Vancomycin Pharmacokinetics Throughout Life: Results from a Pooled Population Analysis and Evaluation of Current Dosing Recommendations

Pieter J. Colin1,2 · Karel Allegaert3,4,5 · Alison H. Thomson6 · Daan J. Touw7,8 · Michael Dolton9 · Matthijs de Hoog10 · Jason A. Roberts11 · Eyob D. Adane12 · Masato Yamamoto13 · Dolores Santos-Buelga14 · Ana Martin-Suarez14 · Nicolas Simon15 · Fabio S. Taccone16 · Yoke-Lin Lo17,18 · Emilia Barcia19 · Michel M. R. F. Struys1,20 · Douglas J. Eleveld1

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Abstract
Background and Objectives Uncertainty exists regarding the optimal dosing regimen for vancomycin in different patient populations, leading to a plethora of subgroup-specific pharmacokinetic models and derived dosing regimens. We aimed to investigate whether a single model for vancomycin could be developed based on a broad dataset covering the extremes of patient characteristics. Furthermore, as a benchmark for current dosing recommendations, we evaluated and optimised the expected vancomycin exposure throughout life and for specific patient subgroups.

Methods A pooled population-pharmacokinetic model was built in NONMEM based on data from 14 different studies in different patient populations. Steady-state exposure was simulated and compared across patient subgroups for two US Food and Drug Administration/European Medicines Agency-approved drug labels and optimised doses were derived.

Results The final model uses postmenstrual age, weight and serum creatinine as covariates. A 35-year-old, 70-kg patient with a serum creatinine level of 0.83 mg dL−1 (73.4 µmol L−1) has a \( V_1 \), \( V_2 \), CL and \( Q_2 \) of 42.9 L, 41.7 L, 4.10 L h−1 and 3.22 L h−1. Clearance matures with age, reaching 50% of the maximal value (5.31 L h−1 70 kg−1) at 46.4 weeks postmenstrual age then declines with age to 50% at 61.6 years. Current dosing guidelines failed to achieve satisfactory steady-state exposure across patient subgroups. After optimisation, increased doses for the Food and Drug Administration label achieve consistent target attainment with minimal (± 20%) risk of under- and over-dosing across patient subgroups.

Conclusions A population model was developed that is useful for further development of age and kidney function-stratified dosing regimens of vancomycin and for individualisation of treatment through therapeutic drug monitoring and Bayesian forecasting.

Key Points

- Current dosing recommendations fail to achieve consistent vancomycin exposure throughout life and across patient subgroups.
- This pharmacokinetic model for vancomycin adequately characterises vancomycin pharmacokinetics across a broad range of patient populations, including those at the extremes of age and weight.

1 Introduction

The glycopeptide antibiotic vancomycin plays an important role in the treatment of Gram-positive bacterial infections. It is currently considered a key therapeutic option in the context of the treatment of serious infections (e.g. community- and hospital-acquired pneumonia, complicated skin and soft-tissue infections, infective endocarditis) and for the empiric treatment of patients at high risk of infections caused by methicillin-resistant \( \text{Staphylococcus aureus} \) or multidrug-resistant \( \text{Staphylococcus epidermidis} \) \([1, 2]\).

Although vancomycin has been in clinical use since its first registration almost six decades ago, questions with respect to the optimal dosing regimen remain. Consequently, a plethora of reports on subpopulation- and context-specific pharmacokinetics and derived dosing regimens have surfaced over the last 25 years. In 2012,
these numerous population-pharmacokinetic (PK) studies led Marsot and co-workers [3] to conclude that initial dosing regimens for vancomycin should depend on creatinine clearance and body weight in adults, and creatinine clearance, body weight and age in children. The assessment report on vancomycin drug products issued in 2017 by the European Medicines Agency [1] is in line with the recommendations by Marsot and co-workers. Nevertheless, it also highlights some known unknowns. For example, the report comments that specific dosing regimens might be required for neonatal and elderly populations and for patients with renal impairment.

Besides getting the initial dose right, optimisation of vancomycin exposure entails the use of therapeutic drug monitoring (TDM), especially in populations where PK variability is large (e.g. preterm neonates, critically ill patients) [1]. Individualised dosing based on TDM data is most efficiently achieved through Bayesian forecasting of PK parameters based on an a priori population-PK model. This technology is currently offered by a range of TDM software packages [4], such as DoseMe® (DoseMe Pty Ltd., Brisbane, QLD, Australia), InsightRx® (Insight Rx Inc., San Francisco, CA, USA), MwPharm++® (Mediware a.s., Prague, Czech Republic) and DosOpt (University of Tartu, Tartu, Estonia) [5].

At present, different vancomycin population-PK models are, however, used across these software packages; and within a package often different models are used for different patient subpopulations. This poses a challenge to clinicians who have to consider the limitations of the models they utilise. Moreover, the clinician might have to switch models when treating different patient populations.

It has previously been shown that when applied to external datasets, there are wide differences in the performance of various currently used PK models [6, 7]. In anaesthesia, this has led to data-sharing initiatives with the intent of replacing different subgroup-specific models with a single pooled population-PK model [8, 9]. Such a model is expected to be more generalisable than other models, making it simpler and more useful for everyday clinical use [10].

