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

Version	**1.0-OSP9.0**
based on *Model Snapshot* and *Evaluation Plan*	https://github.com/Open-Systems-Pharmacology/Triazolam-Model/releases/tag/v1.0
OSP Version	9.0
Qualification Framework Version	2.2

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

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

Table of Contents

1 Introduction

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

Triazolam, sold under the trade name Halcion, among others, belongs to the group of benzodiazepines and is used for short-term treatment of insomnia and circadian rhythm sleep disorders. It is generally administered orally as immediate release tablet, but other forms of administrations, e.g. intravenously or as sublingual tablet, exist as well.

Following oral administration, triazolam is rapidly absorbed with an absolute bioavailability of 44 ± 24% (mean ± standard deviation, Kroboth 1995). Triazolam is widely distributed throughout the body. Its fraction unbound in human plasma averages around 17% and is, within the range of 20 to 1000 ng/mL, not influenced by total triazolam concentrations (Eberts 1981). Triazolam is extensively metabolized via CYP3A4 to α-hydroxy-alprazolam and 4-hydroxy-alprazolam (Eberts 1981, Kronbach 1989) and is therefore often used as victim compound in drug-drug interaction (DDI) studies.

The presented triazolam PBPK model was developed for intravenous (IV) administration and oral (PO) administration of the immediate release tablet given in fasted state in healthy, non-obese adults.

2 Methods

2.1 Modeling Strategy

The general workflow for building an adult PBPK model has been described by Kuepfer et al. (Kuepfer 2016). Relevant information on the anthropometry (height, weight) was gathered from the respective clinical study, if reported. Information on physiological parameters (e.g. blood flows, organ volumes, hematocrit) in adults was gathered from the literature and has been incorporated in PK-Sim®) as described previously (Willmann 2007). 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).

The PBPK model was developed based on clinical data of healthy, non-obese, adult subjects obtained from the literature, covering different single doses of triazolam administered intravenously or orally as immediate release tablet in the fasted state.

Unknown parameters were simultaneously optimized using all available PK data, in particular:

- 6 data sets following single IV administration of 5 different doses of triazolam (0.125 mg, 0.25 mg, 0.5 mg, 0.75 mg, 1 mg)
- 22 data sets following single PO administration of 3 different doses of triazolam as immediate release tablet (0.125 mg, 0.25 mg, 0.5 mg)

Structural model selection was mainly guided by visual inspection of the resulting description of data and biological plausibility. The following parameters were identified using the Parameter Identification module provided in PK-Sim® and MoBi® (Open Systems Pharmacology Documentation):

- `Dissolution time (50% dissolved)`
- `Dissolution shape`
- `Specific intestinal permeability`
- `Mucosa permeability (interstitial<->intracellular)`
- `Lipophilicity`
- `Metabolizing Enzyme - CYP3A4 - kcat`

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 / physicochemical data

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

Parameter	Unit	Literature	Description
Molecular weight	g/mol	343.21 (drugbank.ca)	Molecular weight
pK_a (basic)		1.52 (Konishi 1982)	Acid dissociation constant
logP		2.42 (drugbank.ca)	Partition coefficient between octanol and water
logD		1.63 (Greenblatt 1983a)	Partition coefficient between octanol and water at physiological pH
f_u		0.099 ± 0.015[a] (Jochemsen 1983); 0.11 (Eberts 1981); 0.174 ± 0.020[a] (Friedman 1988); 0.188 ± 0.139[a] (Ochs 1987); 0.213 [0.193 - 0.264][b] (Greenblatt 1983b); 0.229 [0.204 - 0.259][c] (Greenblatt 1983b)	Fraction unbound in human plasma of healthy adults
Water solubility	mg/L	4.53 (drugbank.ca)	Estimated solubility in water

[a] mean ± standard deviation

[b] mean [range] in young males

[c] mean [range] in young females

2.2.2 Clinical data

A literature search was carried out to collect triazolam PK data in healthy adults.

The following publications were found and used for model building and evaluation:

Publication	Study description
Friedman 1986	PO single dose administration of 0.5 mg
Friedman 1988	PO single dose administration of 0.5 mg
Greenblatt 1989	PO single dose administration of 0.25 mg
Greenblatt 1991	PO single dose administration of 0.125 mg
Greenblatt 2000	PO single dose administration of 0.25 mg
Greenblatt 2004	PO single dose administration of 0.25 mg
Hukkinen 1995	PO single dose administration of 0.25 mg
Lilja 2000	PO single dose administration of 0.25 mg
Kroboth 1985	IV single dose administration of 0.25 mg and PO single dose administration of 0.25 mg
O'Connor-Semmes 2001	PO single dose administration of 0.25 mg
Ochs 1984	PO single dose administration of 0.5 mg
Phillips 1986	PO single dose administration of 0.5 mg
Smith 1987	IV single dose administration of 0.125 mg, 0.25 mg, 0.5 mg, 0.75 mg, and 1 mg
Varhe 1994	PO single dose administration of 0.25 mg
Varhe 1996a	PO single dose administration of 0.25 mg
Varhe 1996b	PO single dose administration of 0.25 mg
Varhe 1996c	PO single dose administration of 0.25 mg
Villikka 1997	PO single dose administration of 0.5 mg
Villikka 1998	PO single dose administration of 0.5 mg
von Moltke 1996	PO single dose administration of 0.125 mg

2.3 Model Parameters and Assumptions

2.3.1 Dissolution and absorption

Dissolution of the immediate release tablet of triazolam was described by a Weibull function with the two parameters `Dissolution shape` and `Dissolution time (50% dissolved)` being fitted, together with the other parameters listed in Section 2.1, to observed PK data to better match the observations. `Specific intestinal permeability (transcellular)` was also optimized together with the parameters listed in Section 2.1.

2.3.2 Distribution

In the model, the `fraction unbound (plasma, reference value)` was set to 0.174 which is the reported mean value measured in 19 healthy male and female volunteers aged 20 to 45 years (Friedman 1988). This value is also the approximate average of all pooled values reported in several studies (Jochemsen 1983, Eberts 1981, Greenblatt 1983, Friedman 1988, Ochs 1987). `Lipophilicity` was optimized together with the other parameters listed in Section 2.1 to better match observed PK data. The observed PK data were found to be best described using the model for estimating intracellular-to-plasma partition coefficients according to the method by `Rodgers`

`and Rowland` (Rodgers 2005, Rodgers 2006). Cellular permeabilities were automatically calculated using the method `PK-Sim Standard` (Open Systems Pharmacology Documentation).

