

Building and evaluation of a PBPK model for raltegravir in adults

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1 Introduction

The presented model building and evaluation report evaluates the performance of PBPK model for raltegravir in adults.

Raltegravir, sold under the brand name Isentress, is an antiretroviral medication used to treat HIV/AIDS by blocking the establishment of post-integration HIV latency. It is also used as part of post exposure prophylaxis to prevent HIV infection following potential exposure. Raltegravir is only taken orally and is mainly metabolized by UGT1A1 (~70%) ([Kassahun 2007](#)). The final raltegravir model features metabolism by UGT1A1 and to a minor extent by UGT1A9. Additionally, there is excretion via glomerular filtration. The model adequately describes the pharmacokinetics of raltegravir in adults.

The raltegravir model is a whole-body PBPK model, allowing for dynamic translation between individuals with organs expressing UGT1A1. The raltegravir report demonstrates the level of confidence of the raltegravir PBPK model build with the OSP suite with regard to reliable predictions of Raltegravir PBPK adults during model-informed drug development. The presented raltegravir PBPK model as well as the respective evaluation plan and PBPK report are provided open-source and transparently documented (<https://github.com/Incei/Raltegravir-Model>).

2 Methods

2.1 Modeling strategy

The general concept of building a PBPK model has previously been described by Kuepfer et al. ([Kuepfer 2016](#)) Regarding the relevant 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 ([PK-Sim Ontogeny Database Version 7.3](#)). 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' ([Schlender 2016](#)) or otherwise referenced for the specific process.

First, a base mean model was built using data from the single dose escalation study to find an appropriate structure describing the PK of Raltegravir plasma. The mean PK model was developed using a typical European individual. Unknown parameters were identified 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, additional parameters for different formulations were identified.

A final PBPK model was established and simulations were compared to the reported data to evaluate model appropriateness and to assess model qualification, by means of diagnostics plots and predicted versus observed concentration-time profiles, of which the results support an adequate prediction of the PK in adults.

During model building, uncertainties in data-quality, as well as study differences may cause not being able to adequately describe the PK of all reported clinical study data.

2.2 Data used

2.2.1 In vitro / physico-chemical data

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

Parameter	Unit	Raltegravir literature	Description
MW	g/mol	586.2 (drugbank.ca)	Molecular weight
pKa		7.67 (Moss 2012)	Acid dissociation constant
Solubility (pH)	mg/L	Reference pH-dependent table (Moss 2013)	Solubility
logP		0.58 (Moss 2012)	Partition coefficient between octanol and water
fu		0.17 (Laufer 2009)	Fraction unbound
K _m UGT1A1	μM	99 (Kassahun 2007)	Michaelis-Menten constant
V _{max} UGT1A1	nmol/min/mg	0.89 (Kassahun 2007)	Maximum rate of reaction
K _m UGT1A9	μM	296 (Kassahun 2007)	Michaelis-Menten constant
V _{max} UGT1A9	nmol/min/mg	0.53 (Kassahun 2007)	Maximum rate of reaction

2.2.2 Clinical data

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

The following publications were found in adults for model building and evaluation:

Publication	Study description
Iwamoto 2008	Single- and multiple-dose escalation study in healthy subjects
Iwamoto 2009	Effects of ritonavir and efavirenz on safety, tolerability and pharmacokinetics of raltegravir
Markowitz 2006	Monotherapy, followed by a longer term combination therapy of raltegravir versus efavirenz
Kassahun 2007	Pharmacokinetics study in healthy adults
Rhee 2014	Pediatric formulation study in healthy adults
Wenning 2009	Effect of rifampin on the pharmacokinetics of raltegravir

2.3 Model parameters and assumptions

2.3.1 Absorption

As no intravenous data is currently available to study systemic clearance of raltegravir in vivo, only oral data was used for model building. For oral administration the following parameters play a role with regards to the absorption kinetics of a compound, which can be estimated with PBPK: solubility, lipophilicity and intestinal permeability. Moss et al. ([Moss 2013](#)) published values for raltegravir solubility in population groups with very low pH, low pH, medium pH, high pH and very high pH, after a single 400 mg dose of raltegravir. For the raltegravir PBPK model we have applied the medium pH group for creating a pH dependent solubility profile throughout the intestinal tract. The lipophilicity as well as pKa of raltegravir was also published by Moss et al ([Moss 2012](#), [Moss 2013](#)) to be 0.58 (as log partition coefficient between octanol and water (pH 7) and 6.67 (acid), respectively. These values were applied and fixed into the raltegravir PBPK model, without further optimization. Regarding intestinal transcellular permeability (Pint), Moss et al (Moss 2012) reported a range of apical to basolateral apparent permeability in Caco-2 monolayer at different pH values. Using published functions Pint can be calculated from Caco-2 cell membrane permeability measurements (Parrot et al. ([Parrot 2002](#)), Thelen et al. ([Thelen 2010](#), Sun et al. ([Sun 2002](#)) and Sjögren et al. ([Sjögren 2013](#)). However as no reference/calibrator compound was available to correct for inter-study variability, these functions could not be applied, and it was decided to estimate the Pint from in vivo clinical data instead. Nevertheless, for plausibility check, a theoretical Pint was calculated using the aforementioned functions without correction, resulting in a range of Pint from 2.14E-04 to 1.47E-09 cm/min. The finally estimated (based on in vivo data) Pint falls within this range.

Table 2. Reported Caco-permeability and calculated theoretical effective permeability (intestinal transcellular permeability) values for raltegravir via different reported functions, lacking a reference compound for correcting inter-study variability.

Reference publication of reported function	Ph apical-basolateral	Pe _{eff} (cm/min)	Reference compound available for correcting Inter study variability
Raltegravir Caco permeability (Moss 2012)	7.4	6.60E-6	-
Raltegravir Caco permeability (Moss 2012)	6.5	9.20E-6	-
Parrot 2002	7.4	2.14E-04	Not available
Thelen 2010	7.4	1.47E-09	Not available
Sjögren 2013	7.4	1.03606E-6	Not available
Sun 2002	7.4	2.77E-4	Not available
Sun 2002	6.5	2.86E-4	Not available
Simcyp (*)	6.5	4.62E-4	Not available

2.3.2 Distribution

Laufer et al. ([Laufer 2009](#)) published a fu in humans to be 0.17. Barau et al 2013 reported that raltegravir binds to serum albumin, and not alpha glycoprotein, and are built-in as such into the PBPK model.

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 cell permeability calculation by PK-Sim standard. Specific organ permeability normalized to surface area was automatically calculated by PK-Sim.

2.3.3 Metabolism and Elimination

Kassahun et al. ([Kassahun 2007](#)) studied the absorption, metabolism, and excretion of raltegravir in healthy volunteers after a single oral dose of 200 mg (200Ci) of [¹⁴C] raltegravir. Human liver microsomal incubations confirmed the dominant role of UGT metabolism for raltegravir. Additionally, data from incubations using cDNA-expressed UGTs indicate that the major mechanism of clearance of raltegravir in humans is UGT1A1-mediated glucuronidation. Raltegravir was in particular converted to M2 by UGT1A1 and 1A9. The apparent Km values for the glucuronidation of raltegravir by UGT1A1 and UGT1A9 were 99 (standard deviation (SD): 16) and 296 (SD: 55) µM, respectively. The corresponding Vmax values (nmol/min/mg) were 0.89 (SD: 0.05) for UGT1A1, and 0.53 (SD: 0.06) for UGT1A9.

Based on this information, the reported in vitro Km values for UGT1A1 and 1A9 in the model. Reported Vmax values were of the dimension nmol/min/mg protein and thus not directly transferable into the PBPK model. Therefore, a unique scaling factor fUGT on the in vitro Vmax values was estimated to match observed in vivo data, and keeping the relative relationship between those in vitro values (0.89 and 0.53 nmol/min/mg) for UGT1A1 and UGT1A9 fixed according to:

$$V_{\max, \text{UGT1A1}} = f_{\text{UGT}} * V_{\max, \text{in-vitro, UGT1A1}}$$

$$V_{\max, \text{UGT1A9}} = f_{\text{UGT}} * V_{\max, \text{in-vitro, UGT1A9}}$$

It is especially important to fix the relative contribution of both enzymes as a ratio to ensure that, when scaling to other populations (e.g. children where both UGT's undergo a different ontogeny pattern, or patients who have differently reduced amounts of UGT1A1 vs 1A9) the relative contributions can be adequately scaled. Note that the estimated scaling factor fUGT will be directly implemented into the final in vivo Vmax values (only Vmax,UGT1A1 and Vmax,UGT1A9 will be reported in section [3](#))

Finally, as ~9% of the dose is excreted in human urine as unchanged parent compound, GFR is introduced in the raltegravir PBPK model.

3 Results and Discussion

The PBPK model **raltegravir** was developed with clinical pharmacokinetic data covering 4 different oral formulation and a dose range of 10-1600mg, including single dose (SD) as well as multiple dose (MD) clinical data.

As there were 4 different oral formulations available for model evaluation, all formulations require an estimation of the dissolution kinetics via a Weibull function. This function requires the estimation of 2 parameters, the dissolution time (time where 50% of the drug is dissolved), and dissolution shape (shape parameter of the Weibull function). Therefore, to minimize the amount of parameters for fitting, as a first step, the PK study data (lactose formulation) by Iwamoto et al. ([Iwamoto 2007](#)) was fitted which includes SD escalation and has a broad dose-range (10mg-1600mg) to capture (non-) linearity. During the model-fitting, the following parameters were estimated (all other parameters were fixed to reported values):

- Vmax (as unique scaling factor f_{UGT}, as described in section [2.3.3](#))
- Weibull function parameters: Dissolution time and dissolution shape
- Specific intestinal permeability (transcellular)

The fit resulted in an adequate description of all data. As there is no iv data available, it was not possible to clearly distinguish between clearance and absorption, resulting in a considerable correlation between Vmax and dissolution shape (Weibull). An attempt to fix Vmax to reported in vitro values, and only estimating absorption (lipophilicity and intestinal transcellular permeability) resulted in an underprediction of the clearance, and clearly indicated a need for increase in clearance. As described above, no reported intestinal permeability was found other than caco-permeability. Caco-permeability could not be translated to effective intestinal permeability without a reference compound. Therefore it was decided to continue with the model where both P_{int} and Vmax were estimated.

As a second step, clinical study data for all other formulations summarised in section [2.2.2](#) were included for model fitting, including film-coated tablets (100-400mg MD, 200-400mg SD), chewable tablets (400mg fasted + fed) and oral granules in suspension (400mg). In this step, only the Weibull functions were estimated with all other parameters fixed based on the first step. Finally, as the Weibull functions were highly correlated (as expected), only dissolution shape was estimated as a last step. The model results show that the PBPK model of raltegravir adequately described the data for all formulations and doses available.

3.1 Raltegravir final input parameters

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

Formulation: chewable tablet

Type: Weibull

Parameters

Name	Value	Value Origin	
Dissolution time (50% dissolved)	1.0000049774E-05 min	Parameter Identification	
Lag time	0 min		
Dissolution shape	0.050078869	Parameter Identification	
Use as suspension	Yes		

Formulation: filmcoated tablet (original Merck formulation)

Type: Weibull

Parameters

Name	Value	Value Origin	
Dissolution time (50% dissolved)	500 min	Parameter Identification	
Lag time	0 min		
Dissolution shape	0.03536656	Parameter Identification	
Use as suspension	Yes		

Compound: Raltegravir

Parameters

Name	Value	Value Origin	Alternative	Default	
Solubility table	40 mg/l	Publication-In Vitro-Moss 2013 Table 2	Moss 2013	True	
Lipophilicity	0.58 Log Units	Parameter Identification	Moss 2012	True	
Fraction unbound (plasma, reference value)	0.17	Publication-In Vitro-Laufer 2009	Measurement	True	
Specific intestinal permeability (transcellular)	2.8481843854E-07 cm/s	Parameter Identification	Fit	True	
F	1	Publication-Other-Drugbank.ca			
Is small molecule	Yes				
Molecular weight	444.4163 g/mol	Publication-Other-Drugbank.ca			
Plasma protein binding partner	Albumin				

Calculation methods

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

Processes

Systemic Process: Glomerular Filtration-Kassahun 2007

Species: Human

Parameters

Name	Value	Value Origin	
GFR fraction	1	Publication-In Vitro-Kassahun 2007	

Metabolizing Enzyme: UGT1A1-Kassahun 2007

Molecule: UGT1A1

Parameters

Name	Value	Value Origin	
In vitro Vmax for liver microsomes	2.7351231632 nmol/min/mg mic. protein	Parameter Identification	
Km	99 μ M	Publication-In Vitro-Kassahun 2007	