In this study, we aimed to develop a single PK model for vancomycin, derived from a broad dataset covering the extremes of patient characteristics. Moreover, as a benchmark for current dosing recommendations, we performed simulations using the final population-PK model and evaluated the expected vancomycin exposure throughout life and for specific patient subgroups. Finally, based on these simulations optimised doses were recommended.

2 Materials and Methods

2.1 Component Datasets

Studies on vancomycin pharmacokinetics were identified through a PubMed search (until 27 September, 2017) using search terms: “vancomycin AND population AND pharmacokinetics [Title/Abstract]” OR “vancomycin AND pharmacokinetics [Title/Abstract]”. We excluded studies of patients receiving continuous renal replacement therapy, haemodialysis, haemodiafiltration, extracorporeal membrane oxygenation and non-intravenous administration of vancomycin. Corresponding or senior authors from these studies were invited to contribute their anonymised data and participate in this modelling study. All studies obtained necessary institutional review board approval, as declared in the original papers or as declared by the corresponding or senior author (personal communication).

Postmenstrual age (PMA), postnatal age (PNA), weight, height and serum creatinine (SCR) were extracted from the datasets. Postmenstrual age for patients other than neonates was assumed to be 40 weeks longer than the recorded postnatal age (years). Missing values for SCR were imputed as the population median SCR from that study. Missing values for height were imputed as the population median height from that study or from a similar study (for neonatal studies with missing height) or with height data from a national health survey in that specific population.

Questionable covariate data were corrected whenever possible. These primarily concern overlapping drug infusion records and unrealistic combinations of age, weight and height within a subject. To avoid computational difficulties during model building due to excessively long follow-up times, the dataset was restricted to observations from the first 31 days of therapy.

2.2 Population-Pharmacokinetic Modelling

The vancomycin concentration vs. time data were fitted using the FOCE-I estimation algorithm in NONMEM® (Version 7.3; GloboMax LLC, Hanover, MD, USA). The “tidyverse” package (Version 1.1.1.; Wickham H. 2017) in R® (R Foundation for Statistical Computing, Vienna, Austria) was used to graphically assess the goodness of fit and for simulations.

As a starting point, one-, two- and three-compartmental PK models were fitted to the data. Inter-individual variability on the typical population parameter estimates was assumed to be log-normally distributed. Residual unexplained variability was modelled using a combined proportional and additive error model. Inter-occasion variability...
was not tested in the model owing to difficulties in defining an occasion in the context of this dataset where dosing and sampling times/frequency vary considerably.

Modifications to the structural and/or covariate model were accepted only if they resulted in a decrease in the objective function value (OFV) and an increased in-sample predictive performance. A decrease in OFV was judged statistically significant if inclusion of an additional parameter decreased the OFV by more than 3.84 points. As a measure of in-sample prediction performance, the absolute relative prediction errors (APEs) were calculated (Eq. 1) by comparing the measured vancomycin concentrations for each individual $i$ at time point $j$ ($\text{VAN}_{ij}$) with the population-predicted concentrations (PRED). The median of the distribution of APEs (MdAPE) was used to compare the imprecision of candidate models during model building and to compare the final model against earlier published models.

$$\text{APE}(\%) = \left| \frac{\text{VAN}_{ij} - \text{PRED}_{ij}}{\text{PRED}_{ij}} \right| \times 100\%.$$  

To ascertain that model building was not driven by the most populated subgroup, we stratified the calculation of the prediction error. The following subgroups were created: pre-term and term newborns (PMA < 0.87 years), children and adolescents (age < 18 years), adults (age < 65 years), elderly (age > 80 years), very elderly (age ≥ 80 years), underweight (BMI < 18.5 kg m$^{-2}$) and obese adults (BMI > 30 kg m$^{-2}$). During model building, the average MdAPE across the aforementioned subgroups was taken as an overall measure of predictive performance. Covariates tested for inclusion in the model were: weight (kilograms), PMA (years), PNA (days), SCR (mg dL$^{-1}$), sex, critical illness and presence of severe burn injuries. Height and related covariates such as body mass index and fat-free mass were not tested as height was missing in most neonates and some adults.

2.3 A Priori Included Covariate Models

In line with earlier work by Holford et al. [11] and Germovsek et al. [12, 13] prior to inclusion of additional covariates in the model we corrected for size and maturational changes. For this, PK parameters were scaled to weight according to allometric theory [14], with an exponent of 1 for volume terms ($V_1, V_2, V_3$) and an exponent of 0.75 for clearance terms ($CL, Q_2, Q_3$). A sigmoidal maturation function was used to scale clearance with PMA according to Eq. 2 with $\gamma$ defining the steepness of the non-linear relationship and $PMA_{50}$ being the PMA when clearance reaches 50% of maximal values.

$$\text{Maturation function} = \frac{PMA^{\gamma}}{PMA^{\gamma} + PMA_{50}^{\gamma}}.$$  

