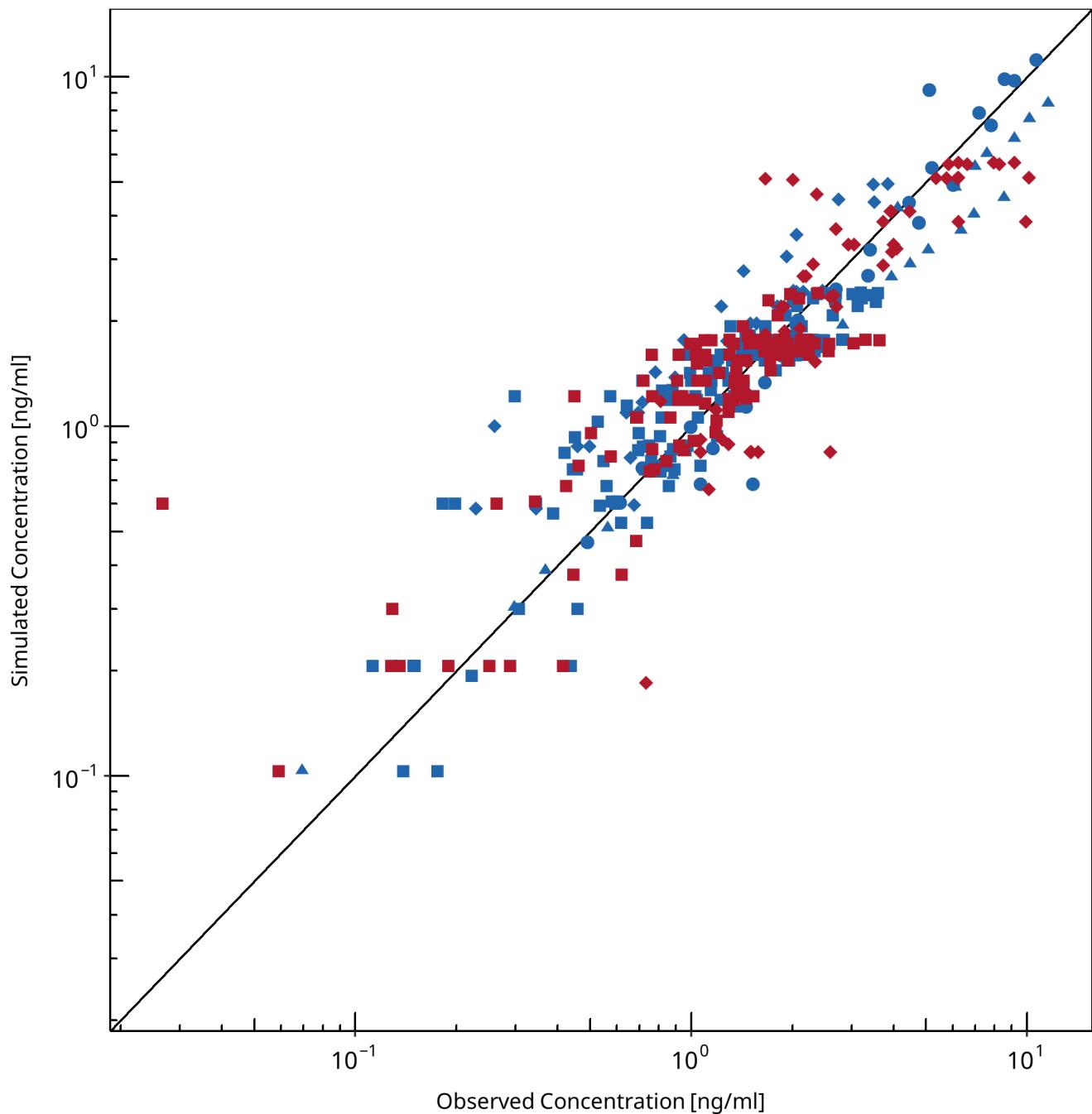


Figure 3-1: Felodipine concentration in plasma

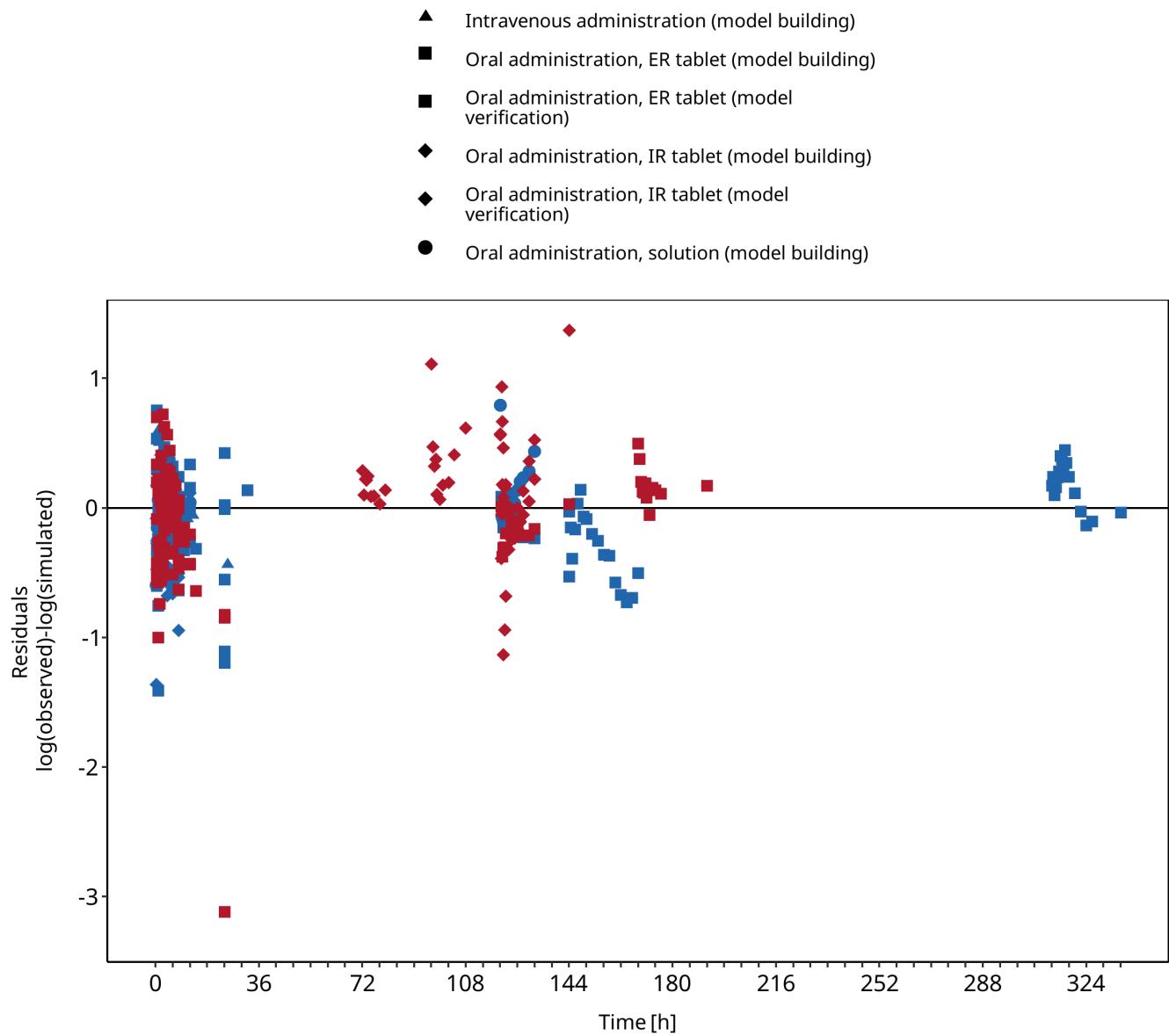


Figure 3-2: Felodipine concentration in plasma