Metabolizing Enzyme: UGT1A9-Kassahun 2007

Molecule: UGT1A9

Parameters

Name	Value	Value Origin	
In vitro Vmax for liver microsomes	1.6287812095 nmol/min/mg mic. protein	Parameter Identification	
Km	296 μ M	Publication-In Vitro-Kassahun 2007	

Formulation: Weibull (granules)

Type: Weibull

Parameters

Name	Value	Value Origin	
Dissolution time (50% dissolved)	0.00010000047426 min	Parameter Identification	
Lag time	0 min		
Dissolution shape	0.0654456264	Parameter Identification	
Use as suspension	Yes		

Formulation: Weibull (lactose formulation)

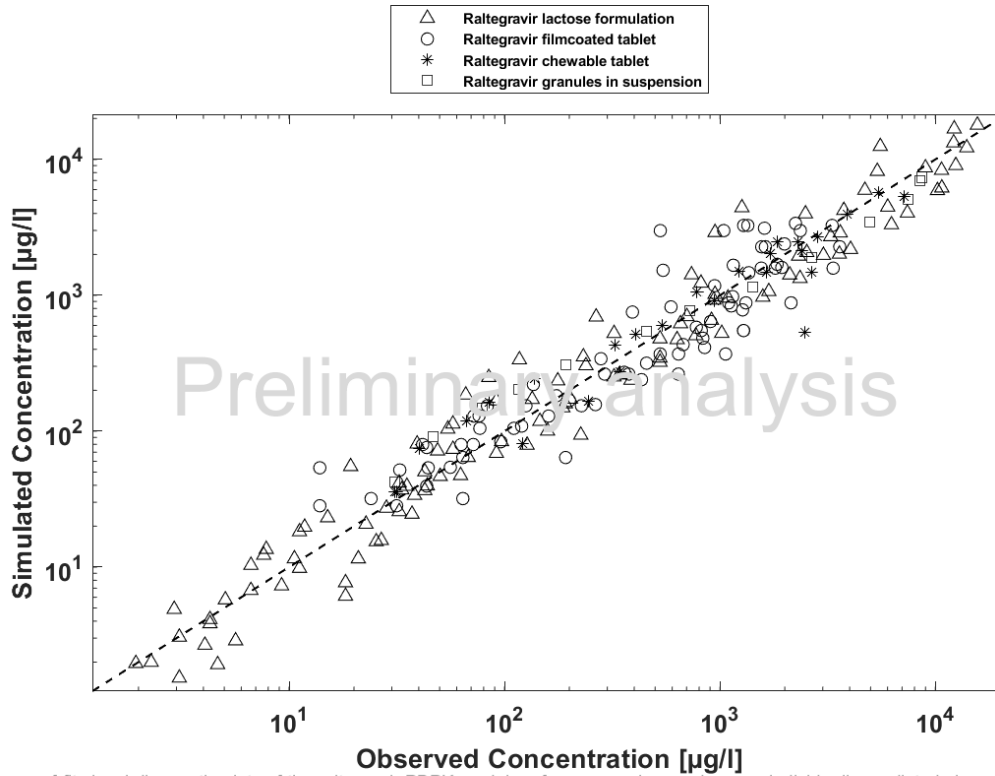
Type: Weibull

Parameters

Name	Value	Value Origin	
Dissolution time (50% dissolved)	2.30152527E-10 min	Parameter Identification	
Lag time	0 min		
Dissolution shape	0.0389537131	Parameter Identification	
Use as suspension	Yes		

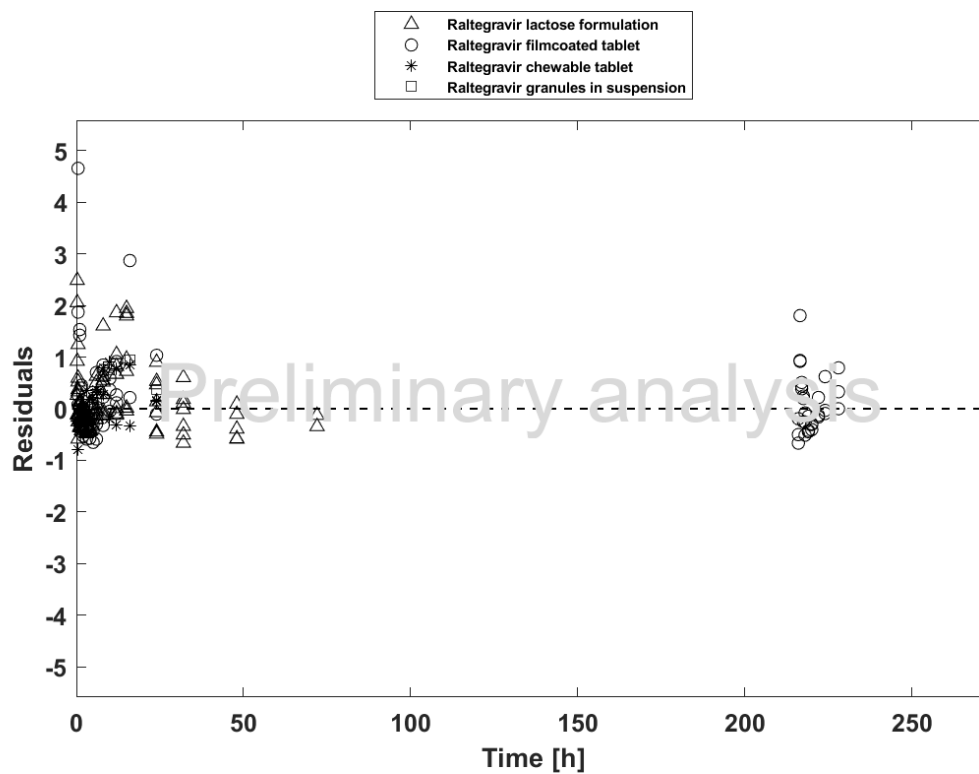
3.2 Raltegravir Diagnostics Plots

Below you find the goodness-of-fit visual diagnostic plots for raltegravir PBPK model performance (observed versus individually simulated plasma concentration and weighted residuals versus time) of all data used for model building.



Goodness-of-fit visual diagnostic plots of the raltegravir PBPK model performance: observed versus individually predicted plasma concentration versus time of all adult data.

GMFE = 1.487148

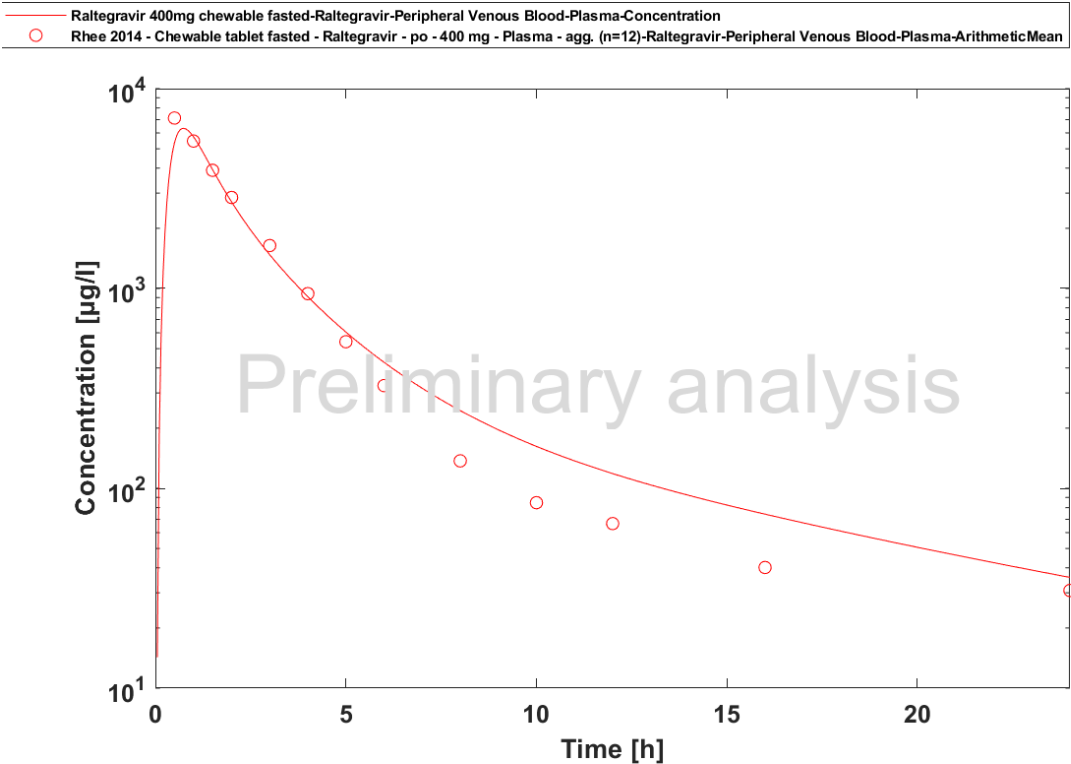


Goodness-of-fit visual diagnostic plots of the raltegravir PBPK model performance: weighted residuals versus time of all adult data.

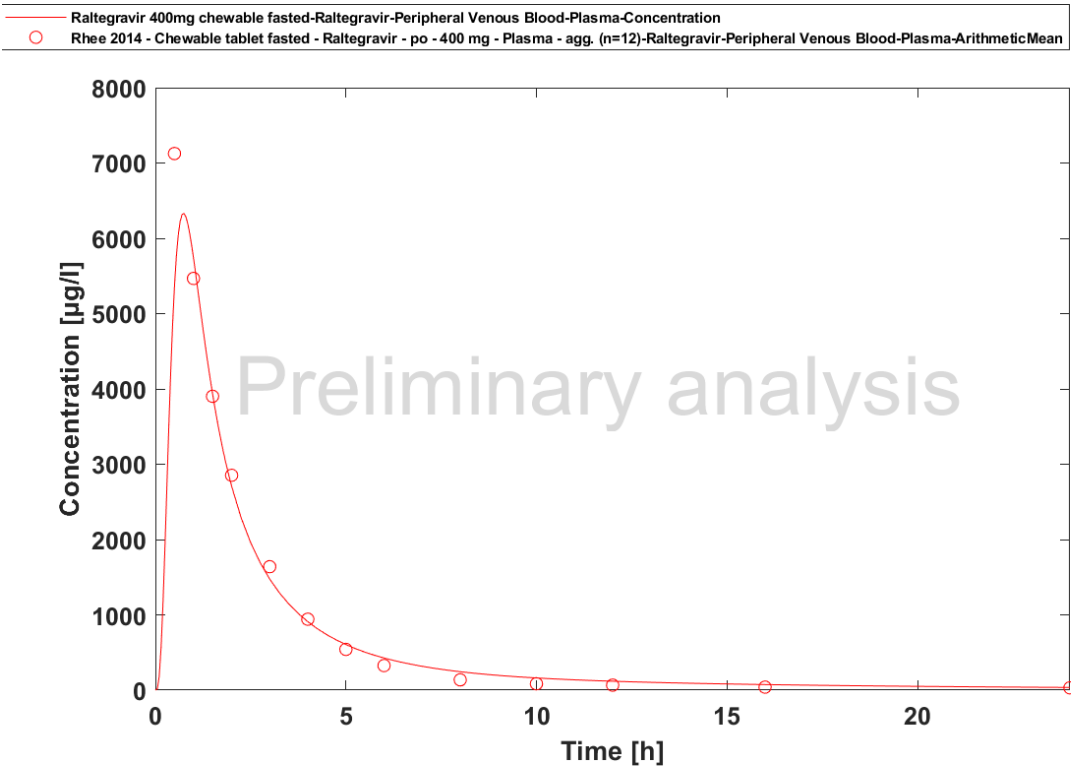
GMFE = 1.487148

3.3: Raltegravir Concentration-Time profiles

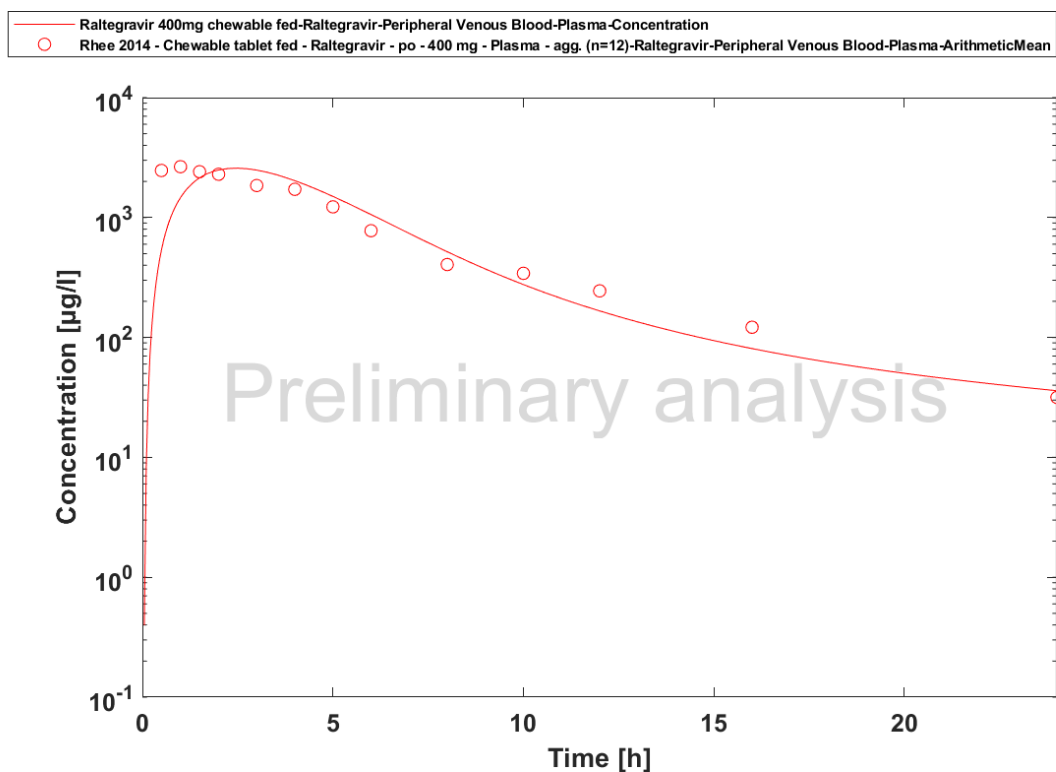
Simulated versus observed plasma concentration-time profiles of all data are listed below.