2.3.3 Elimination

Triazolam is extensively metabolized via CYP3A to the two metabolites α-hydroxy-triazolam and 4-hydroxy-triazolam. In the model, these two biotransformation pathways were separately described via Michaelis-Menten kinetics. The `Km` values for each pathway were fixed to reported literature values, namely 74.2 µmol/L for the α-OH pathway and 305 µmol/L for the 4-OH pathway (von Moltke 1996). Together with the other parameters listed in Section 2.1, the `kcat` values were optimized while keeping the ratio between both values constant (by selecting the option `Use as Factor`). The gene expression profile of CYP3A4 was loaded from the internal PK-Sim® database using the expression data quantified by RT-PCR (Open Systems Pharmacology Documentation).

3 Results and Discussion

The PBPK model for triazolam was developed and verified with clinical PK data.

The next sections show:

1. the final model 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: Section 3.3.

3.1 Final input parameters

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

Formulation: Halcion

Type: Weibull

Parameters

Name	Value	Value Origin
Dissolution time (50% dissolved)	1.7958147418 min	Parameter Identification-Parameter Identification-Value updated from 'IV + Oral' on 2018-11-13 16:52
Lag time	0 min	
Dissolution shape	2.5169993312	Parameter Identification-Parameter Identification-Value updated from 'IV + Oral' on 2018-11-13 16:52
Use as suspension	Yes	

Compound: Triazolam

Parameters

Name	Value	Value Origin	Alternative	Default
Solubility at reference pH	4.53 mg/l	Unknown-drugbank.ca	Measurement	True
Reference pH	7	Unknown-drugbank.ca	Measurement	True
Lipophilicity	1.897007419 Log Units	Parameter Identification-Parameter Identification-Value updated from 'IV + Oral' on 2018-11-13 16:52	Optimized	True
Fraction unbound (plasma, reference value)	0.174	Publication-In Vivo-PMID: 3360971	Measurement	True
Specific intestinal permeability (transcellular)	7.0220146601E-05 cm/min	Parameter Identification-Parameter Identification-Value updated from 'IV + Oral' on 2018-11-13 16:52	Optimized	True
Cl	2			
Is small molecule	Yes			
Molecular weight	343.21 g/mol			

Name	Value	Value Origin	Alternative	Default
Molecular weight	345.21 g/mol			
Plasma protein binding partner	Unknown			

Calculation methods

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

Processes

Metabolizing Enzyme: CYP3A4-alpha-OH pathway

Molecule: CYP3A4

Parameters

Name	Value	Value Origin
In vitro Vmax for liver microsomes	2.36 nmol/min/mg mic. protein	Publication-In Vitro-PMID: 8632299
Km	74.2 µmol/l	Publication-In Vitro-PMID: 8632299
kcat	4.0317206142 1/min	Parameter Identification-Parameter Identification-Value updated from 'IV + Oral' on 2018-11-13 16:52

Metabolizing Enzyme: CYP3A4-4-OH pathway

Molecule: CYP3A4

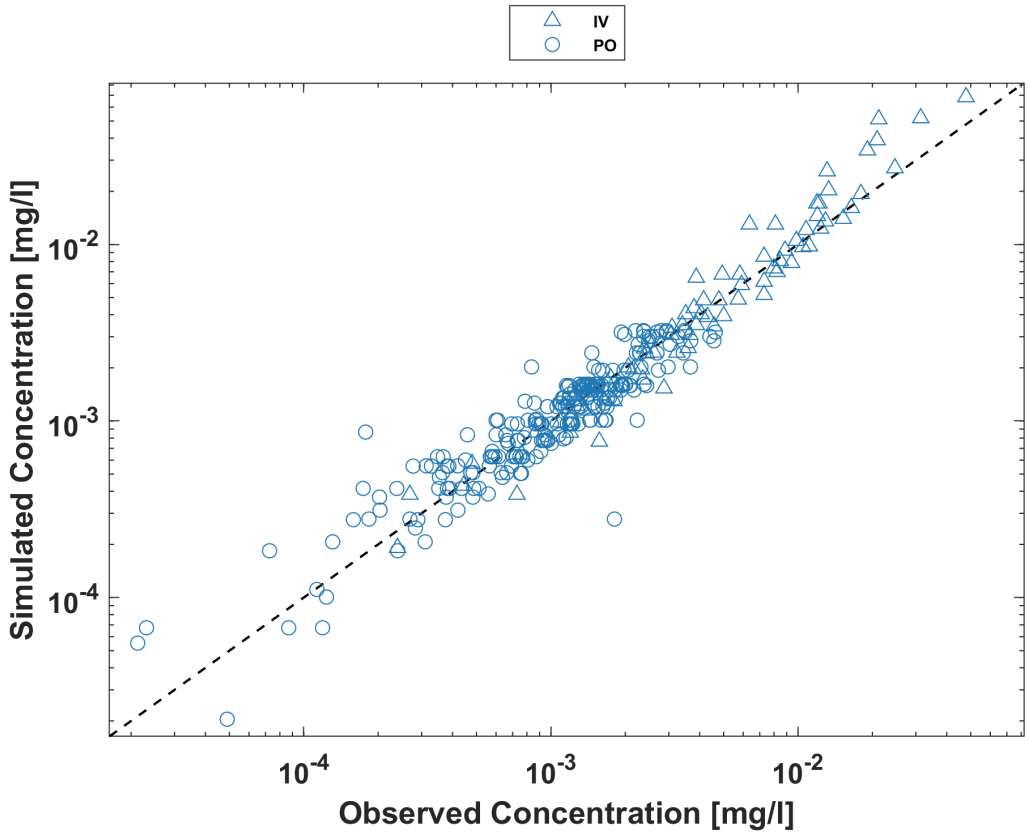
Parameters

Name	Value	Value Origin
In vitro Vmax for liver microsomes	10.27 nmol/min/mg mic. protein	Publication-In Vitro-PMID: 8632299
Km	305 µmol/l	Publication-In Vitro-PMID: 8632299
kcat	17.5448180963 1/min	Parameter Identification-Parameter Identification-Value updated from 'IV + Oral' on 2018-11-13 16:52