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

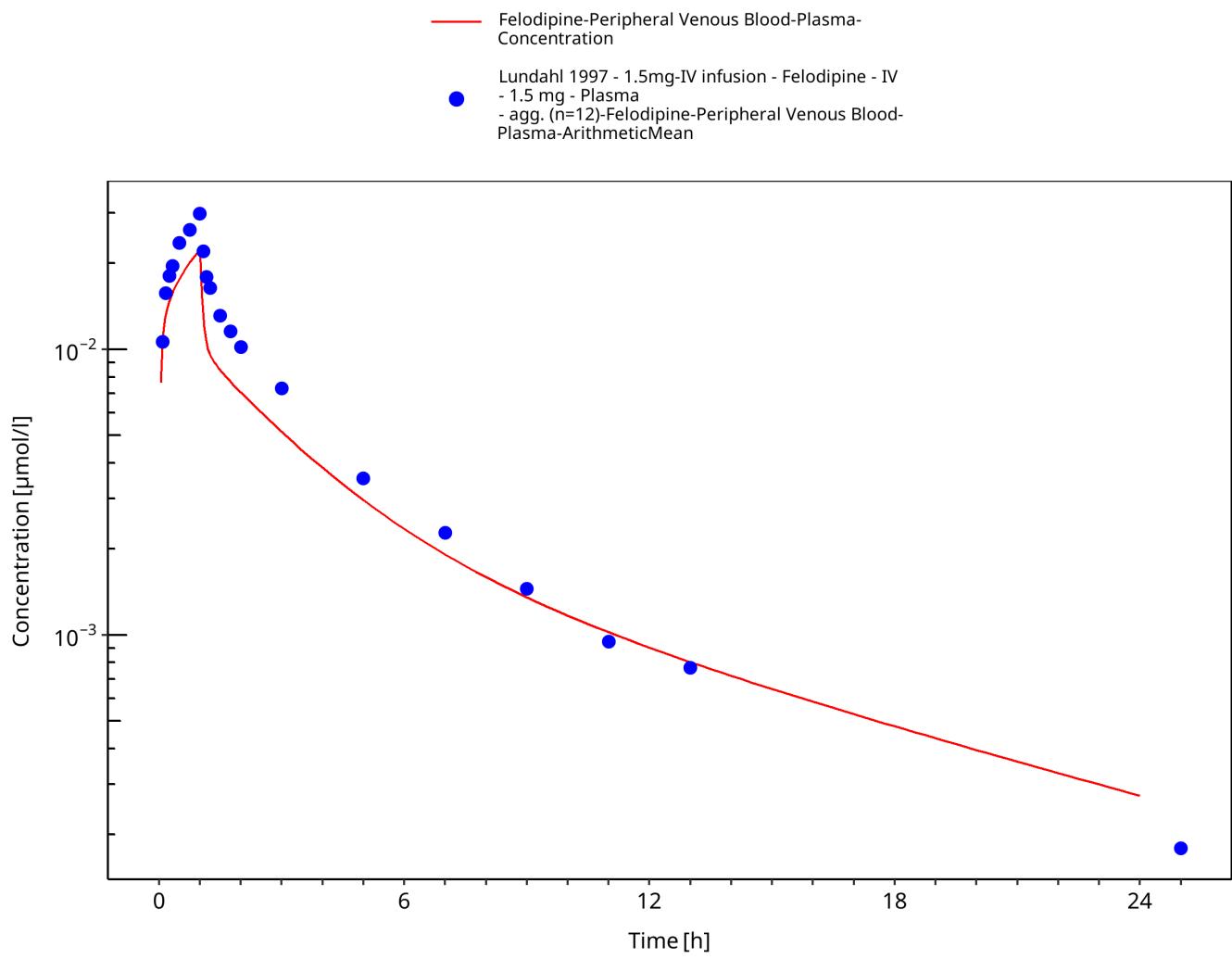


Figure 3-3: Time Profile Analysis

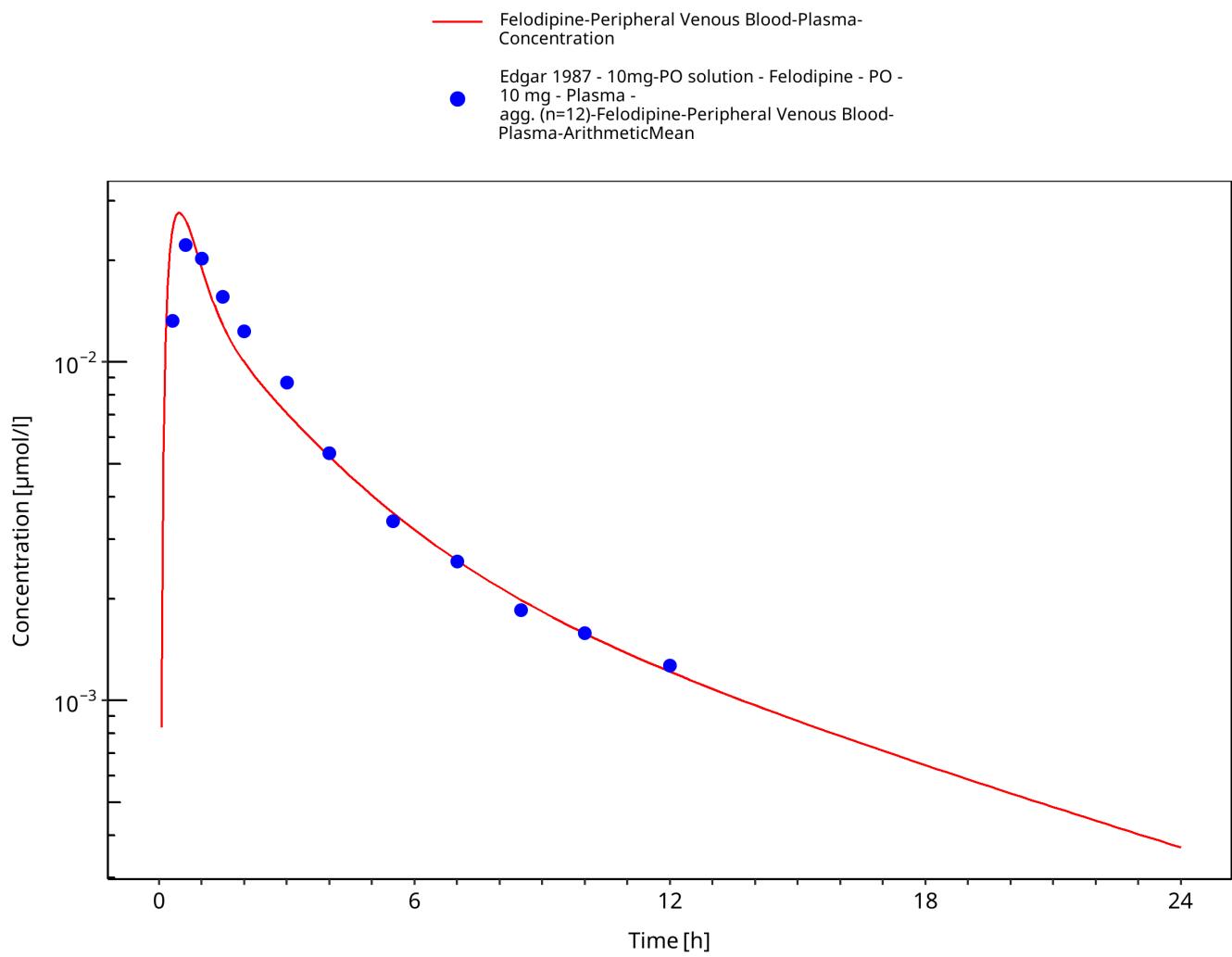


Figure 3-4: Time Profile Analysis