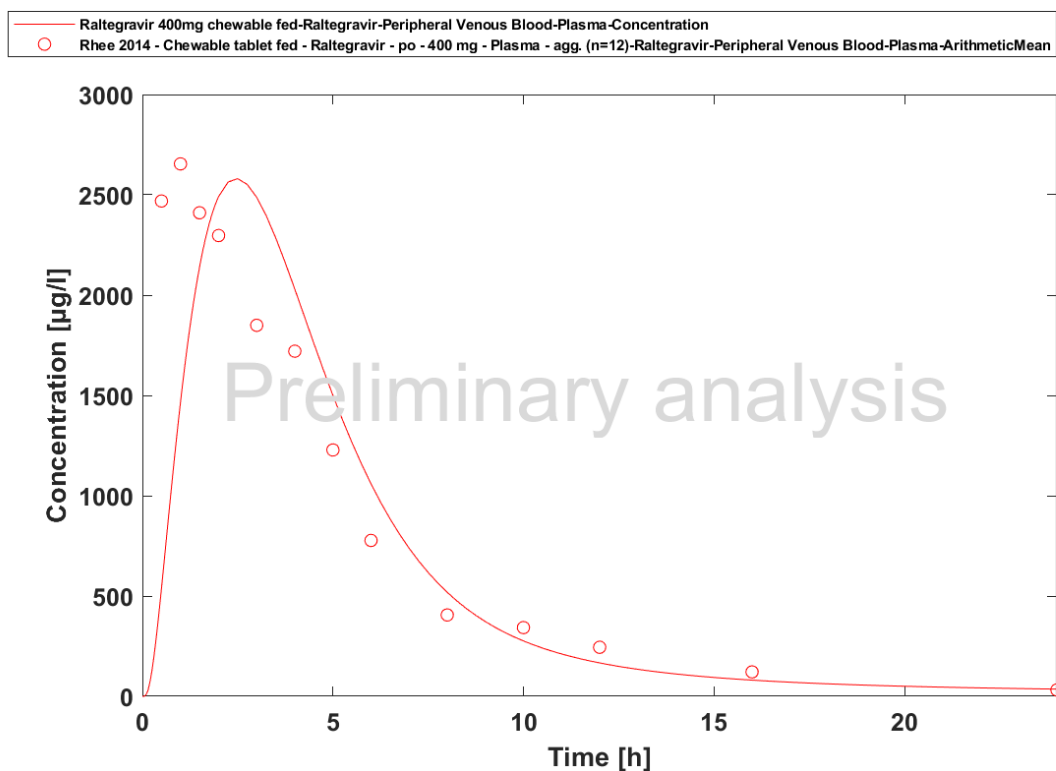
Time Profile Analysis



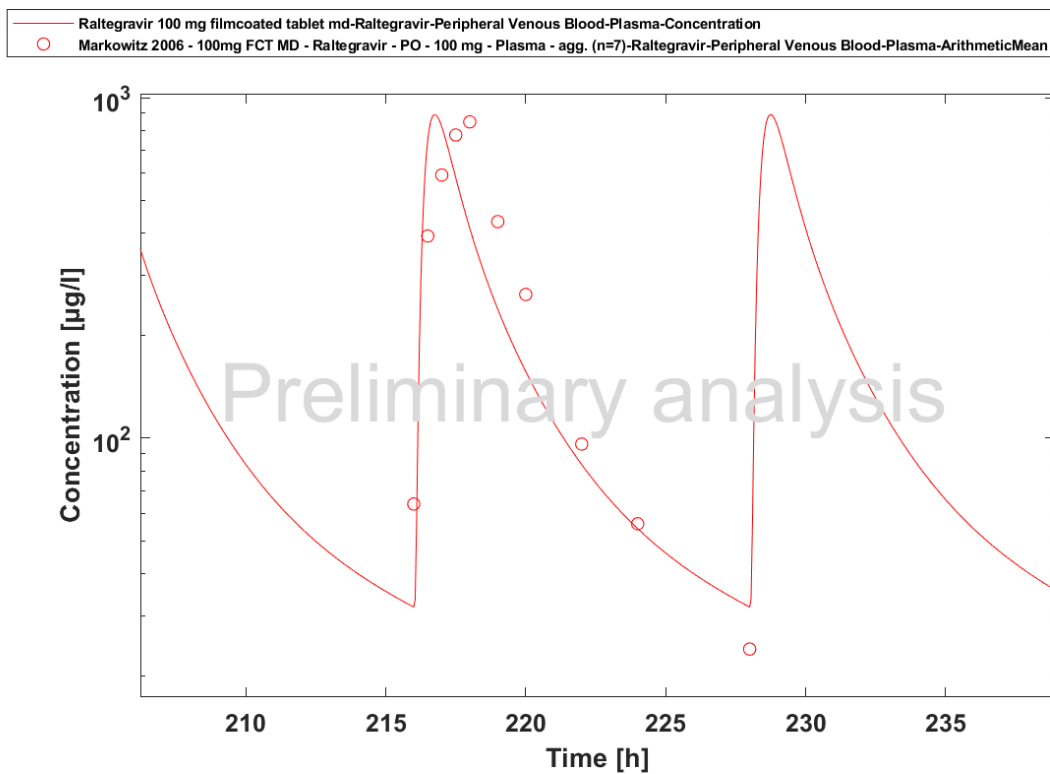
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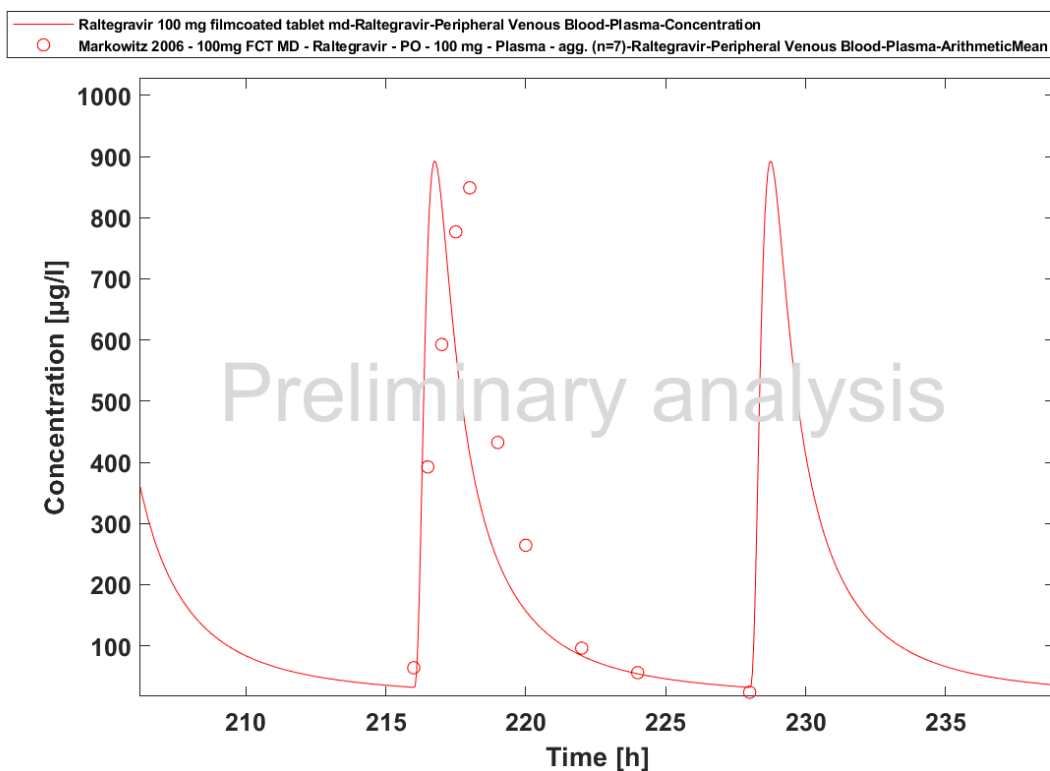
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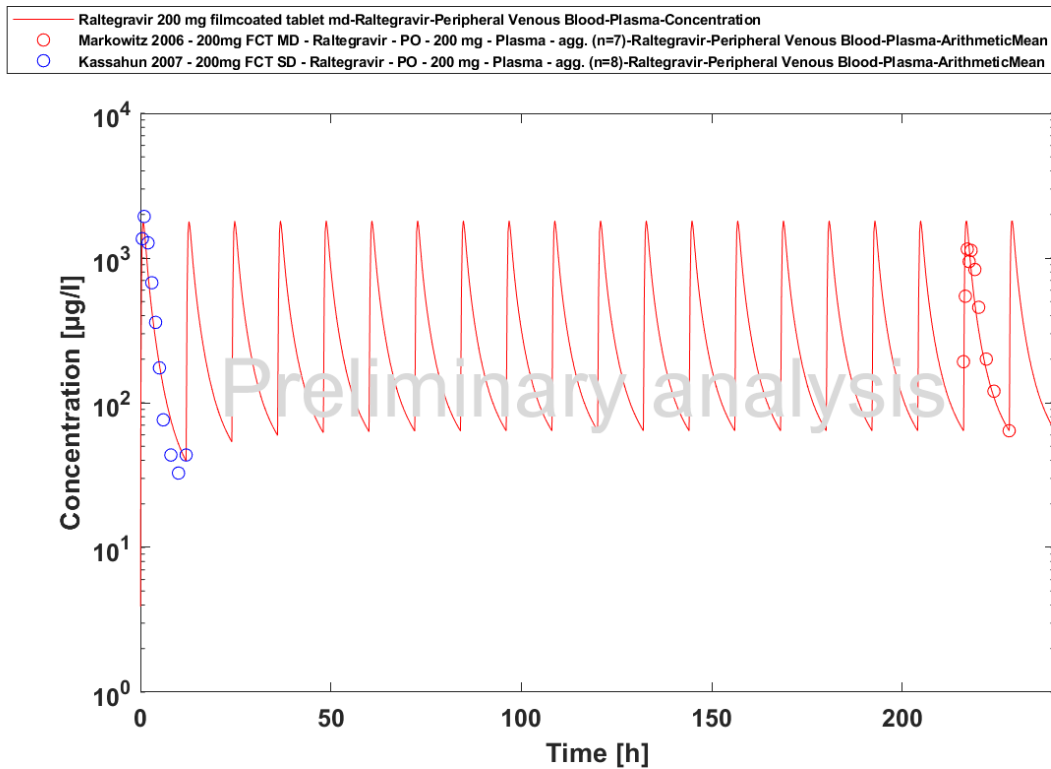
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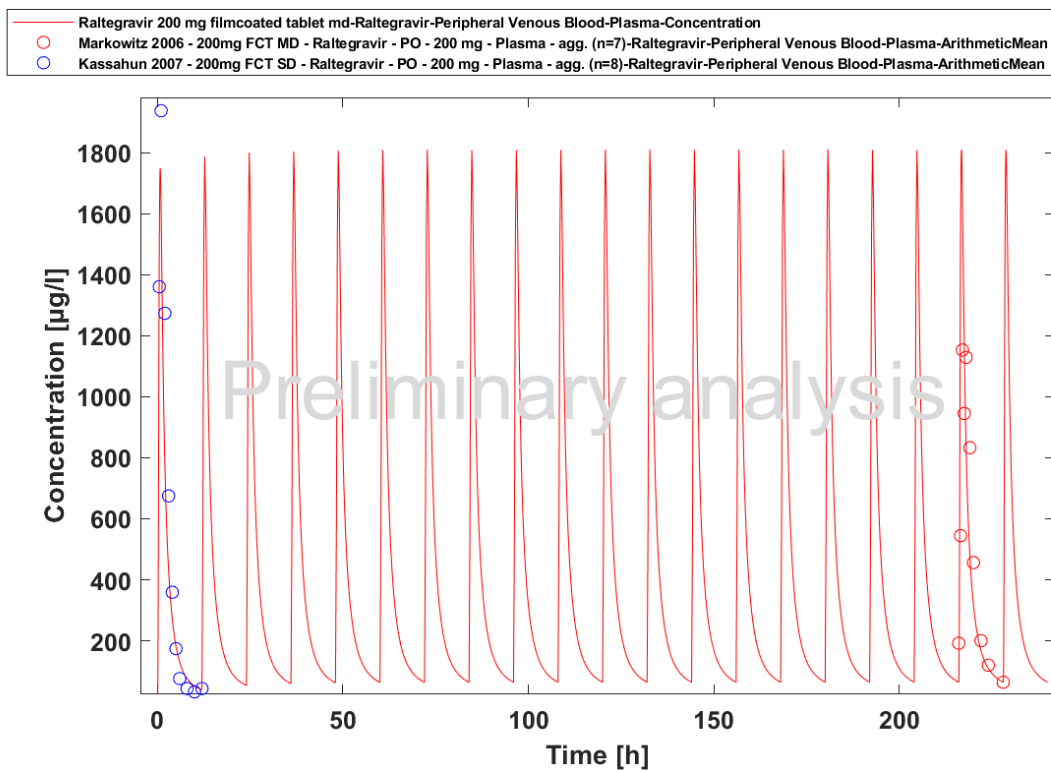
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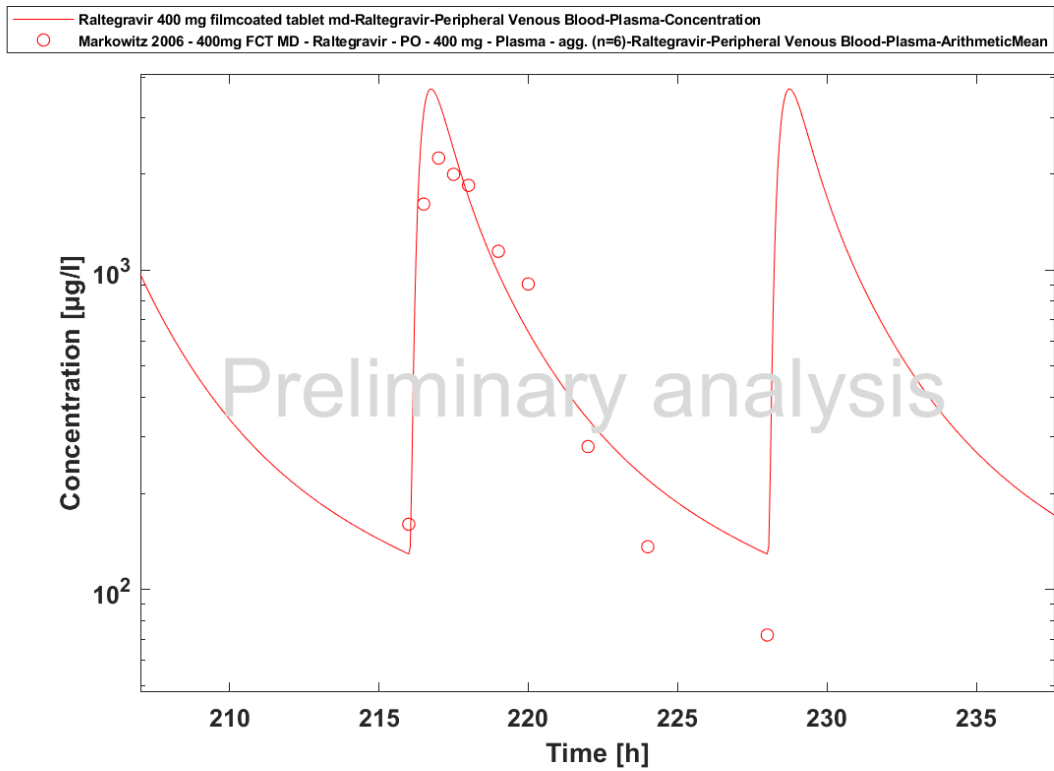