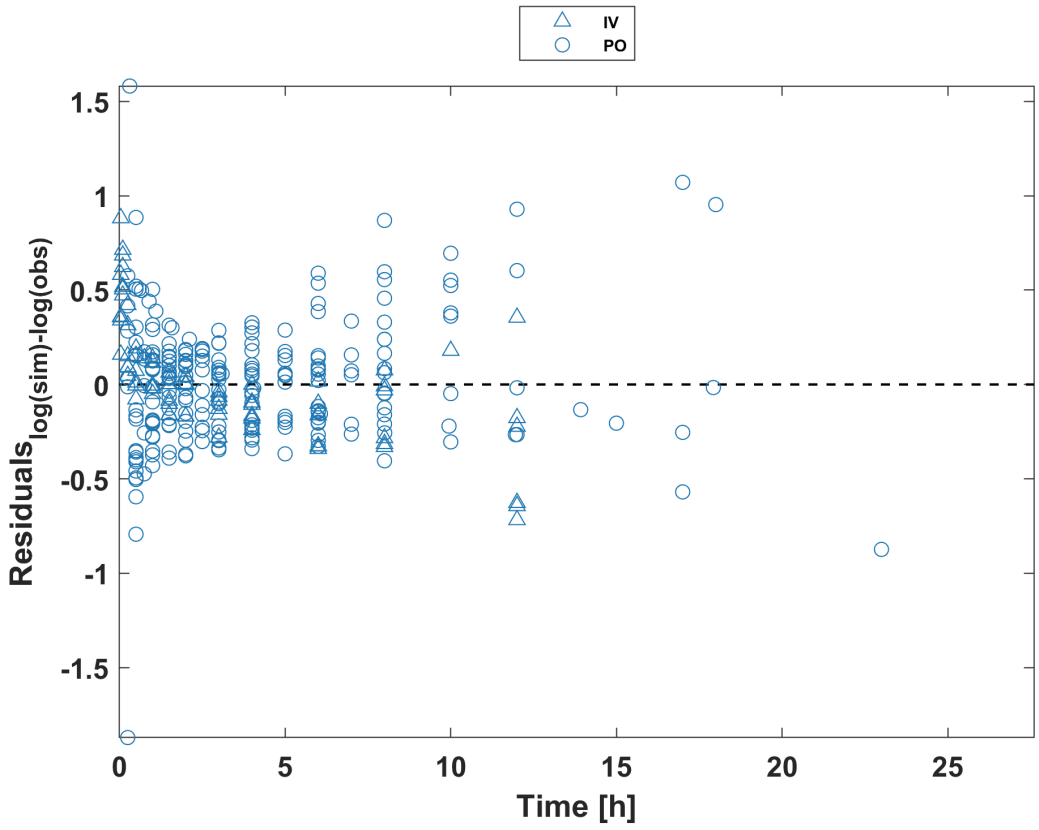
3.2 Diagnostics Plots

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.