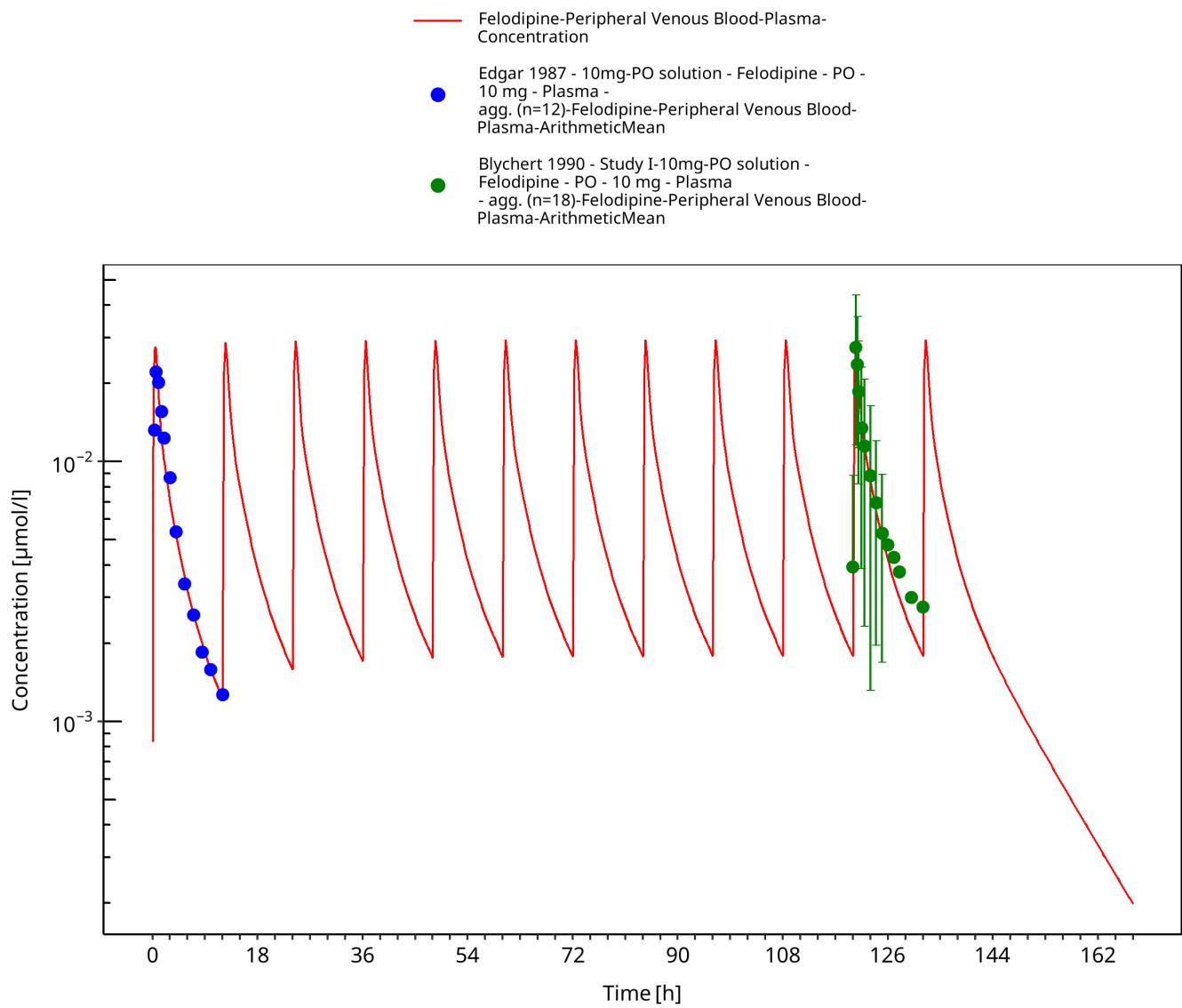


Figure 3-5: Time Profile Analysis

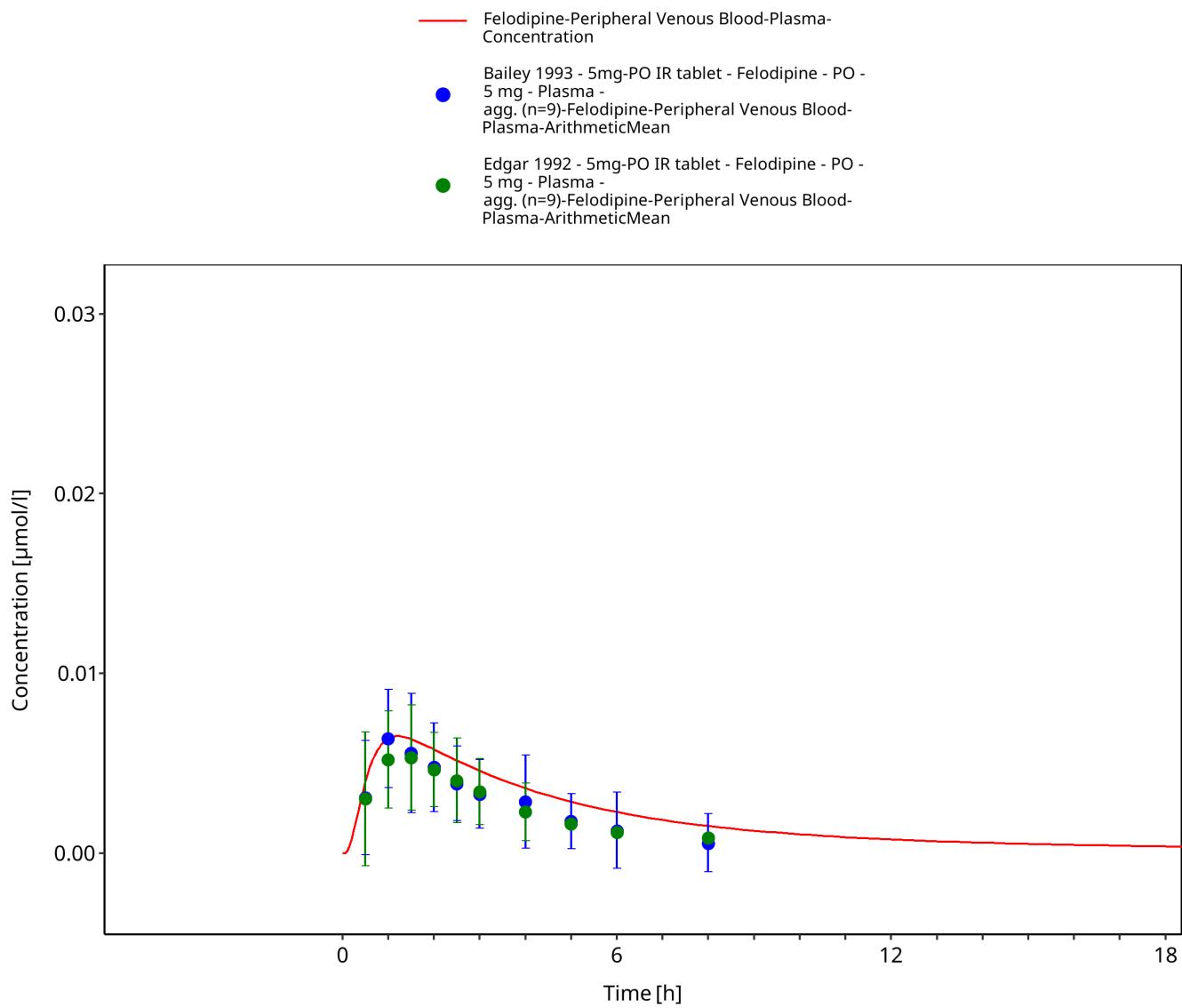


Figure 3-6: Time Profile Analysis

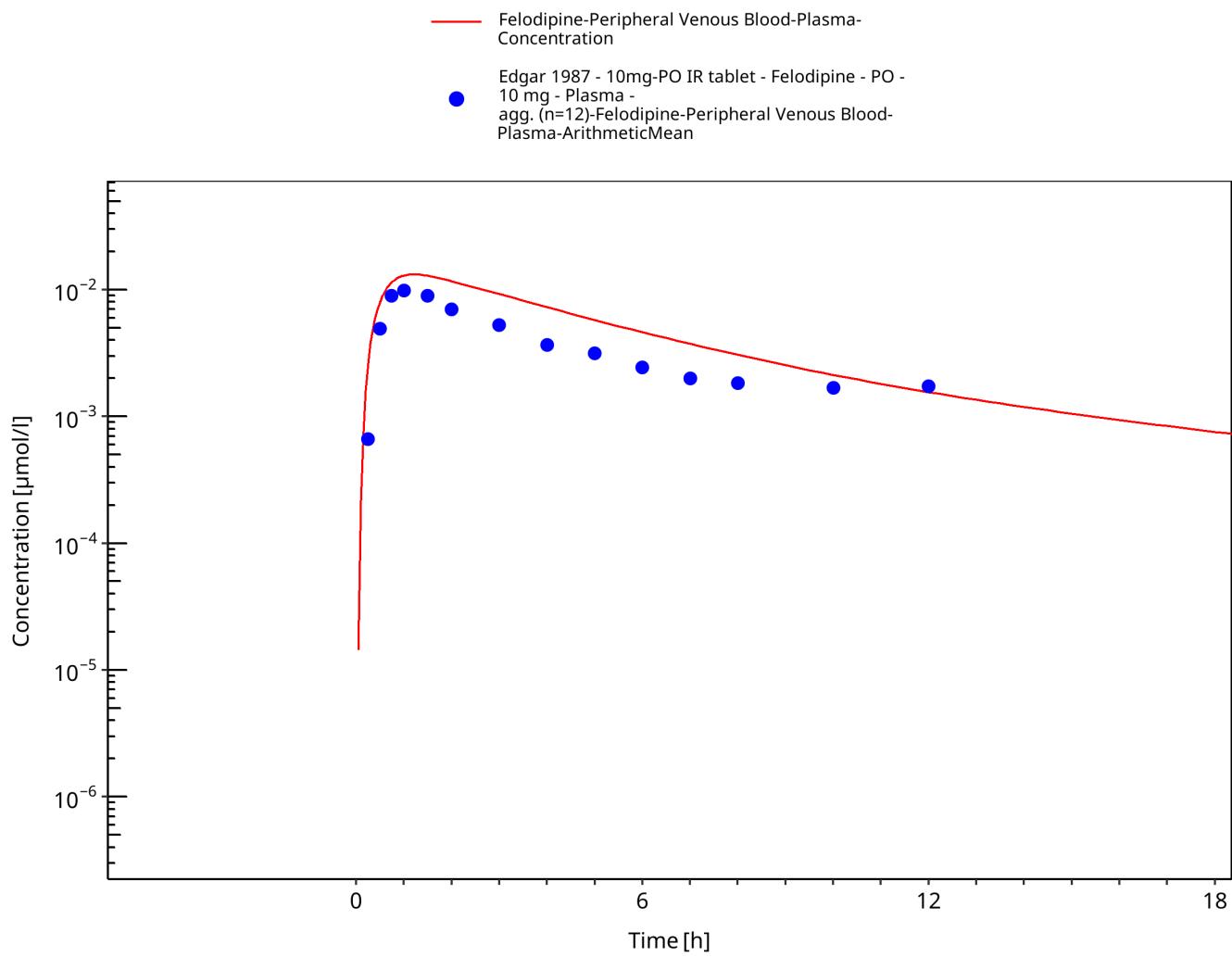