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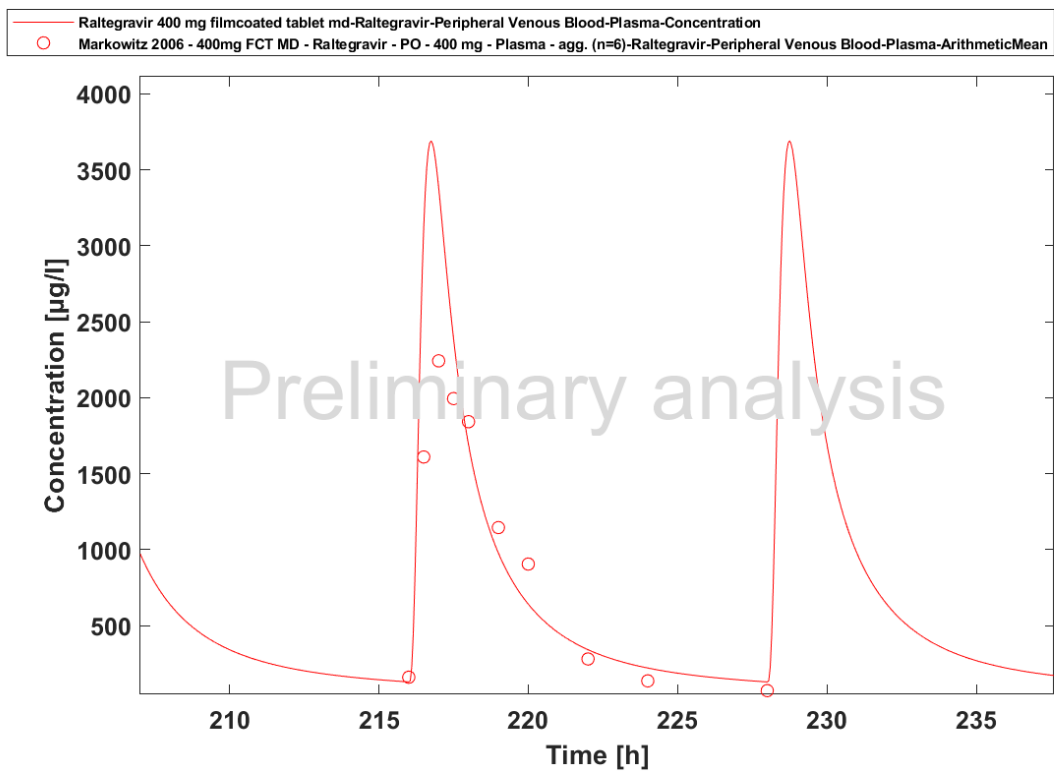
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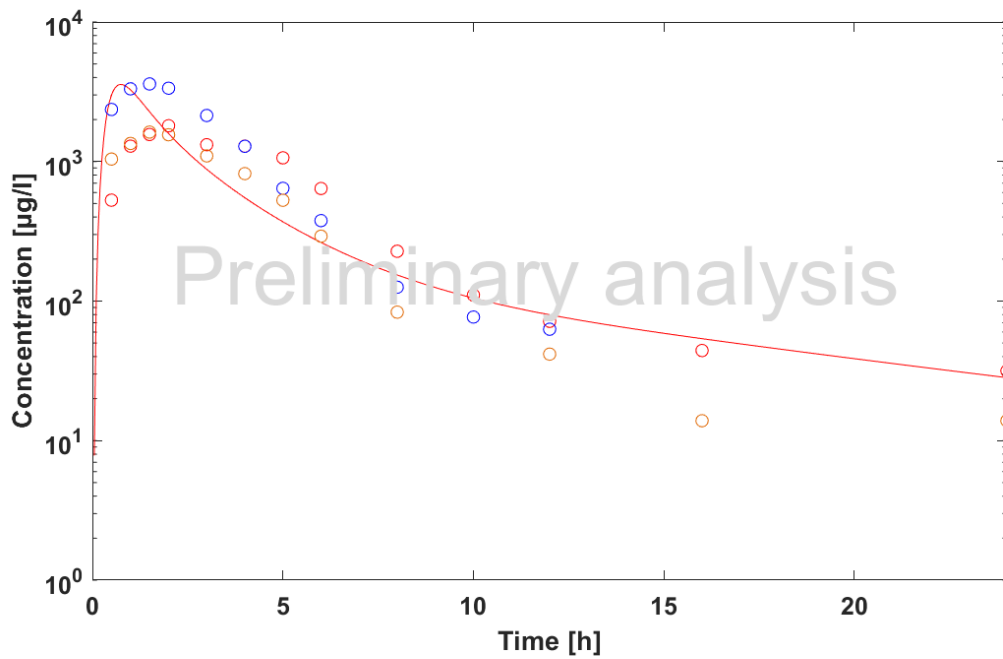
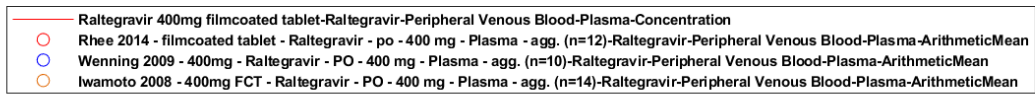
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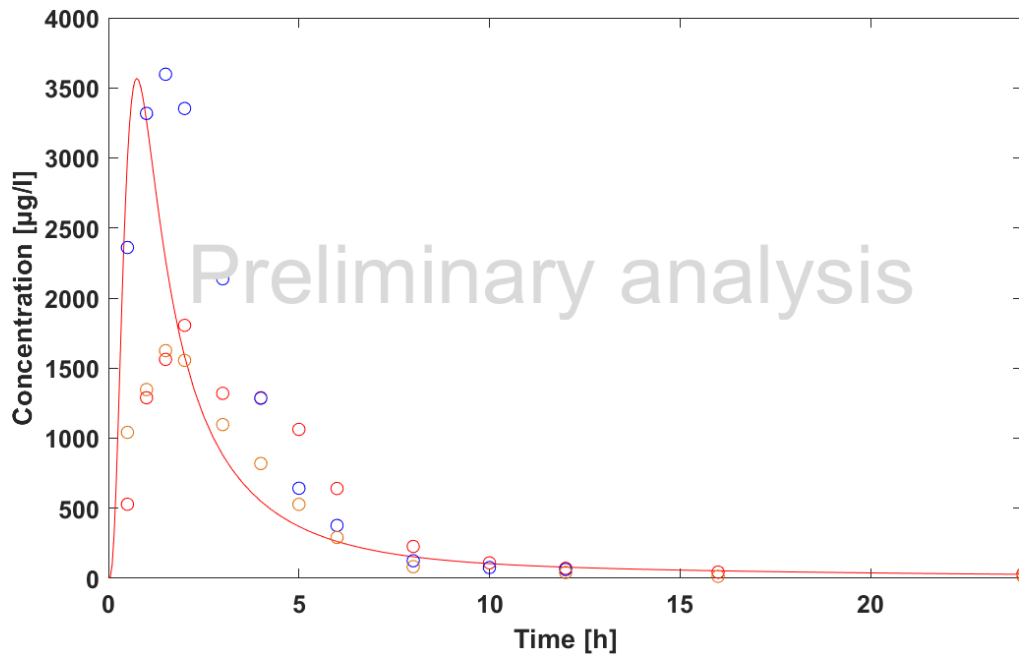
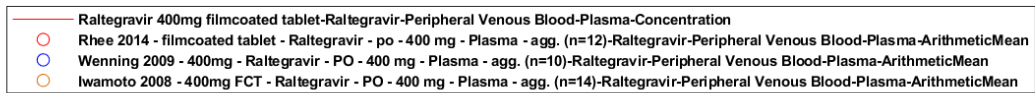
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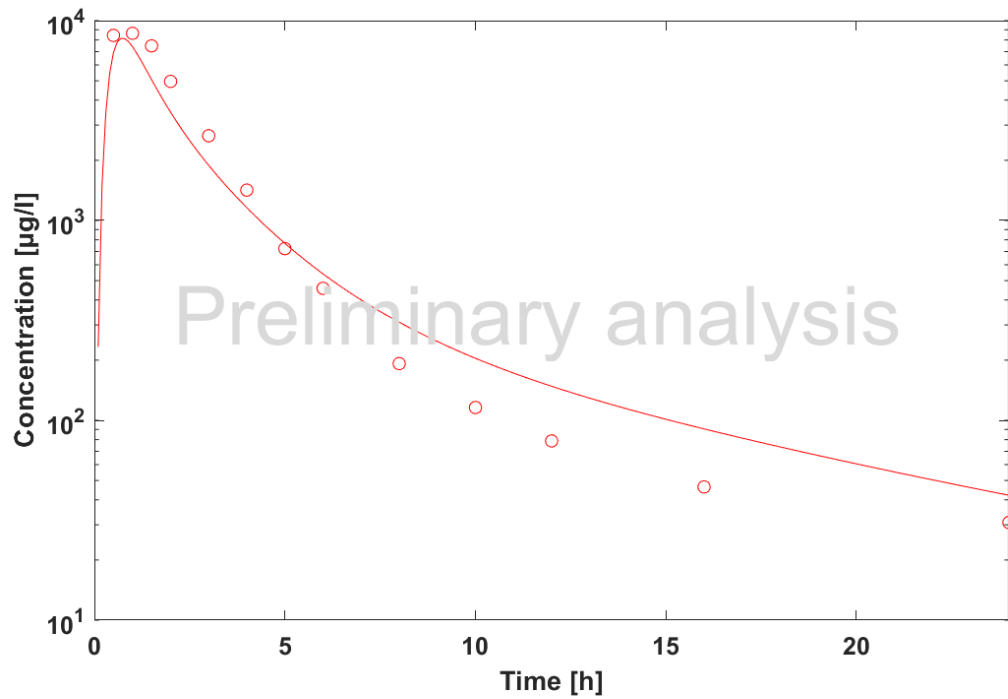