Goodness of fit plot for concentration in plasma

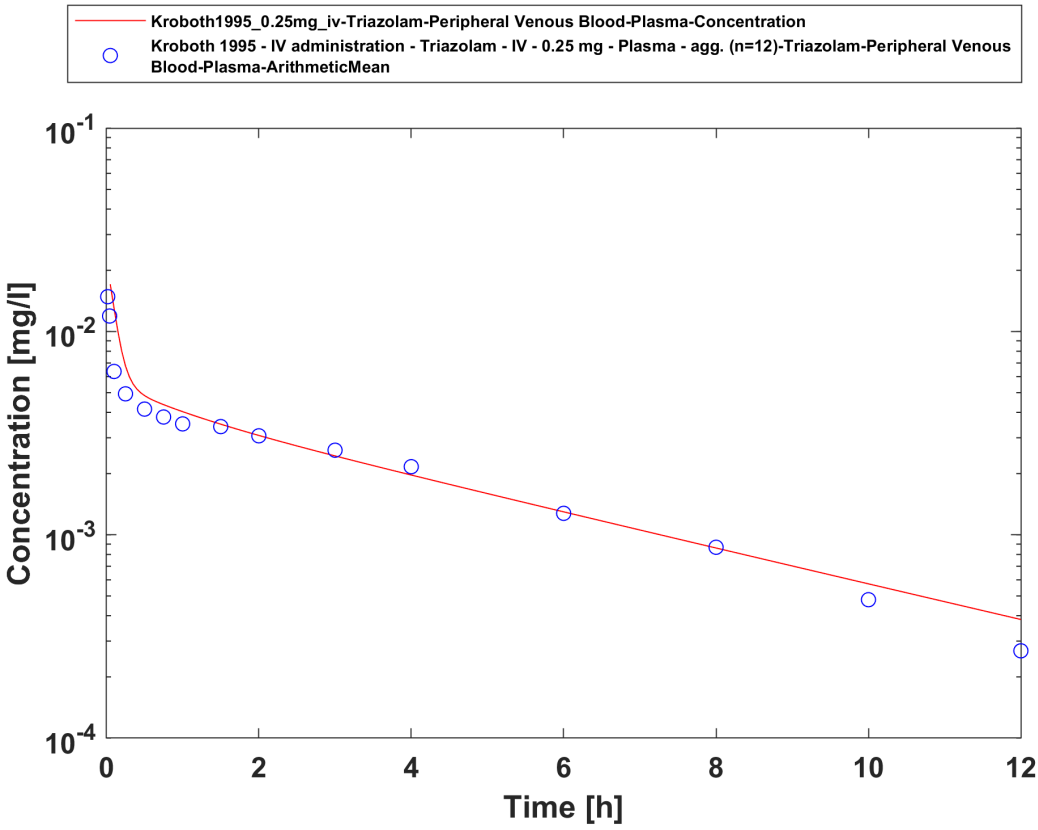


Goodness of fit plot for concentration in plasma

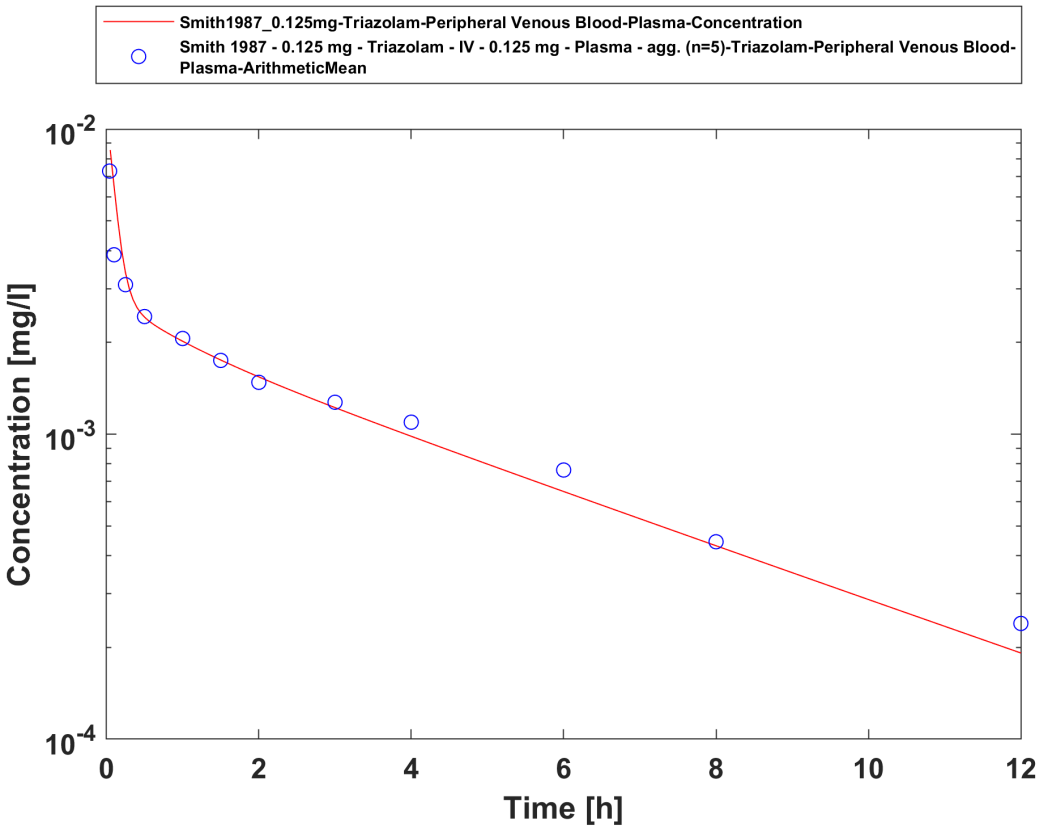
GMFE = 1.272636