Figure 3-7: Time Profile Analysis

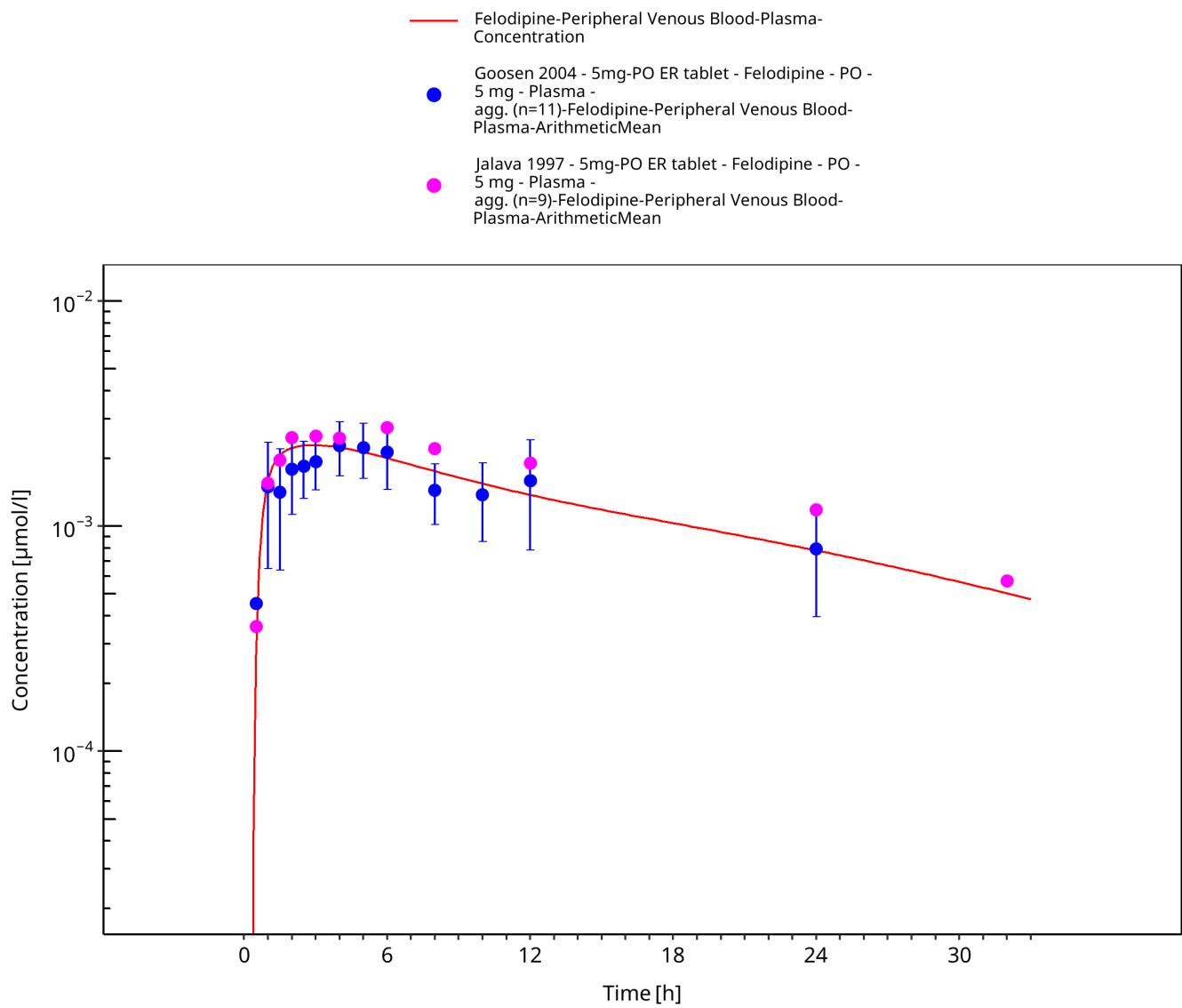


Figure 3-8: Time Profile Analysis

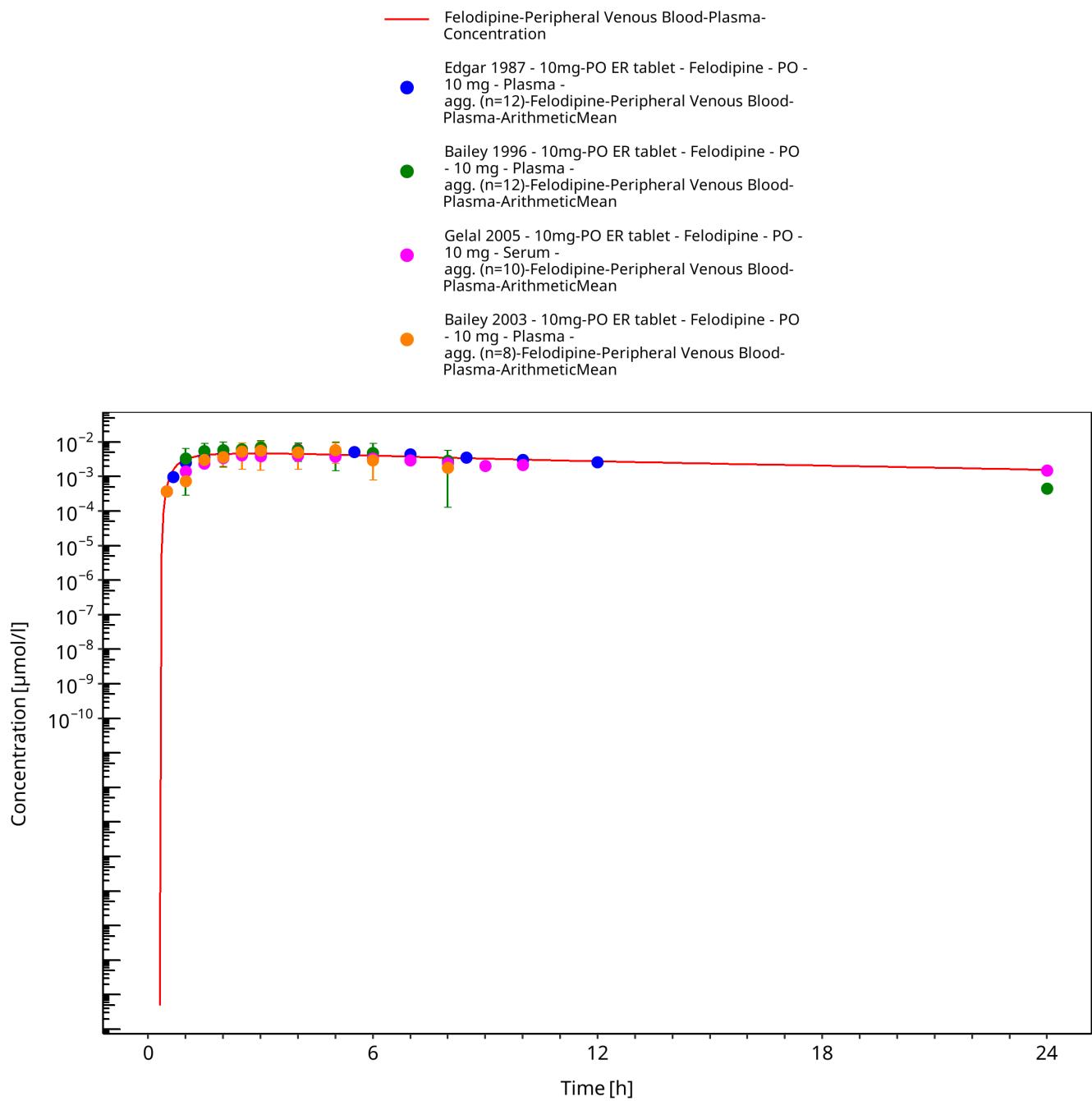


Figure 3-9: Time Profile Analysis