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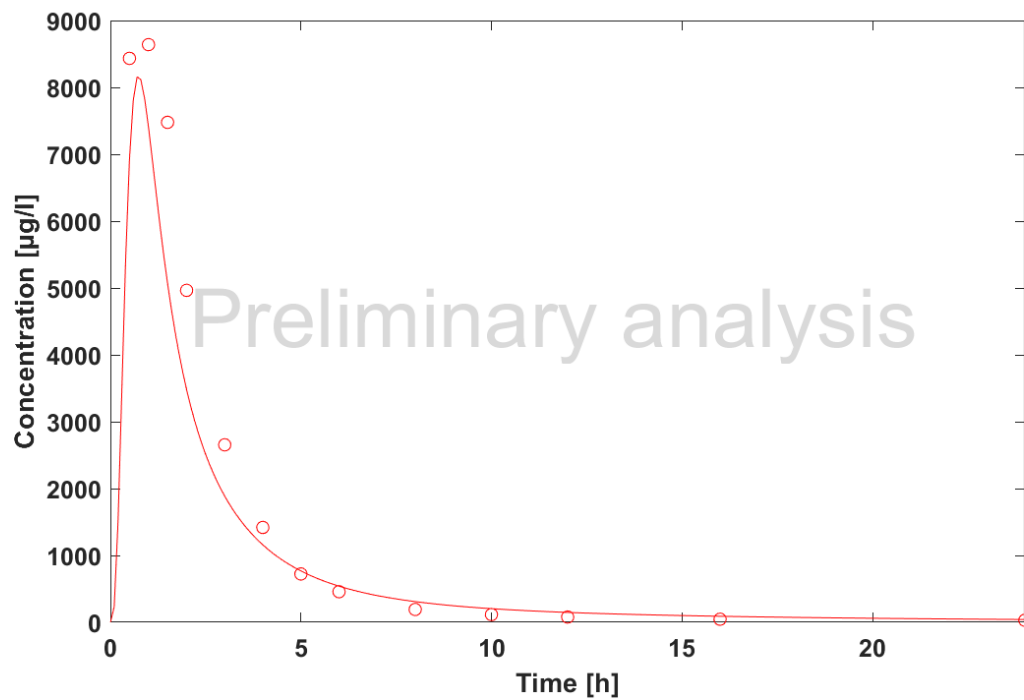
Time Profile Analysis 1

— Raltegravir 400mg (granules in suspension)-Raltegravir-Peripheral Venous Blood-Plasma-Concentration
○ Rhee 2014 - granules suspension - Raltegravir - po - 400 mg - Plasma - agg. (n=12)-Raltegravir-Peripheral Venous Blood-Plasma-ArithmeticMean

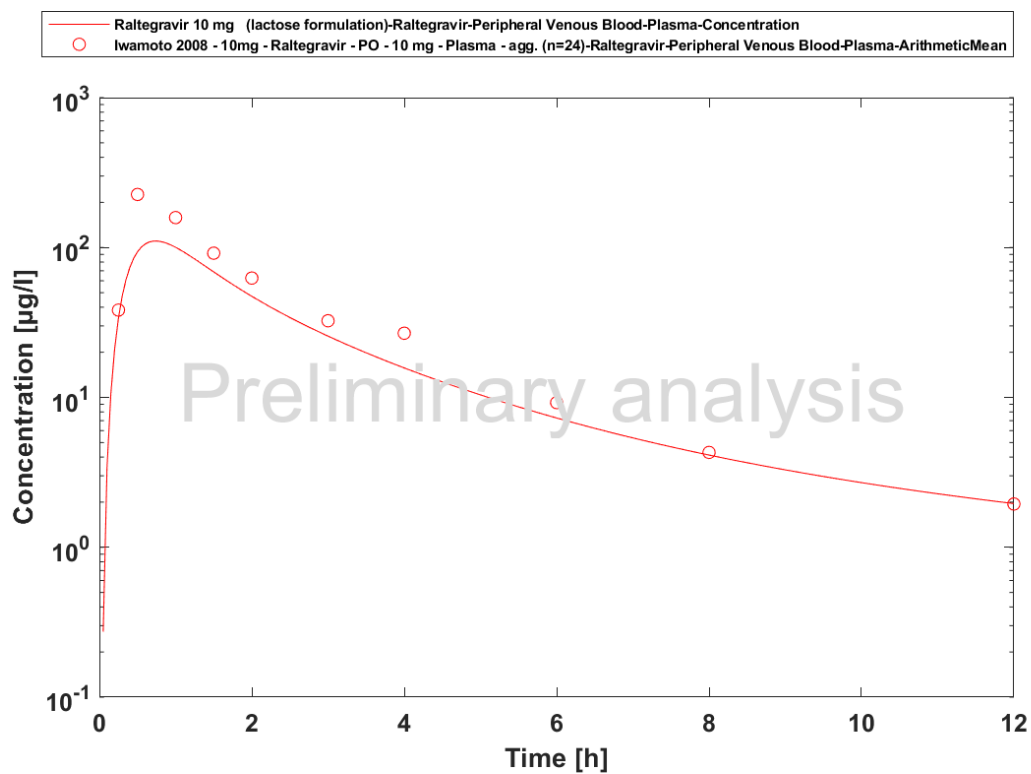


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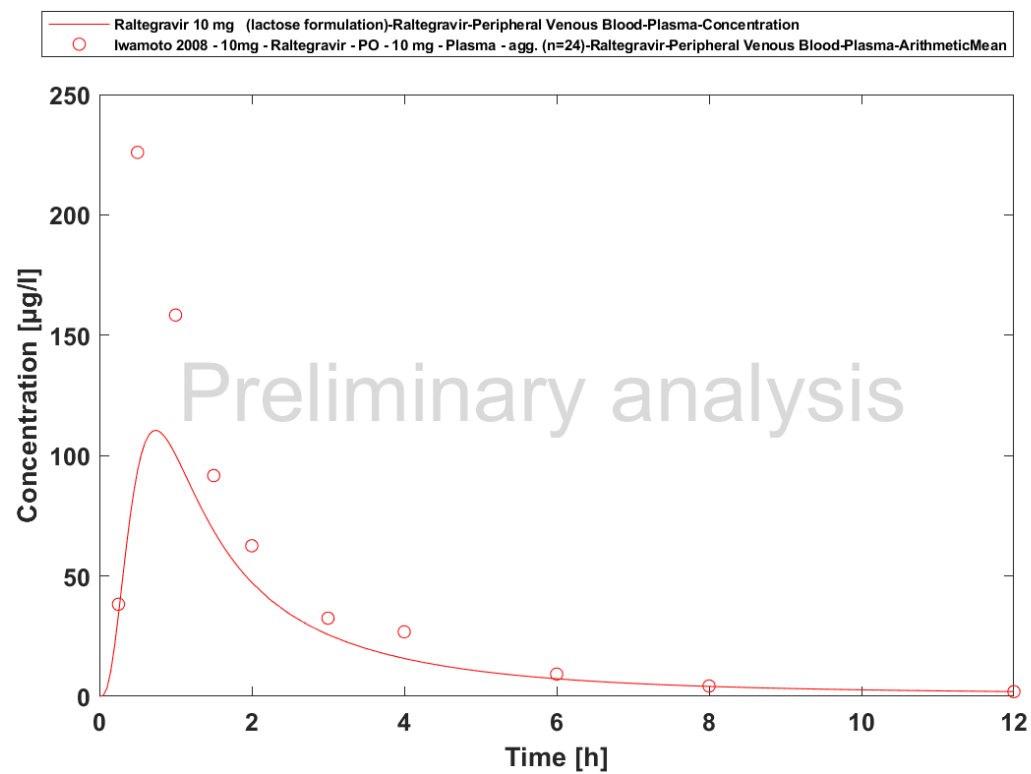
— Raltegravir 400mg (granules in suspension)-Raltegravir-Peripheral Venous Blood-Plasma-Concentration
○ Rhee 2014 - granules suspension - Raltegravir - po - 400 mg - Plasma - agg. (n=12)-Raltegravir-Peripheral Venous Blood-Plasma-ArithmeticMean