3.3 Concentration-Time Profiles

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



Time Profile Analysis



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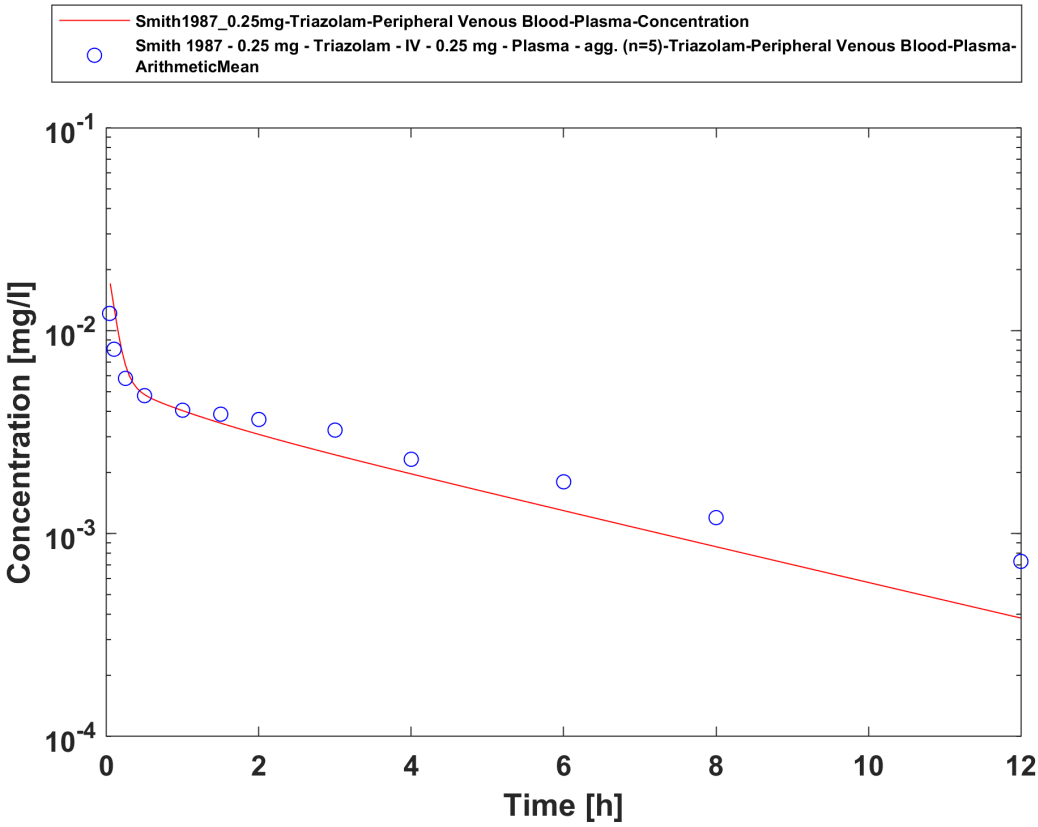