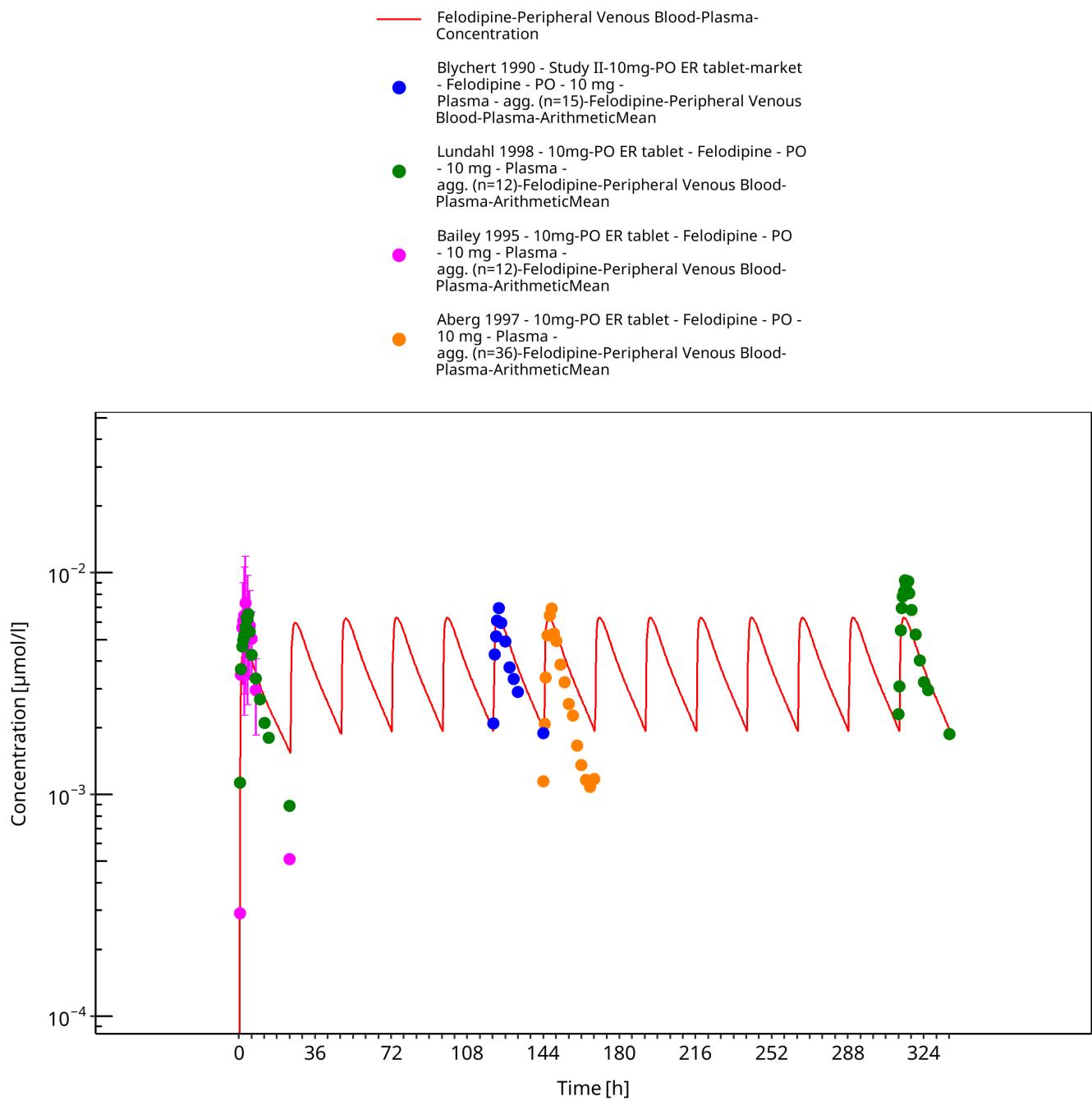


Figure 3-10: Time Profile Analysis

3.3.2 Model Verification

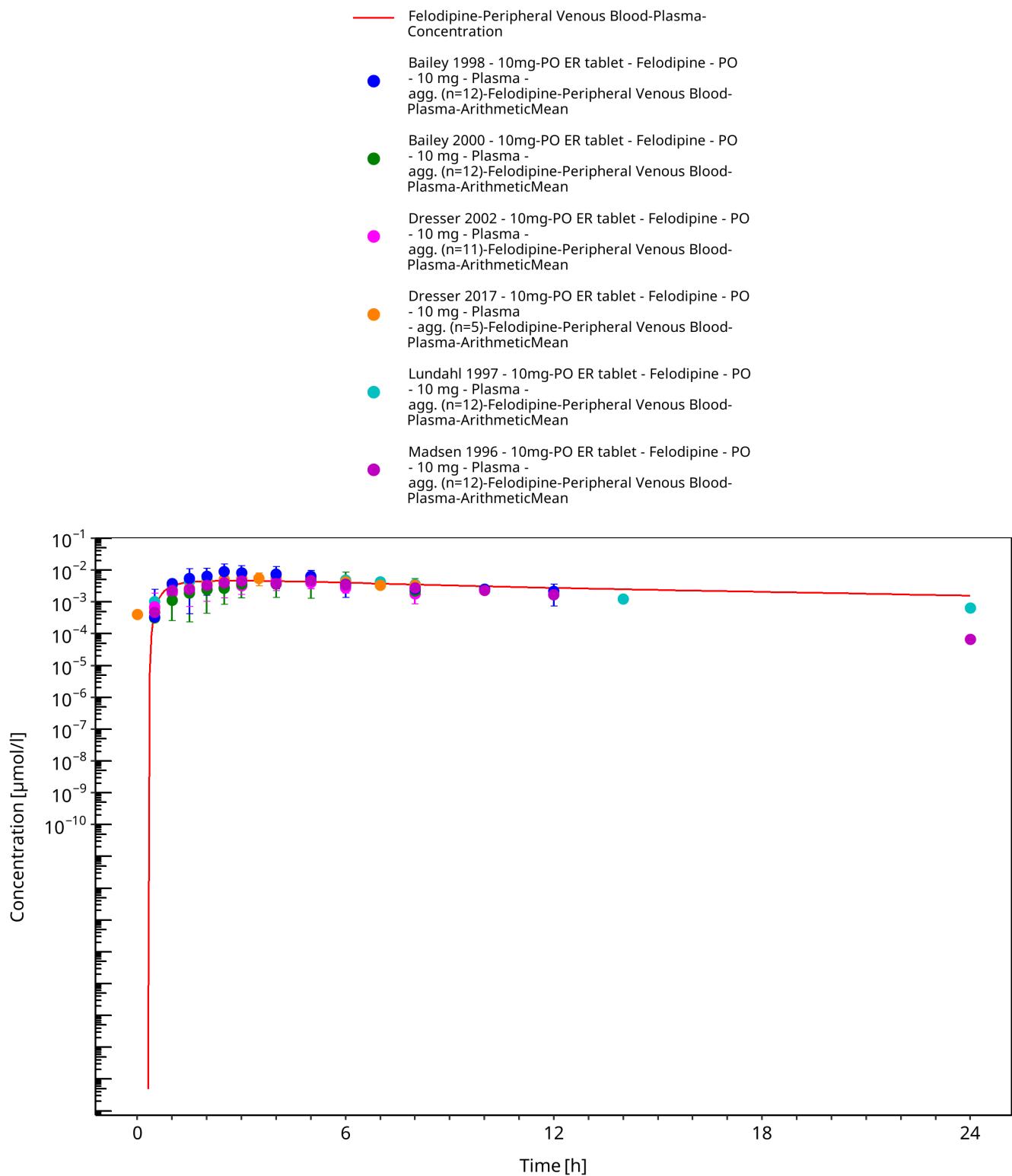


Figure 3-11: Time Profile Analysis