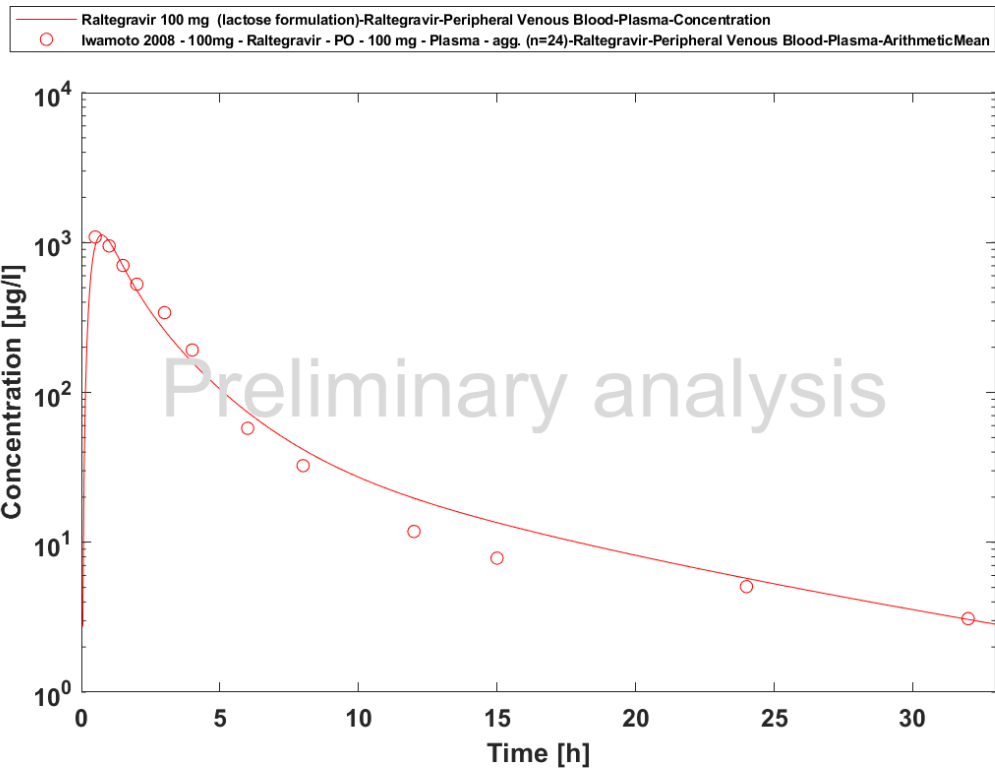
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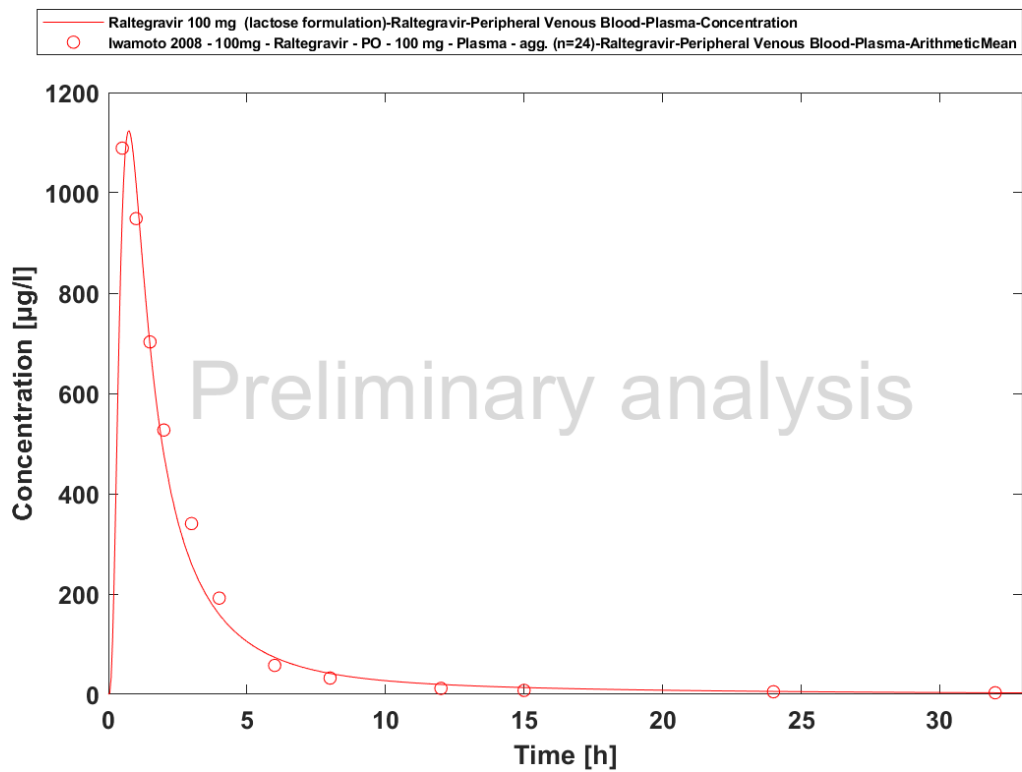
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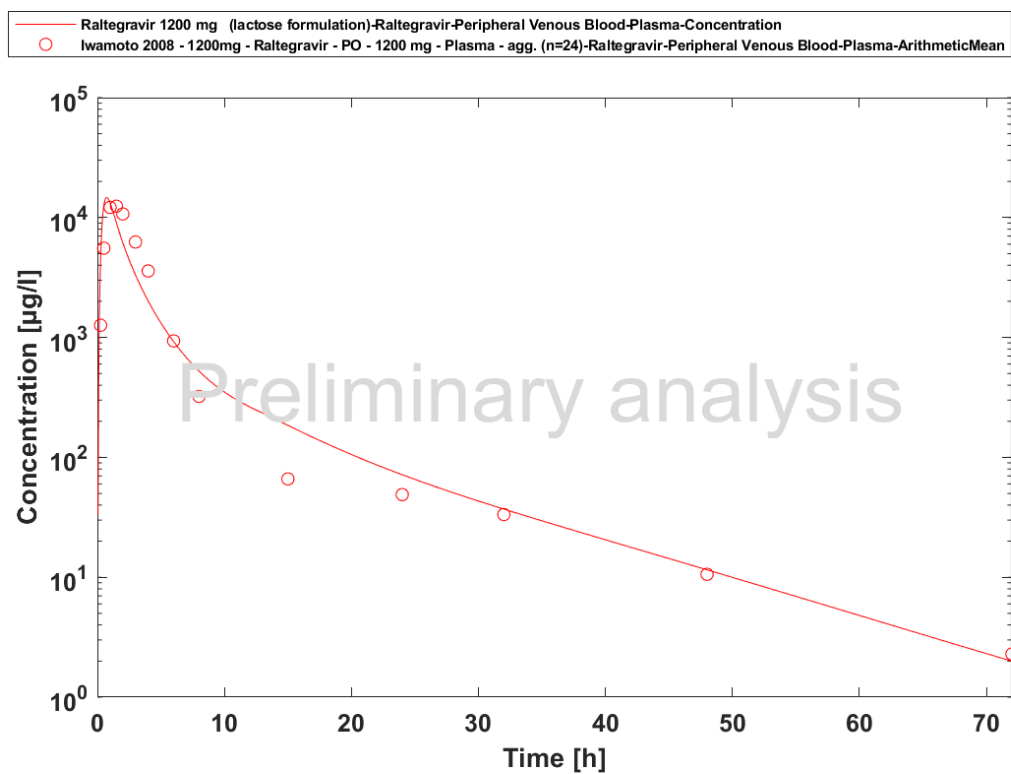
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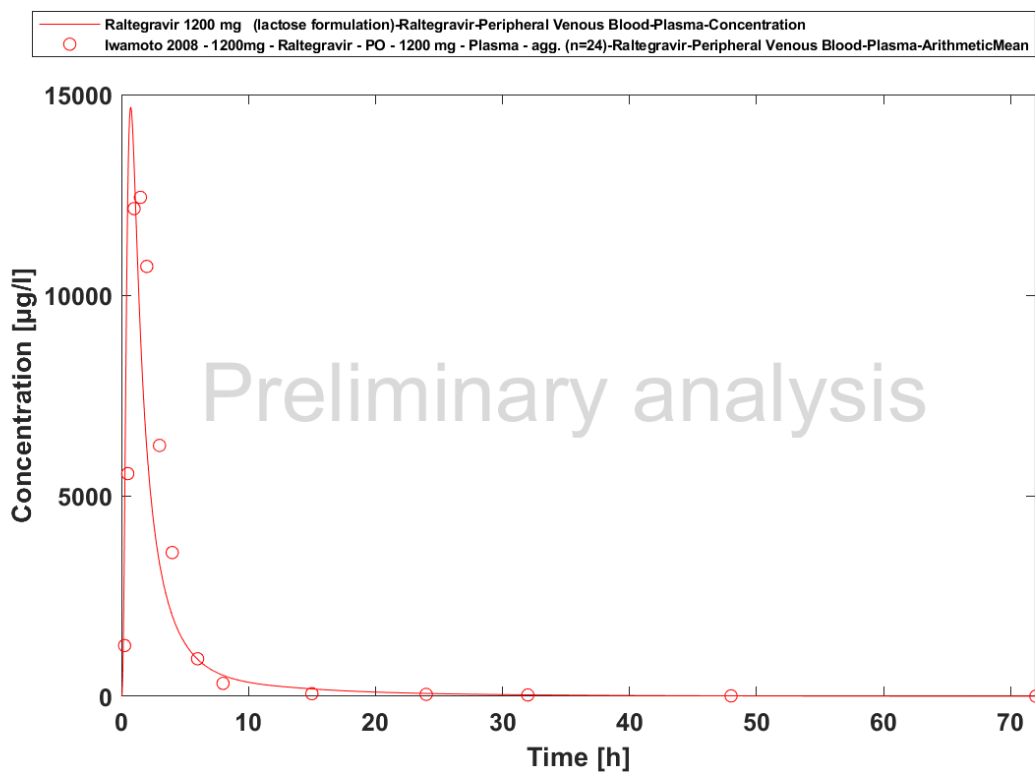
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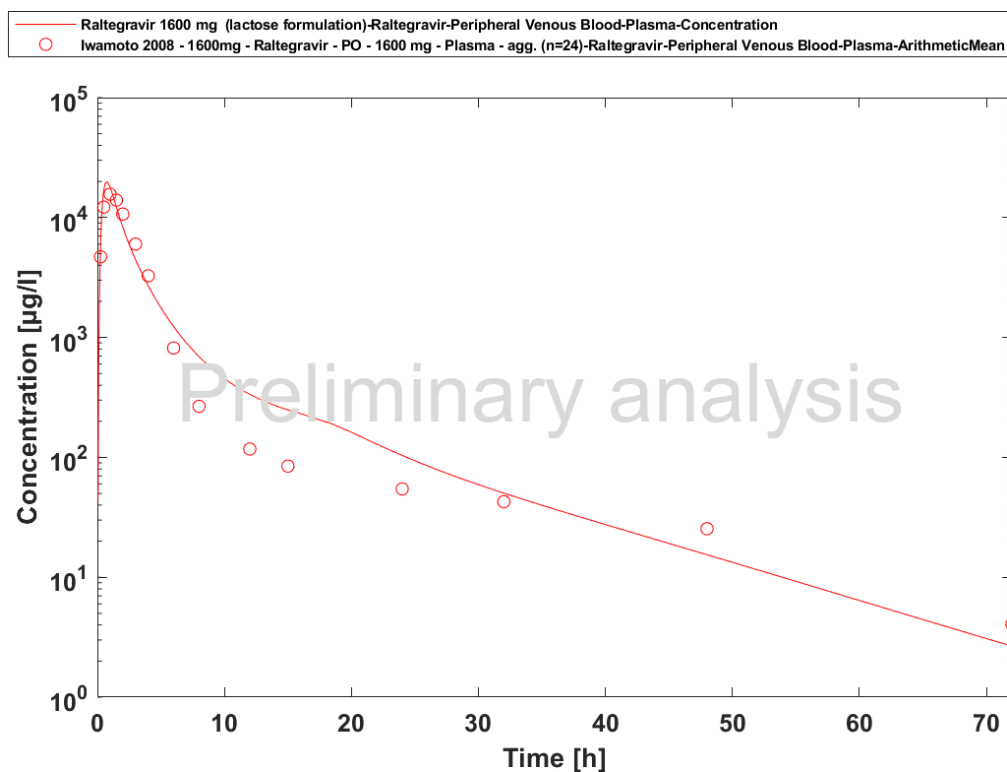
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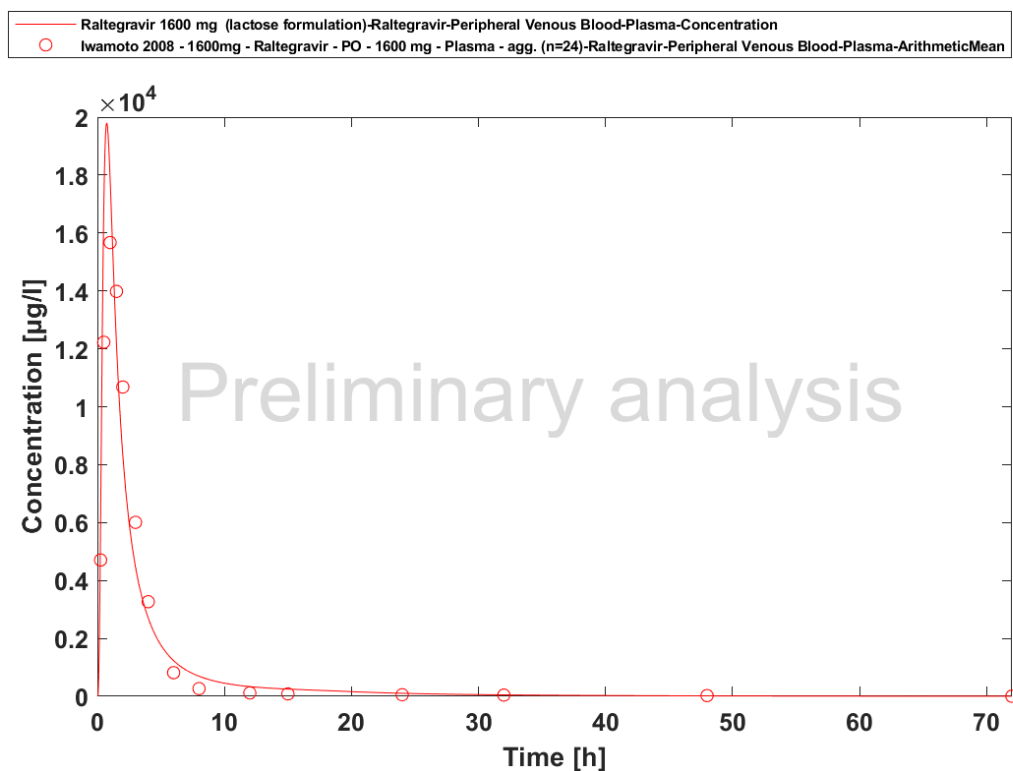
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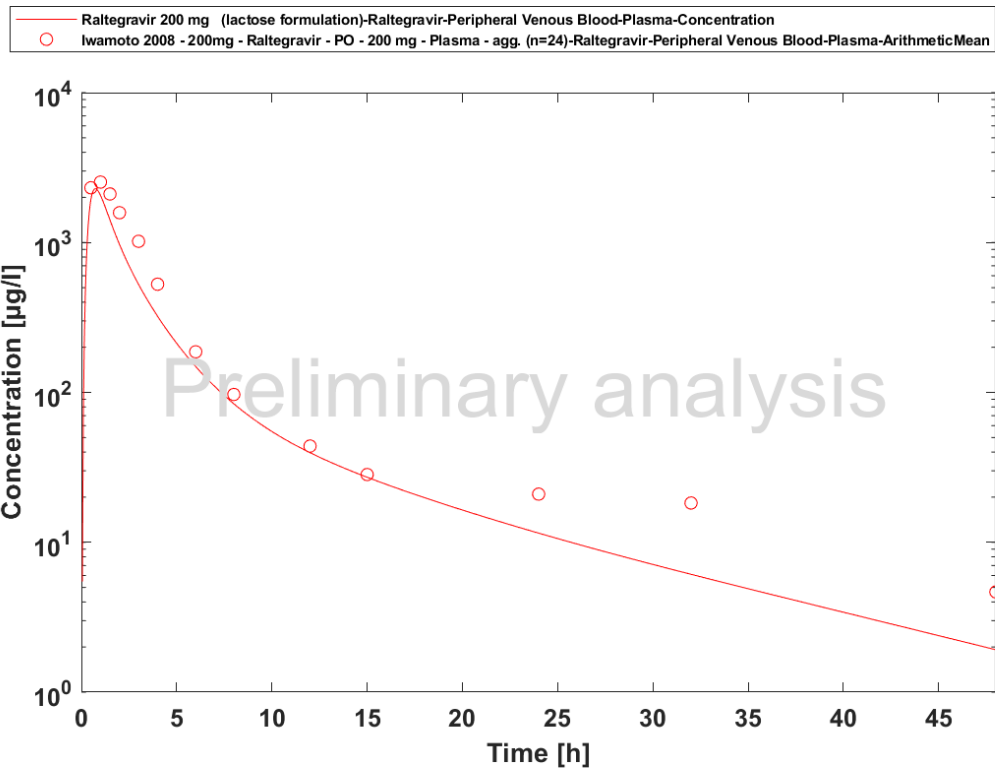
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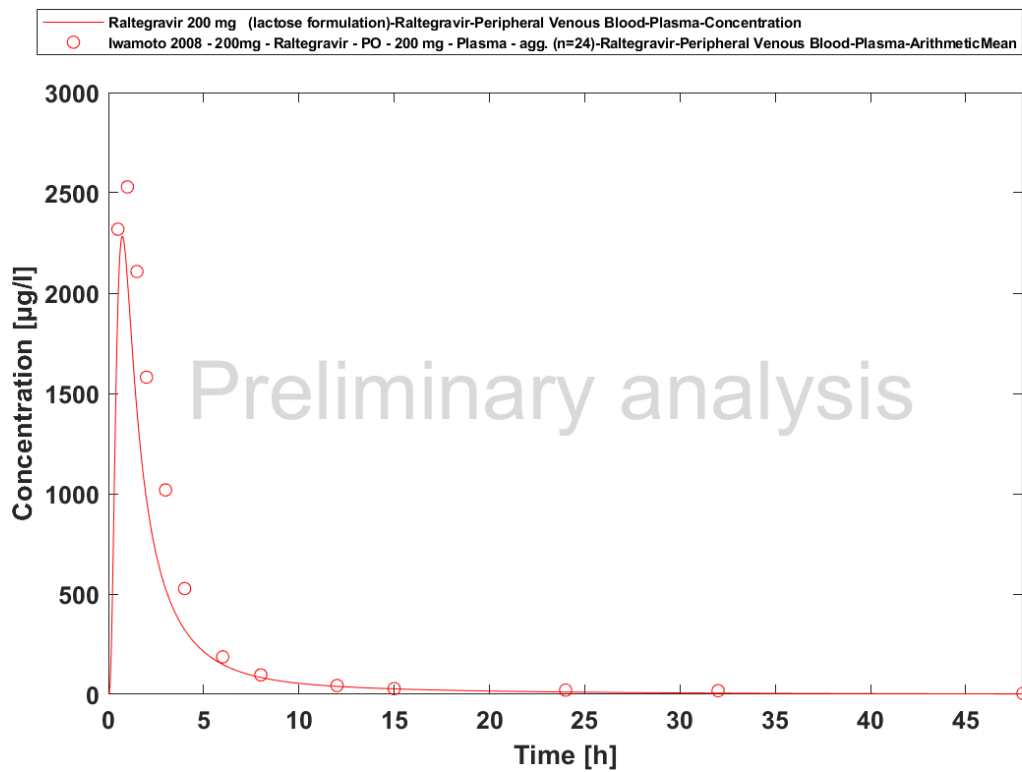