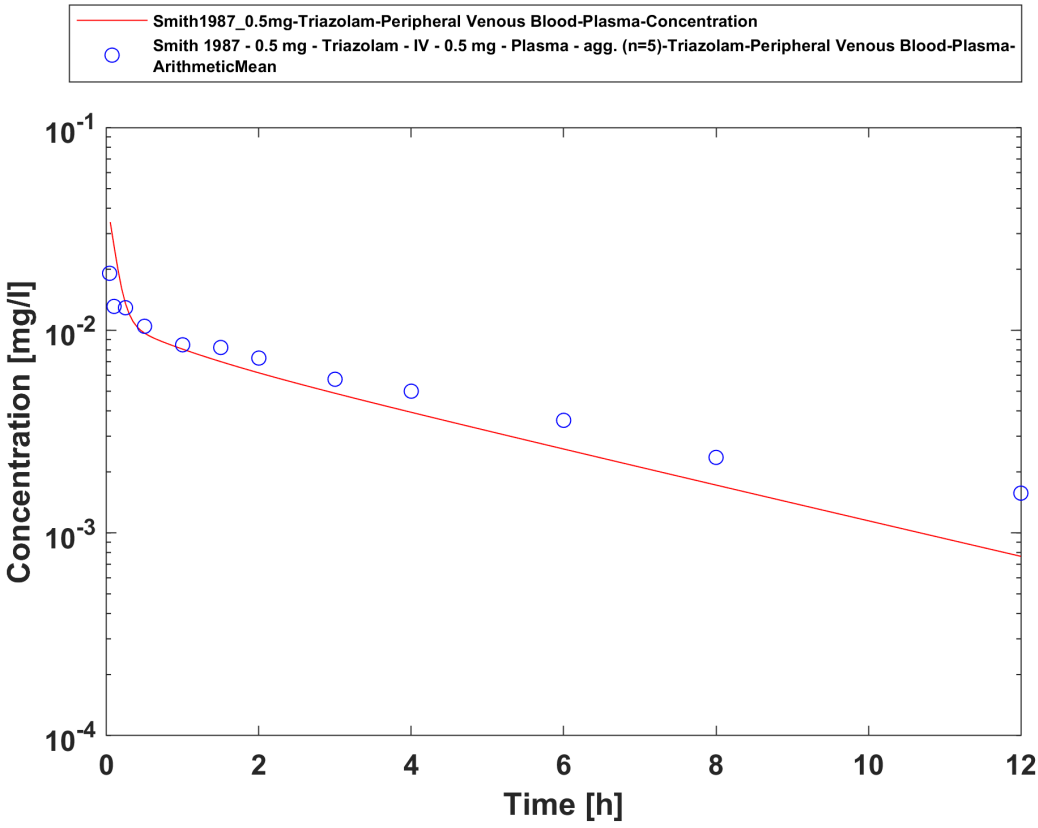
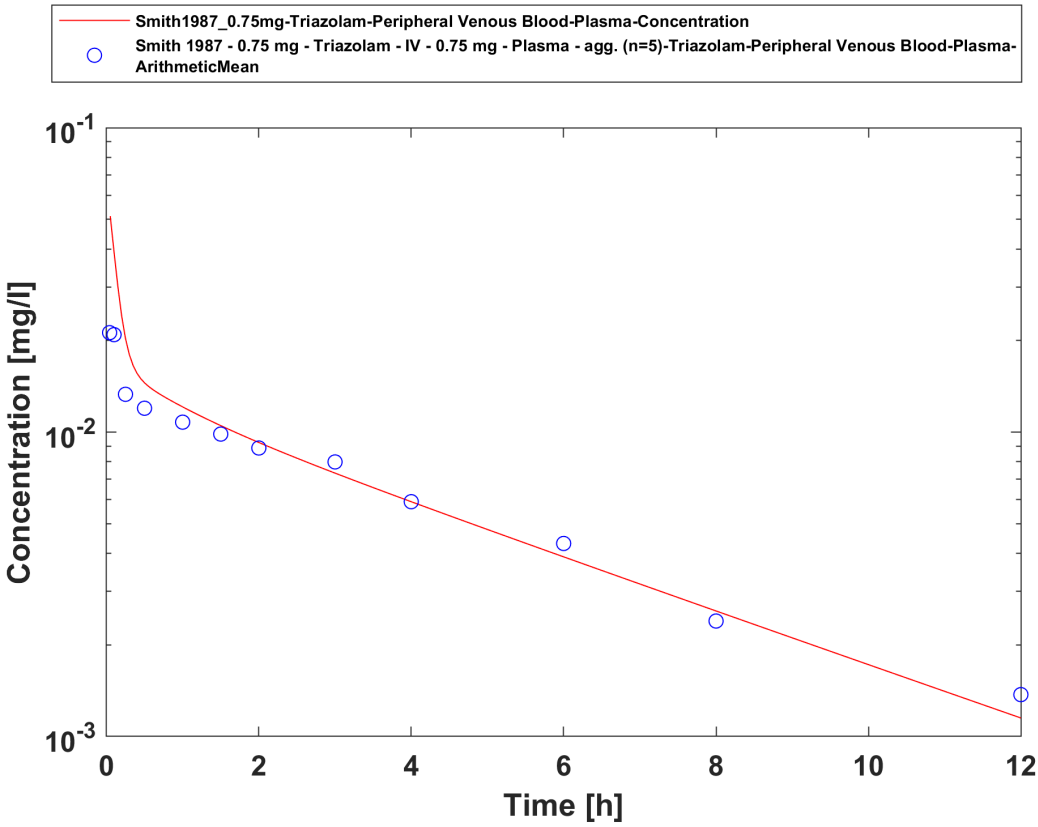


Time Profile Analysis



Time Profile Analysis



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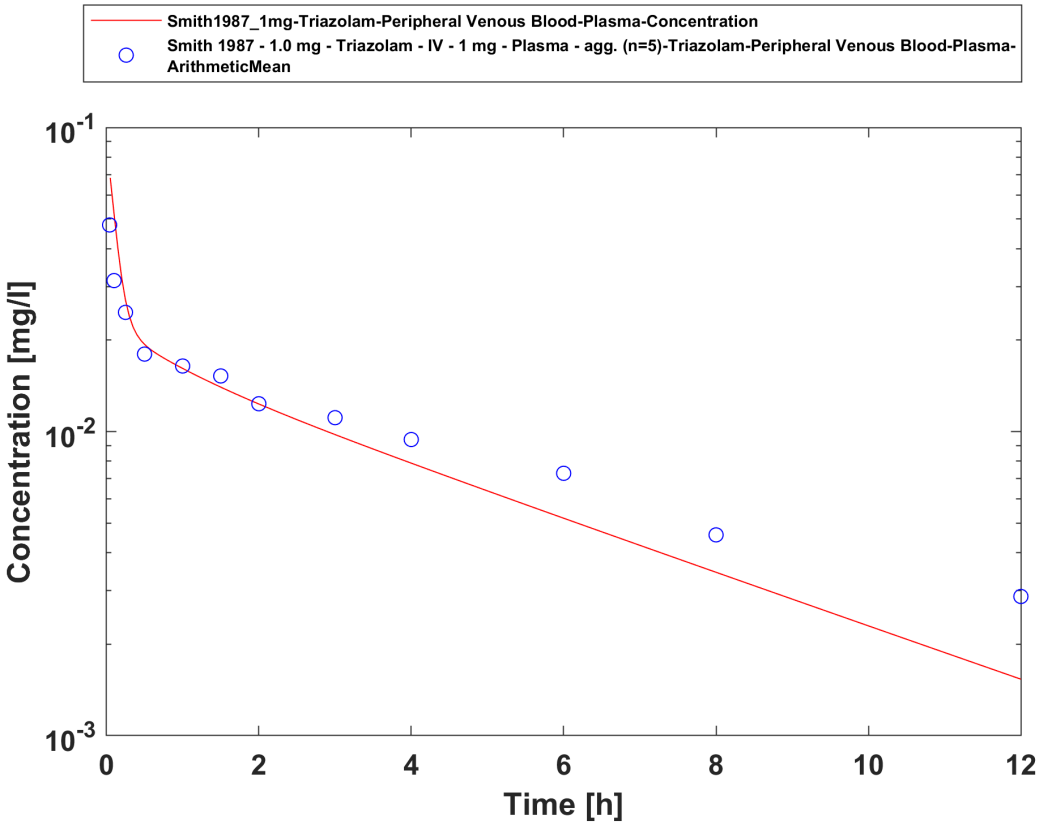