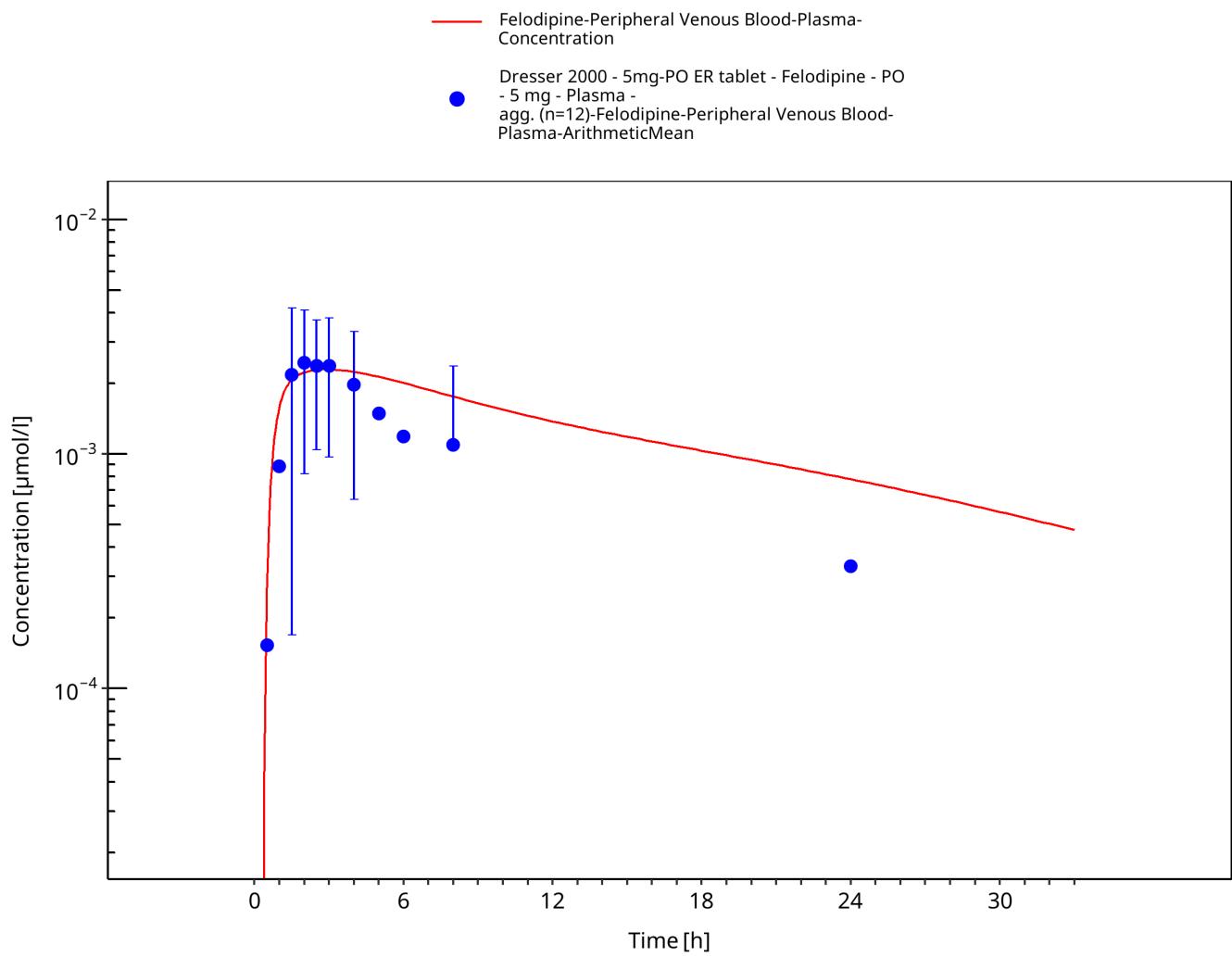


Figure 3-12: Time Profile Analysis

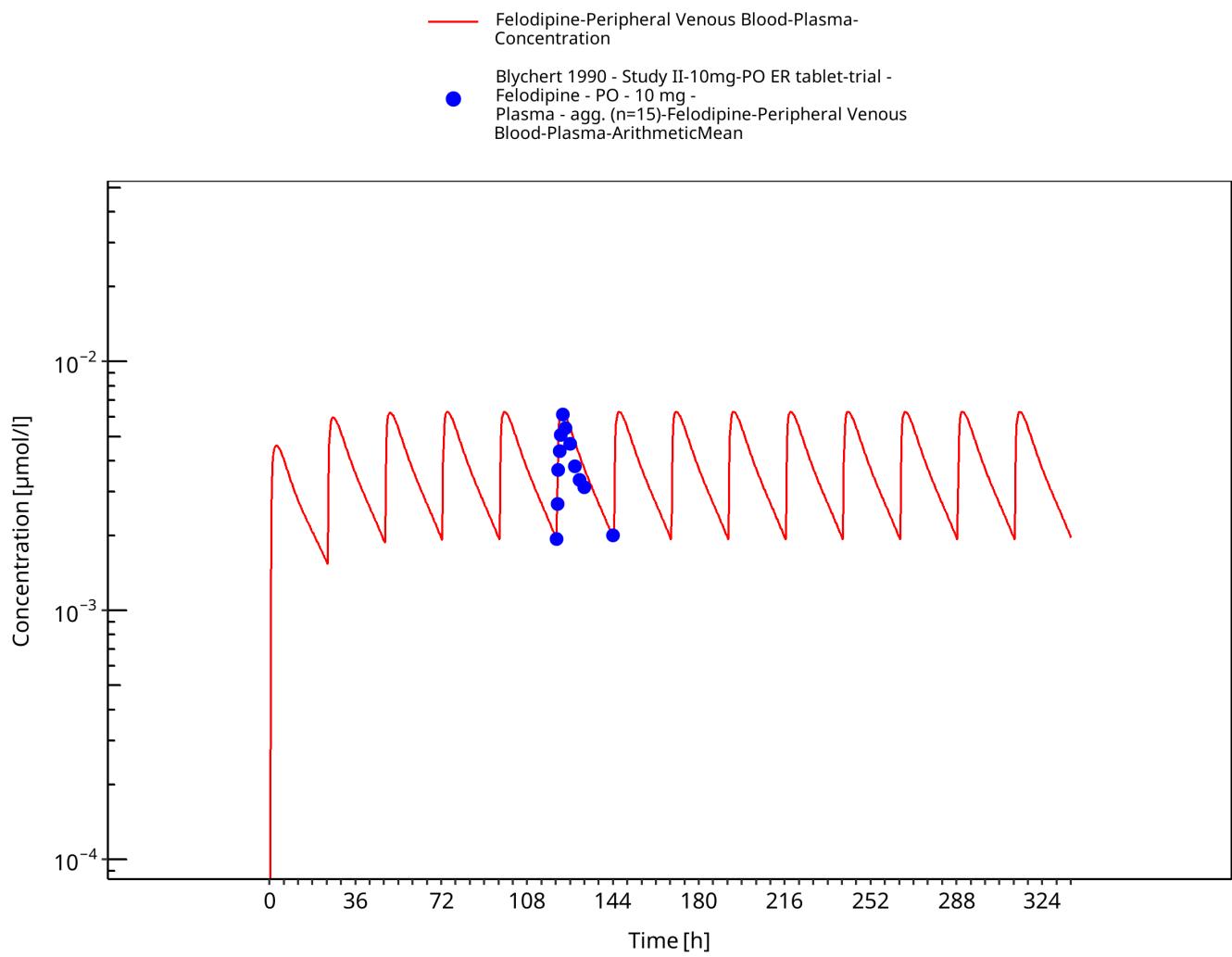


Figure 3-13: Time Profile Analysis

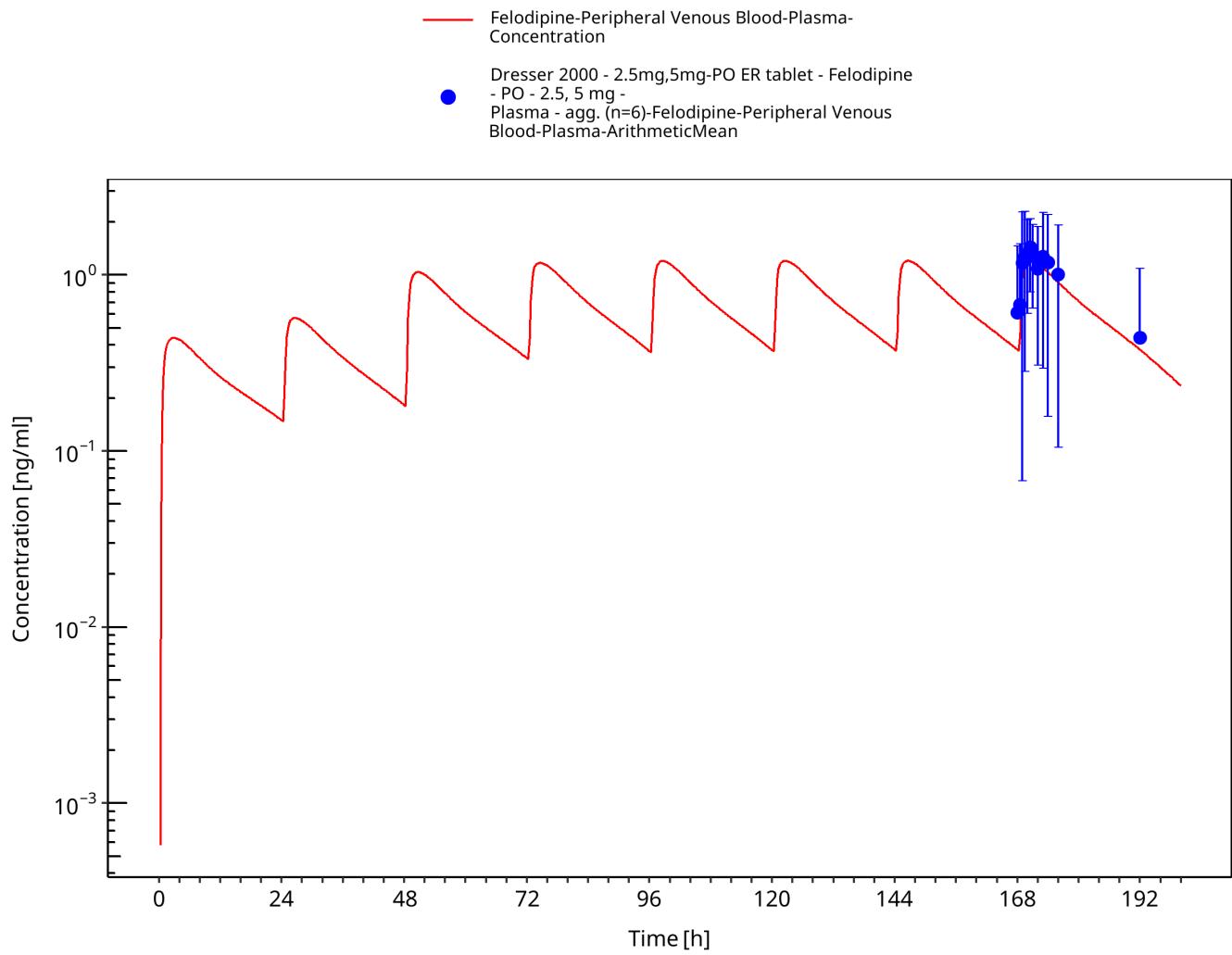