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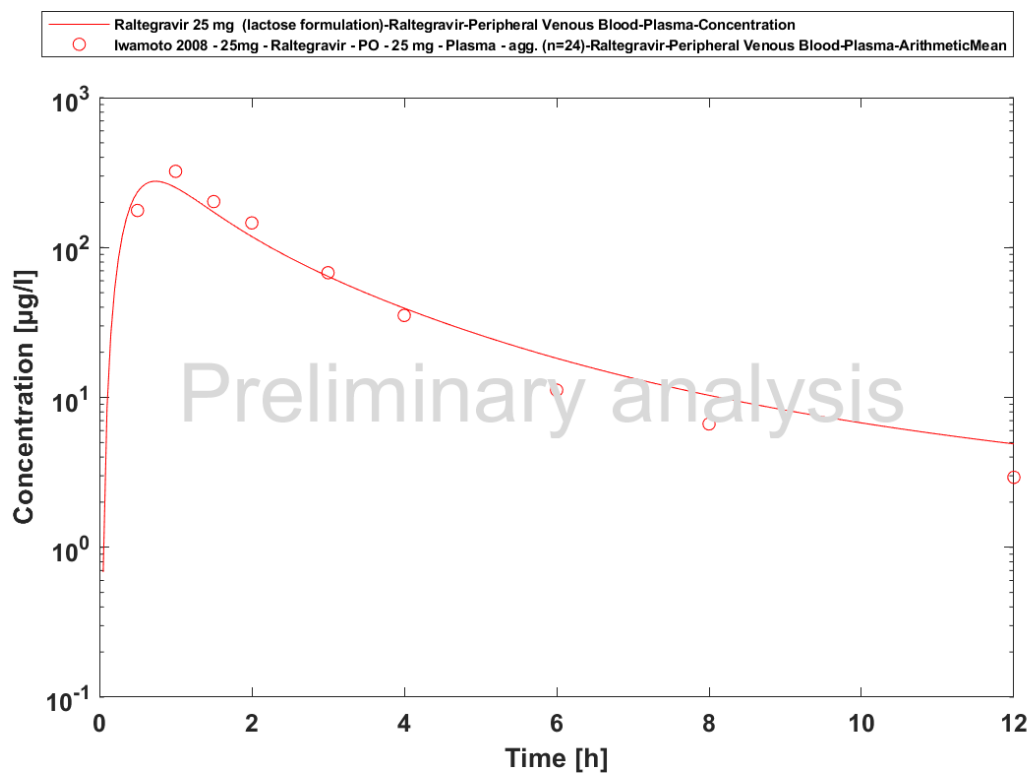
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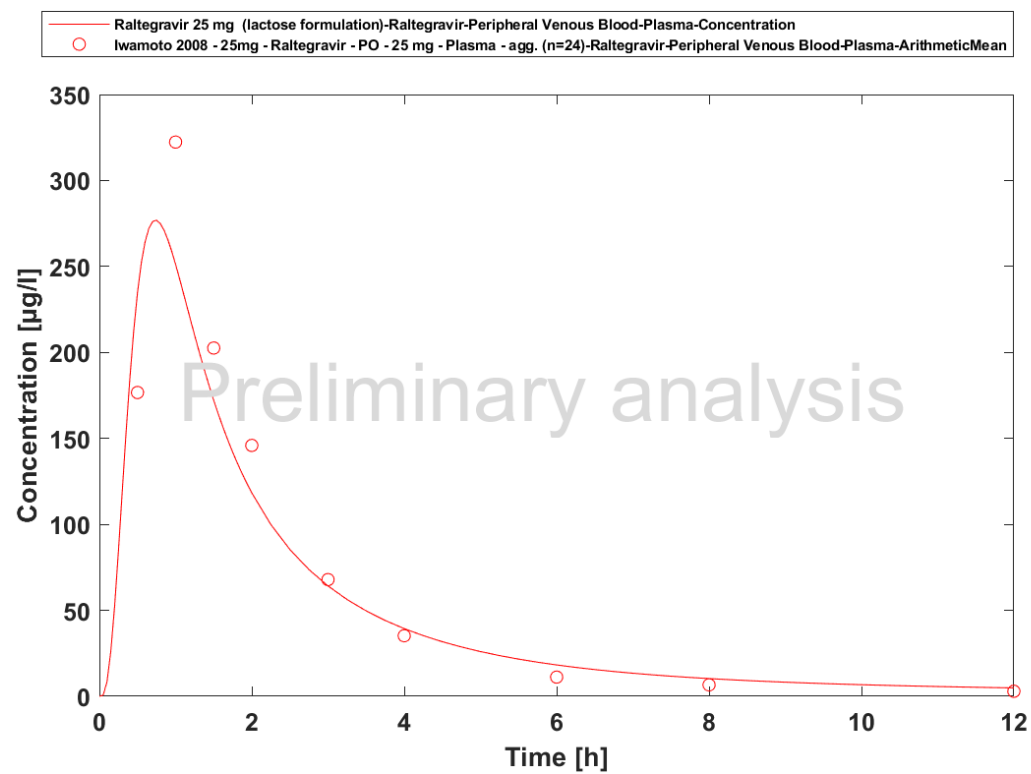
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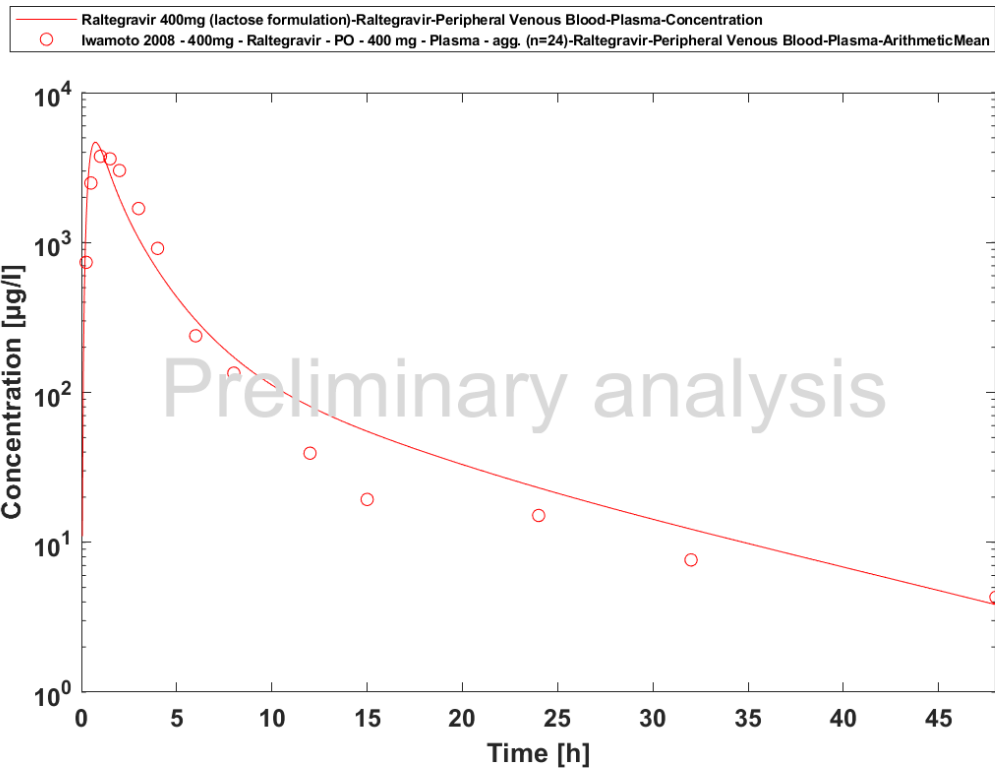
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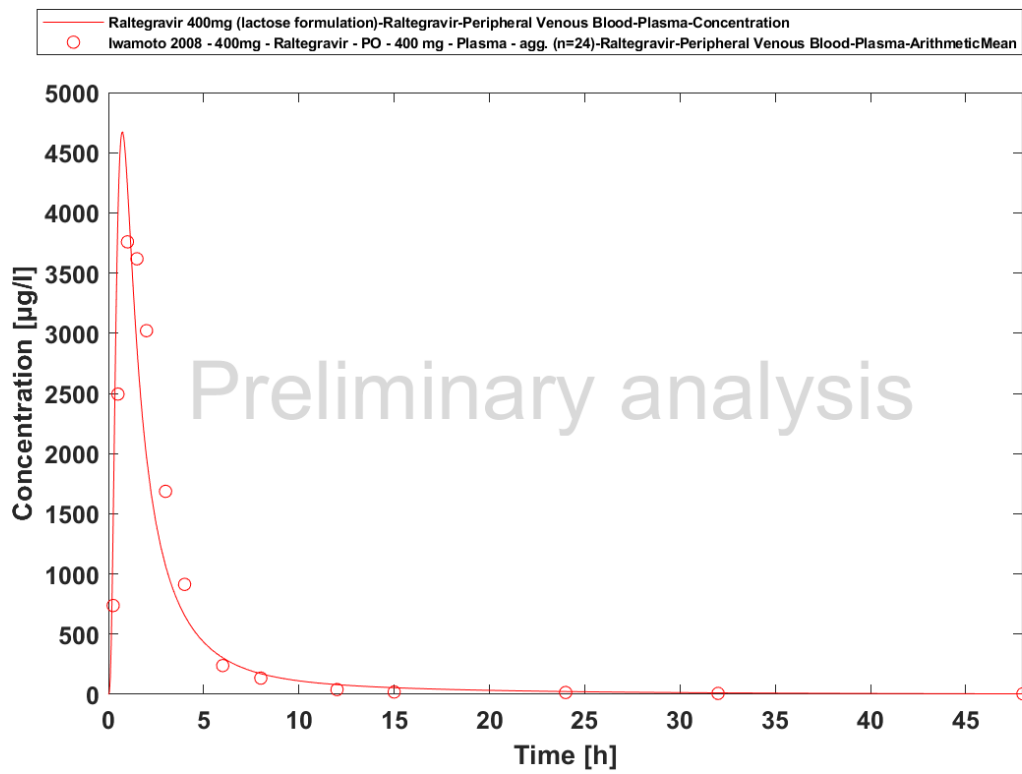
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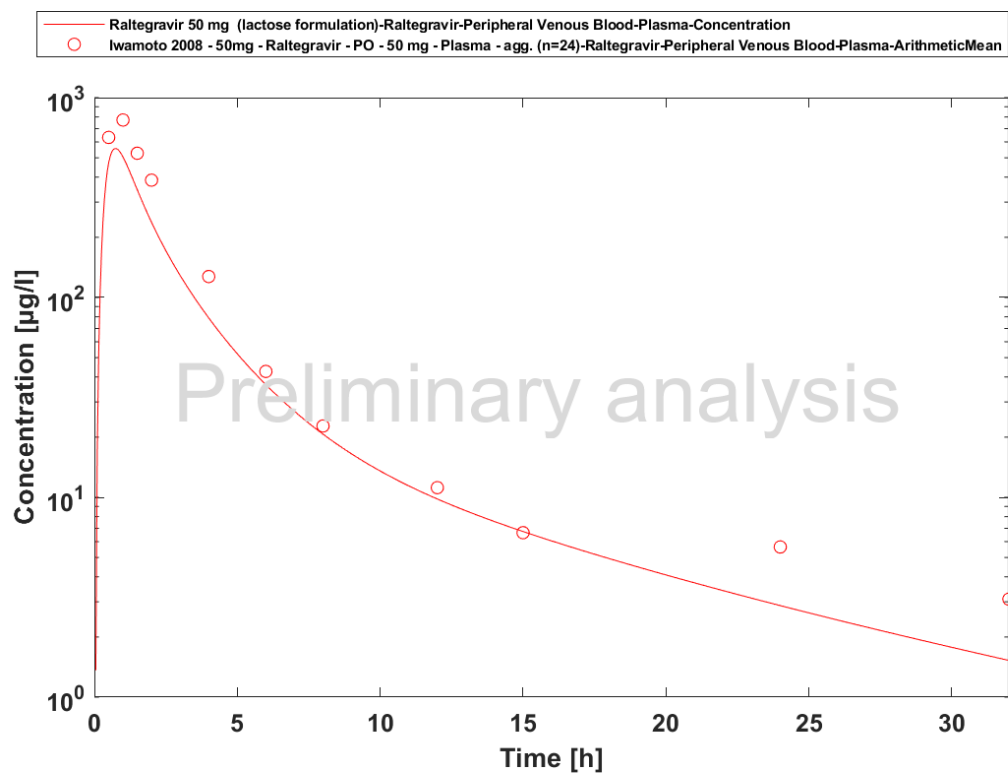
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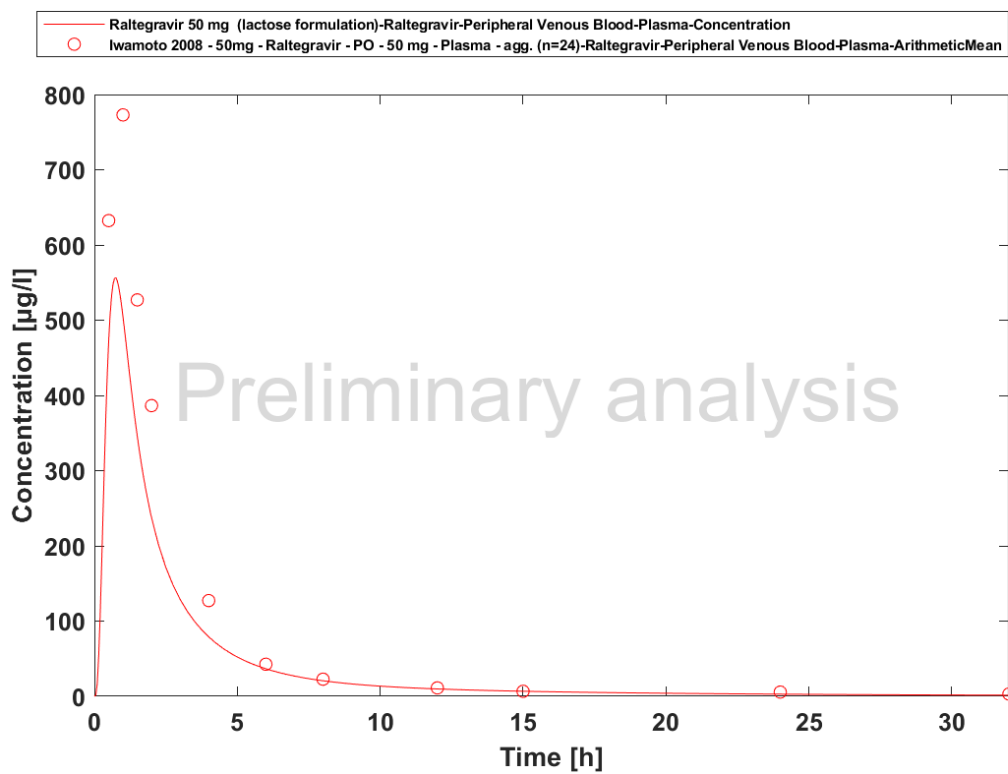
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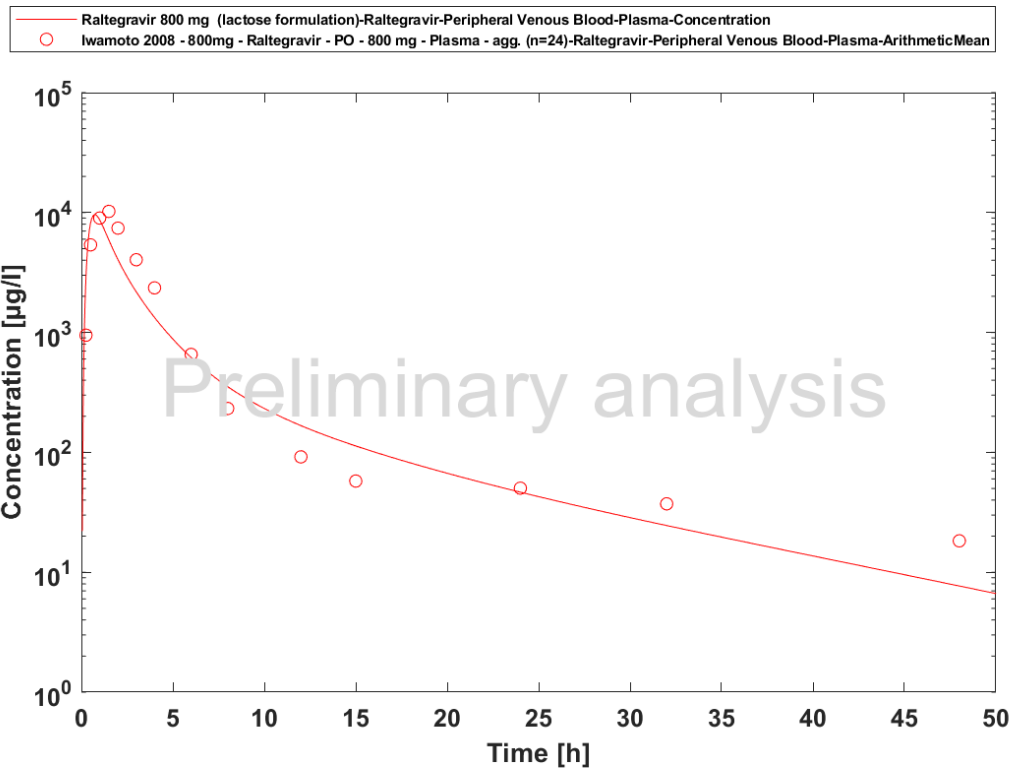