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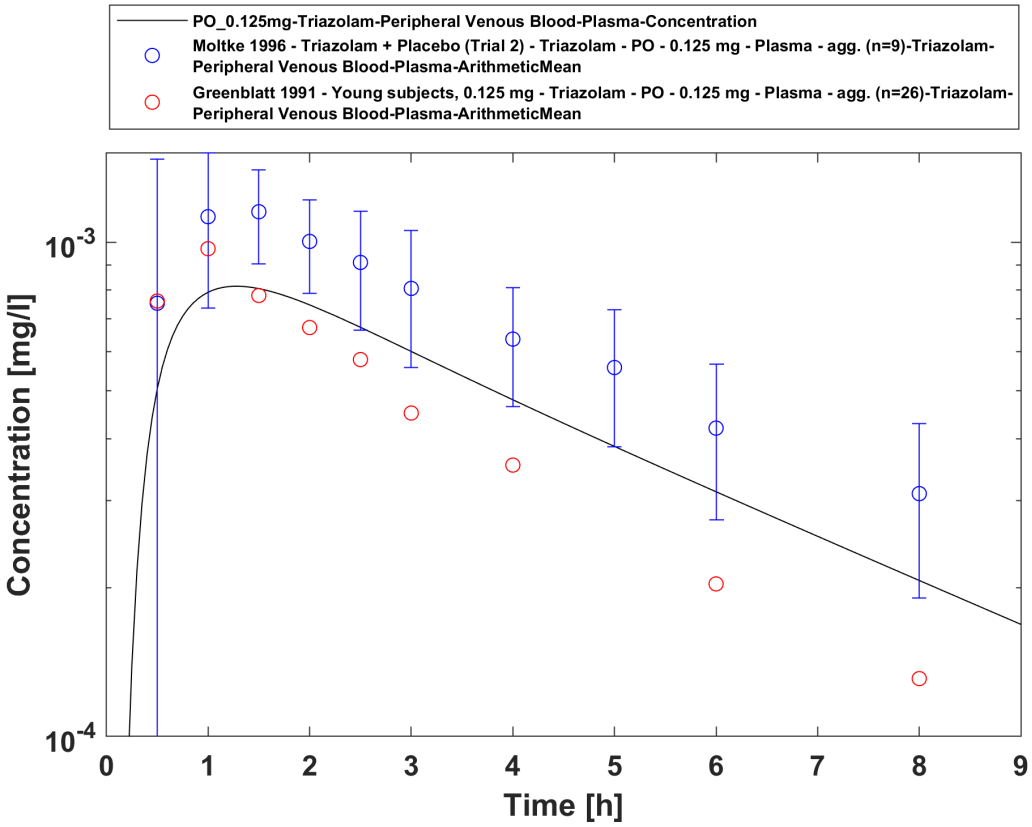
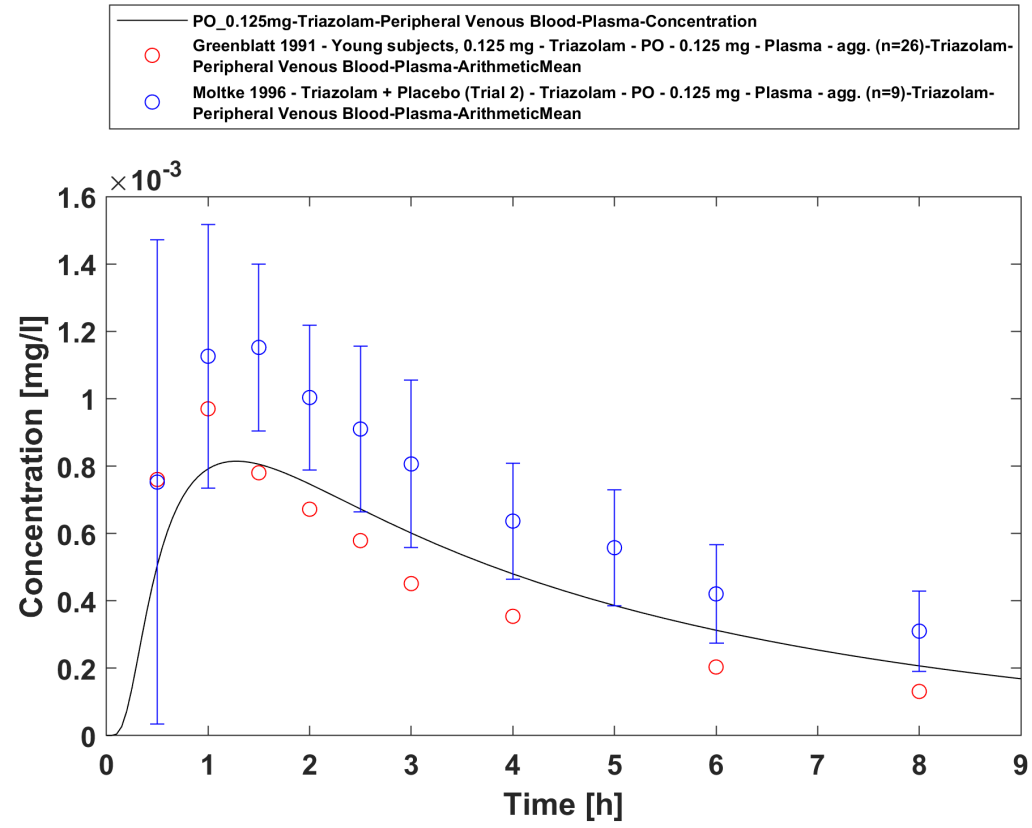
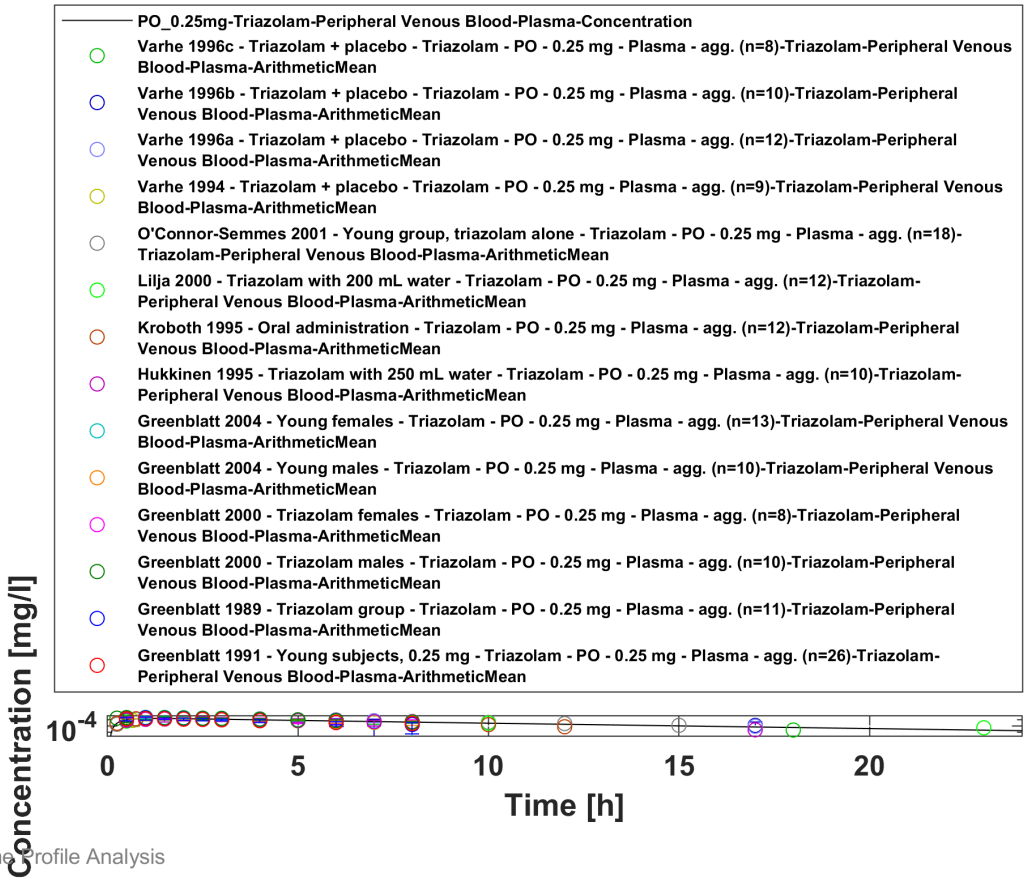