Figure 3-14: Time Profile Analysis

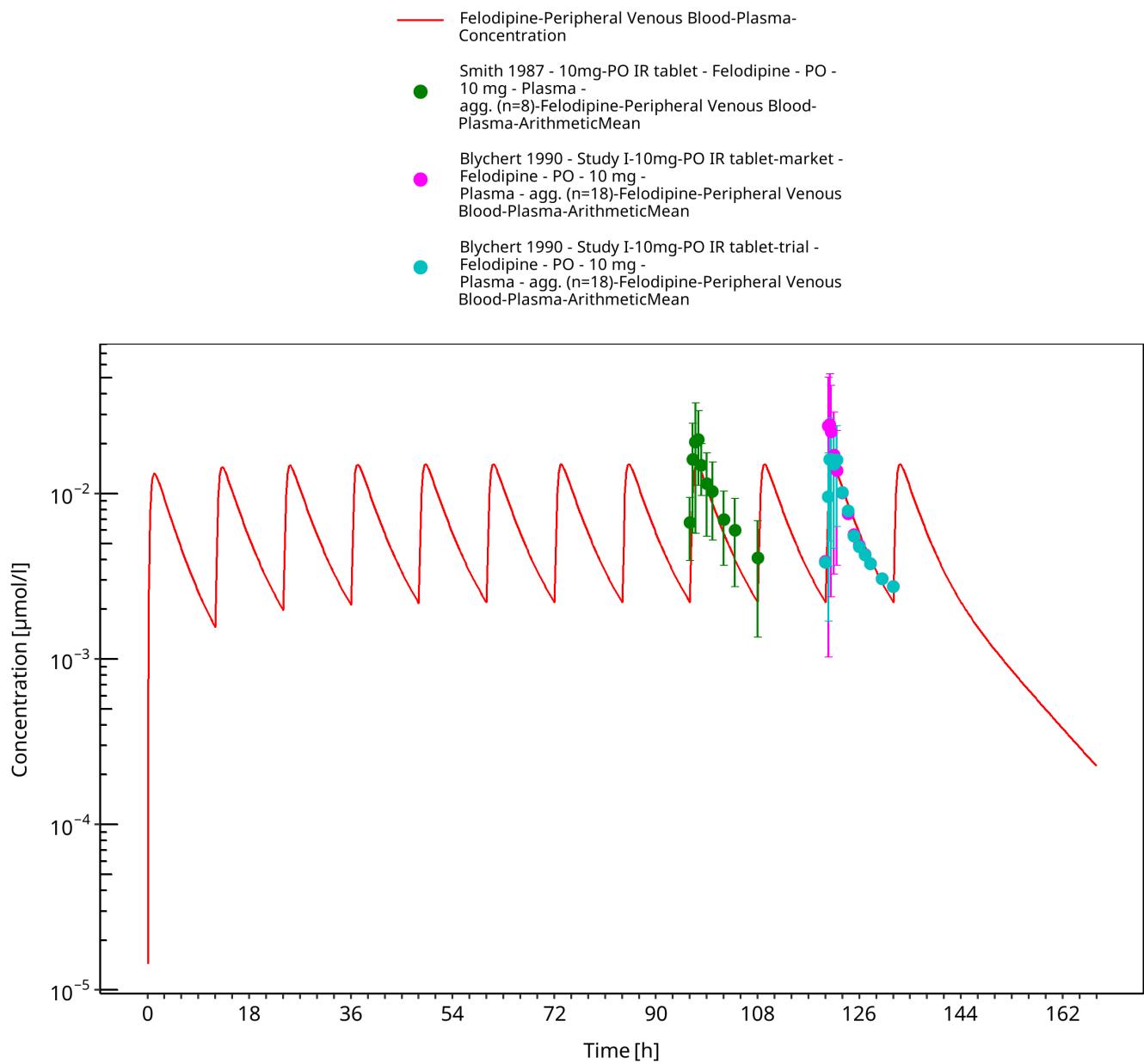


Figure 3-15: Time Profile Analysis

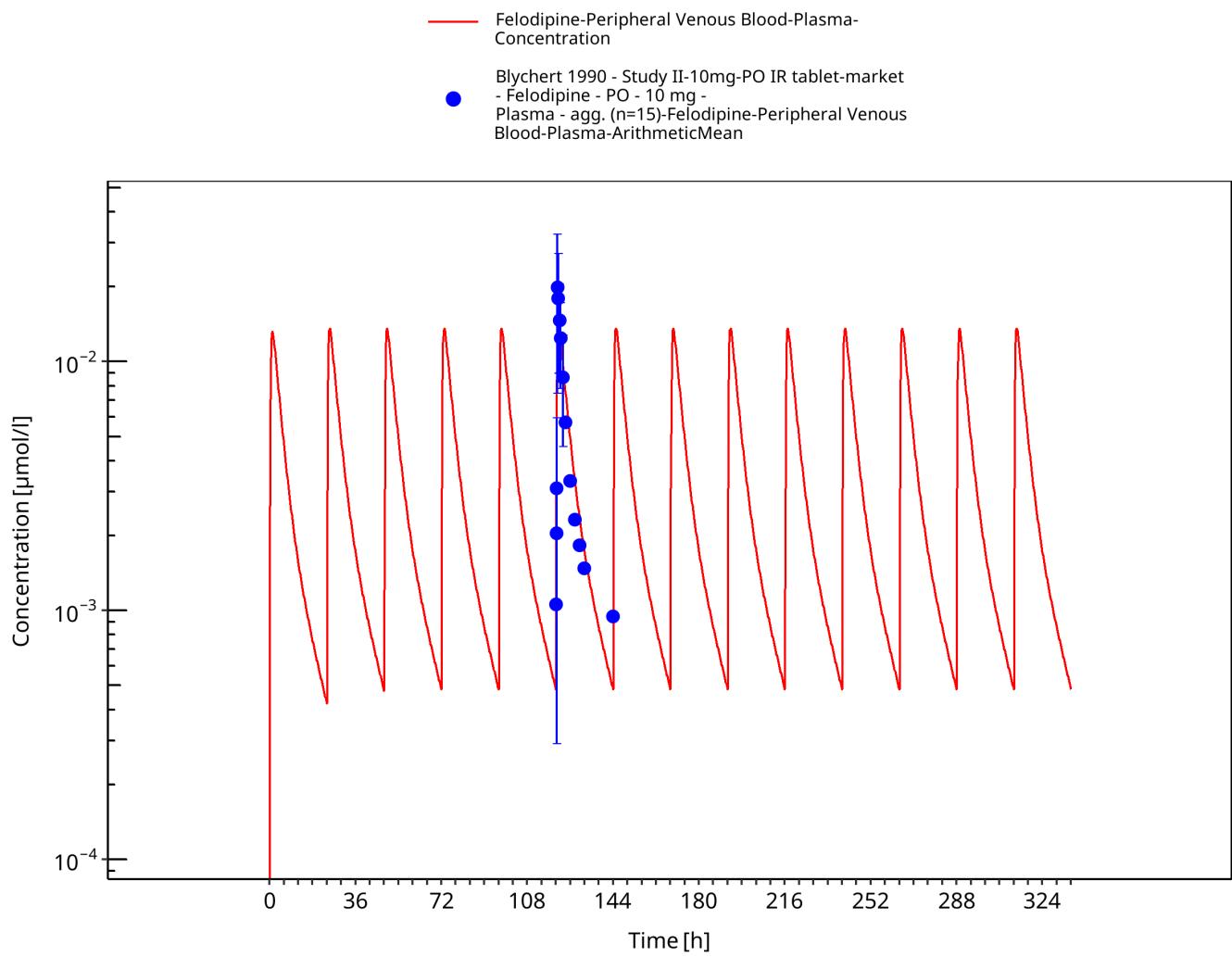


Figure 3-16: Time Profile Analysis