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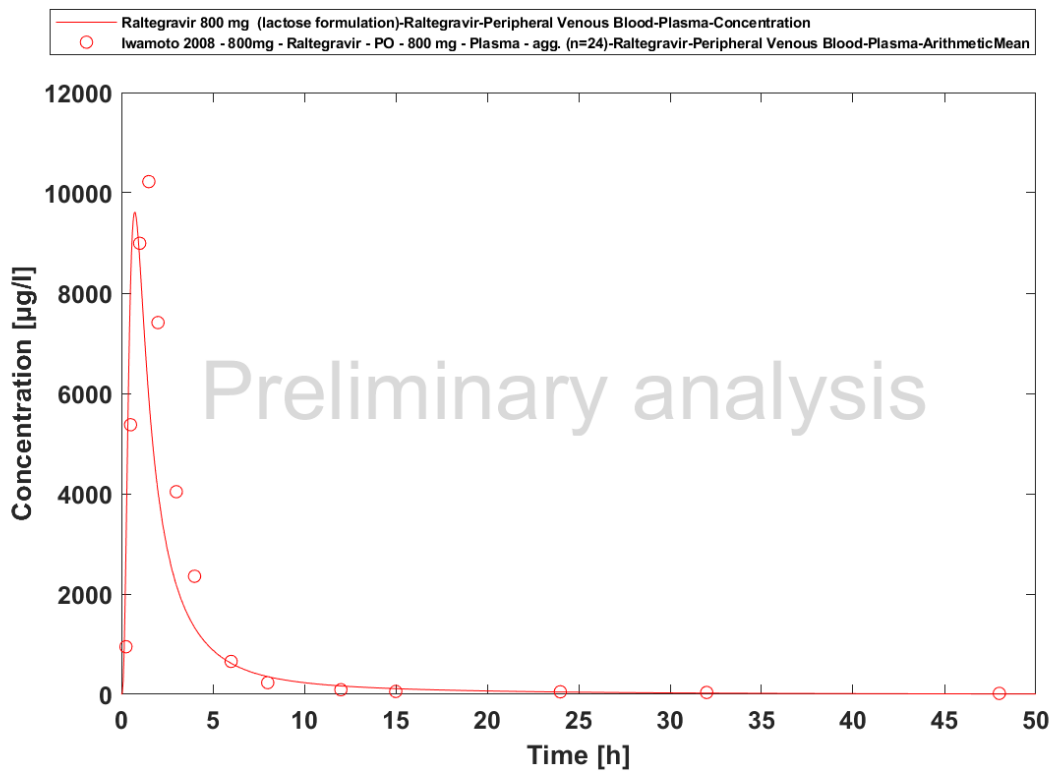
Time Profile Analysis



Time Profile Analysis 1



Time Profile Analysis



Time Profile Analysis 1

4 Conclusion

The final raltegravir PBPK model applies metabolism by UGT1A1, UGT1A9 and glomerular filtration and adequately describes the pharmacokinetics of raltegravir in adults receiving SD, MD of Raltegravir ranging from 10mg to 1600mg, including four different oral formulations.

This model could be applied for the investigation of DDI, and translation to special populations such as pediatrics with regard to UGT1A1 and 1A9 metabolism.

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