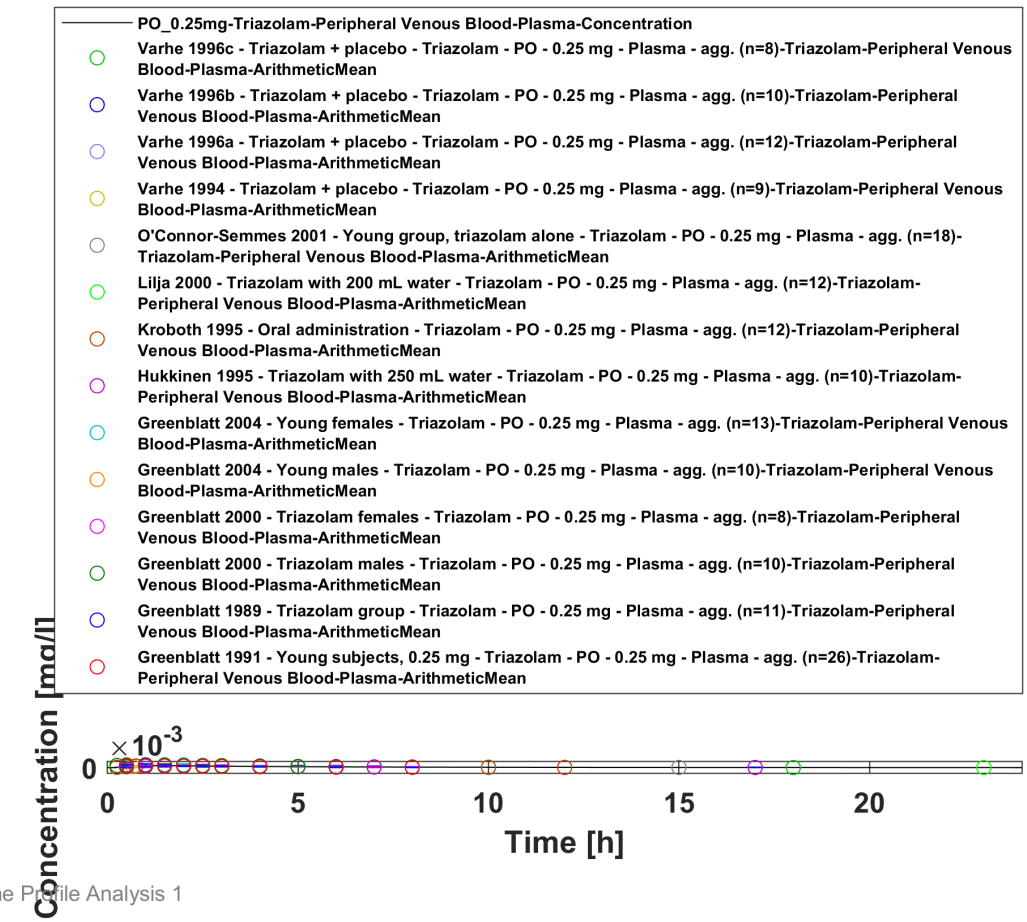
Time Profile Analysis



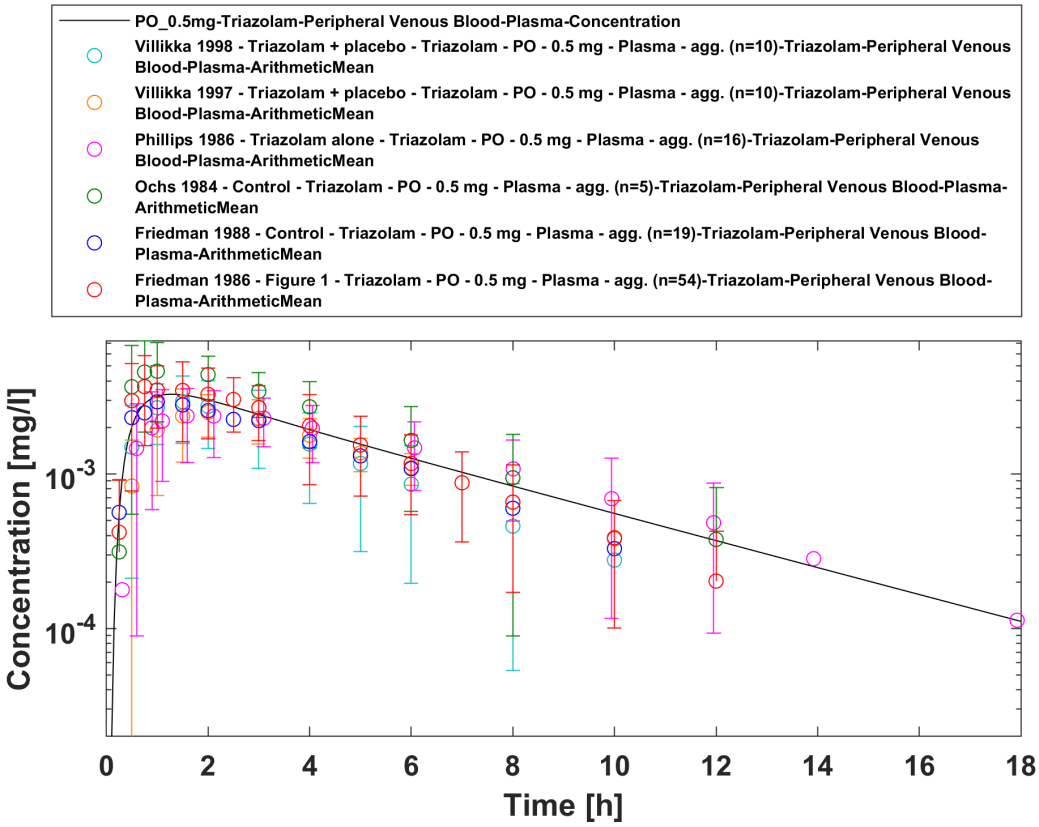
Time Profile Analysis 1



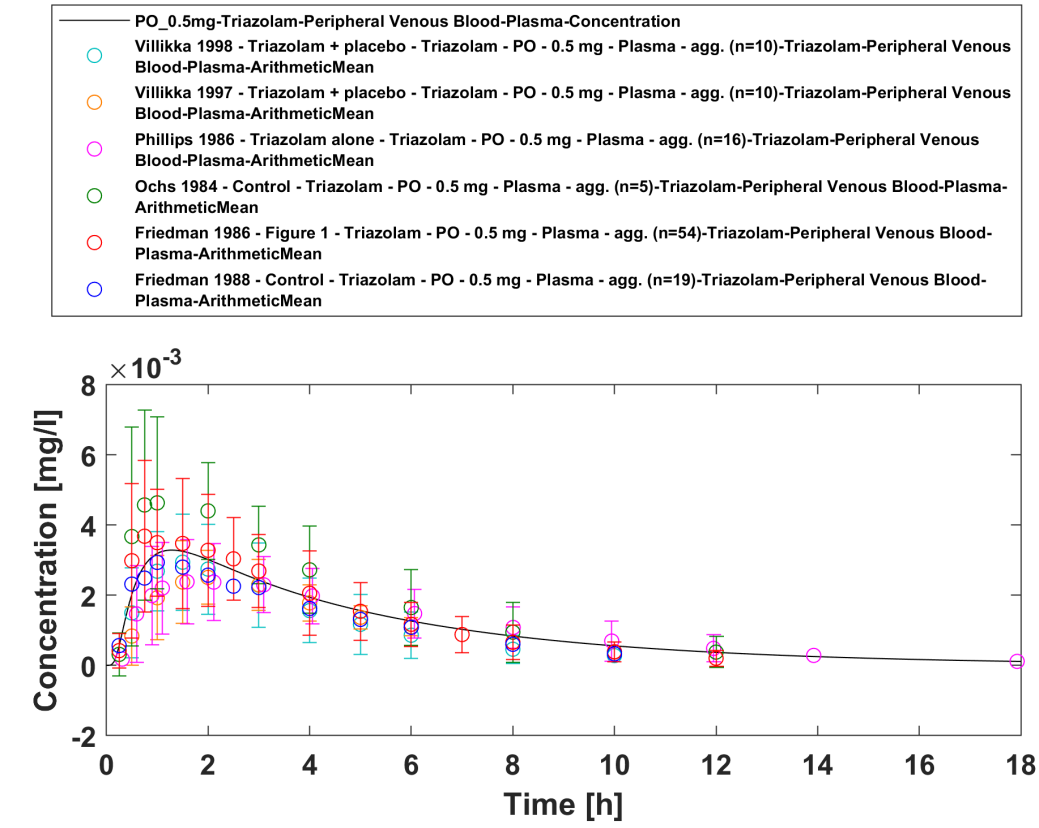
Time Profile Analysis



Time Profile Analysis 1



Time Profile Analysis



Time Profile Analysis 1

4 Conclusion

The final triazolam PBPK model applies metabolism by CYP3A4, modelled as two separate pathways yielding α-hydroxy-triazolam and 4-hydroxy-triazolam as metabolites. Overall, the model adequately describes the observed PK of triazolam in healthy, non-obese adults receiving different single IV or PO doses of triazolam.

5 References

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