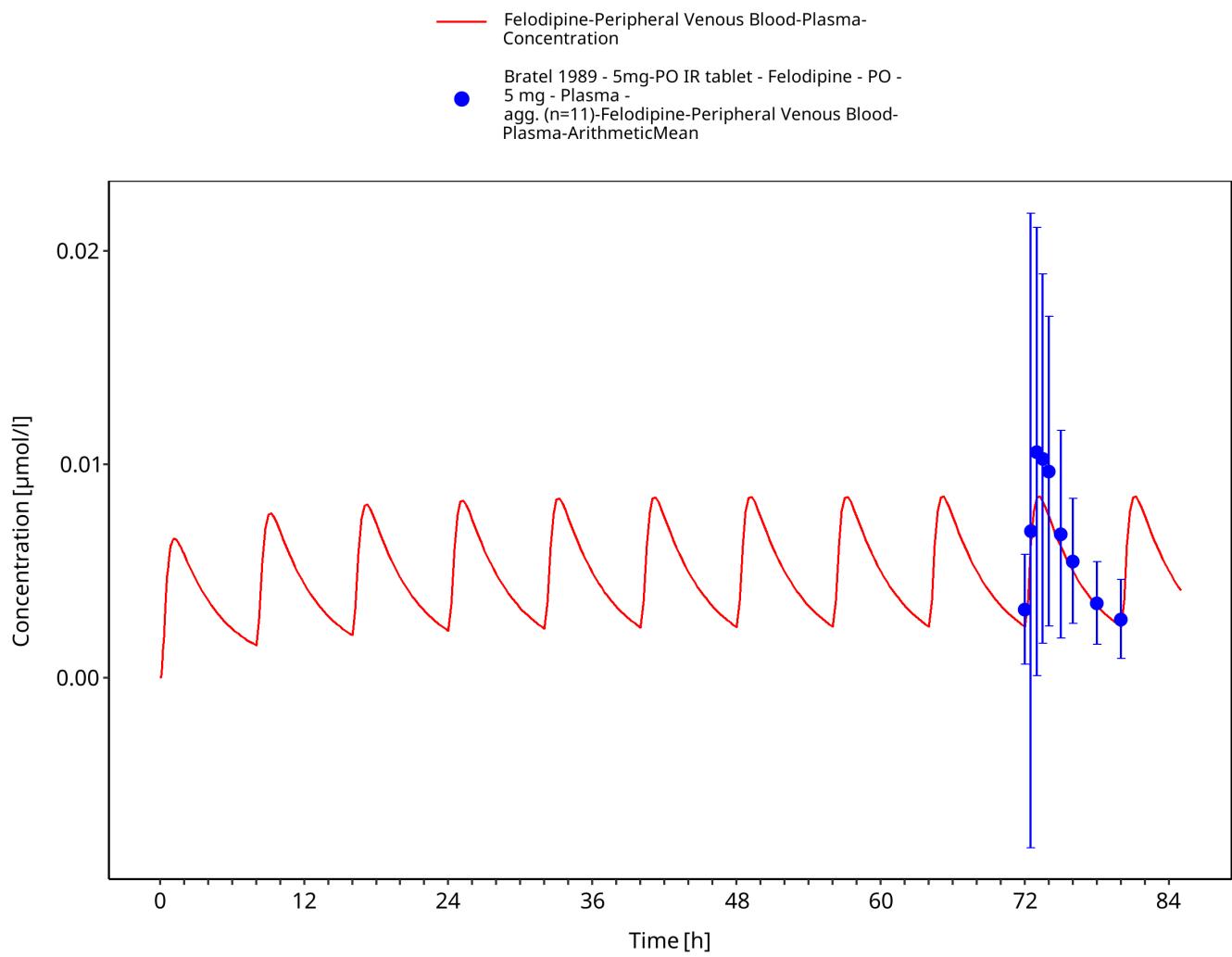


Figure 3-17: Time Profile Analysis

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.

5 References

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