2.4 Testing Serum Creatinine as a Covariate in the Model

The influence of SCR on clearance was tested using an exponential function as shown in Eq. 3. This function predicts decreasing clearance with increasing SCR values with $\theta_{\text{SCR}}$ defining the steepness of the relationship. Serum creatinine was included in the dataset as a time-varying covariate with backward constant interpolation between observations.

$$F_{\text{Scr}} = e^{(-\theta_{\text{SCR}} \times (\text{SCR} - \text{SCR}_{\text{std}}))}.$$  

Parameter values were standardised by centering SCR observations according to a standardised SCR ($\text{SCR}_{\text{std}}$) value. Different approaches for defining $\text{SCR}_{\text{std}}$ were compared. A first approach consisted of using the median observed SCR from the dataset. Other approaches were explored in an effort to derive age-, weight- and sex-adjusted $\text{SCR}_{\text{std}}$ values. For this, empiric functions were fitted to the covariate data using fractional polynomial regression (R package “mfp: Multivariable Fractional Polynomials”; Version 1.5.2) in line with the work of Ceriotti et al. [15], or custom non-linear models in R$^8$.

2.5 Evaluation and Optimisation of Current Dosing Recommendations

As examples of contemporary dosing guidelines for vancomycin approved by the European Medicines Agency and the US Food and Drug Administration (FDA), we used the summary of product characteristics (SmPC) for “Vancomycin 500 mg Powder for Solution for Infusion” (Consilient Health Ltd; available from www.medicines.org.uk; consulted on 23 May, 2018) and the label for “Vancomycin Hydrochloride for Injection USP” (ANI Pharmaceuticals, Inc.; available from www.fda.gov; consulted on 23 May, 2018). The posologies outlined by the SmPC and the FDA label are summarised in Tables S1 and S2 of the Electronic Supplementary Material (ESM), respectively.

Steady-state vancomycin exposure was simulated using the post hoc-predicted clearance for all patients in our data-set according to Eq. 4:

$$\text{AUC}_{24\text{h}} = \frac{\text{DOSE} \times 24}{CL^2},$$  

where $\text{AUC}_{24\text{h}}$ is the area under the concentration–time curve for a 24-h period in steady state and $\text{DOSE}$ and $\tau$ are the amount of vancomycin administered and the dosing interval, respectively. The predicted $\text{AUC}_{24\text{h}}$ was then used to calculate the proportion of patients who were under- and over-dosed. Under-dosing was assumed when the $\text{AUC}_{24\text{h}}$ was below 400 mg L$^{-1}$ h, a frequently cited threshold for
efficacy [16, 17] for the treatment of pathogens with a minimum inhibitory concentration of 1 mg L\(^{-1}\). Over-dosing was defined as an AUC\(_{24h}\) exceeding 700 mg L\(^{-1}\) h, a recently advocated safety threshold for renal toxicity [18].

In the final part of this study, we attempted to optimise the daily doses in the SmPC and the FDA label. For this, in line with the above, post hoc-predicted clearance for all patients was used to predict the proportion of patients achieving an AUC\(_{24h}\) above 400 mg L\(^{-1}\) h and below 700 mg L\(^{-1}\) h \(f_{\text{Target}}\). A non-linear optimisation routine based on the Nelder-Mead Simplex [19] as implemented in R\(^\circ\) (R package “nloptr”; Version 1.0.4) was used to optimise \(f_{\text{Target}}\) using the doses in the SmPC and the label as control variables. For practical purposes, optimised daily doses were rounded to the nearest 50 mg and 0.5 mg kg\(^{-1}\).

3 Results

3.1 Data

In total, 39 publications were identified. All senior and/or corresponding authors for these publications were contacted via e-mail on multiple occasions. We obtained 14 previously published data sets [20–33]. Our pooled dataset contains information across a broad range of patient subgroups ranging from premature neonates [20, 24, 30, 32] to extremely obese patients [26] and from adult Japanese healthy volunteers [27] to critically ill and trauma patients [25, 31, 33]. A summary of the included studies is shown in Table 1. The distributions of patient characteristics and vancomycin concentrations are shown in Fig. S1 of the ESM. In total, 8300 vancomycin drug concentrations from 2554 individuals were included in the dataset. Individuals were adults (720), newborns (559), elderly patients (512), obese adults (274), children and adolescents (118).

Initial analysis of the dataset identified outliers \((n = 10)\). The data for these individuals were primarily biased because of missing dosing information prior to the first observation, potential sampling errors (e.g. reported vancomycin concentrations > 100 mg L\(^{-1}\)) or dosing regimens that were significantly different from other comparable individuals from the same study. Because of the small number of outliers identified (0.4% of individuals), we decided to remove these patient records from the dataset.

3.2 Population-Pharmacokinetic Modelling

We found that a two-compartment model better described the data compared with a one-compartment model \((\Delta\text{OFV} = -1155)\). A three-compartment model had a lower OFV \((\Delta\text{OFV} = -85)\). However, goodness-of-fit plots for both models were indistinguishable and likelihood profiling [34] revealed high uncertainty on the estimate for the inter-compartmental clearance to the slow peripheral compartment \((Q3)\). Therefore, we decided to retain the two-compartment model as the final model.

We found significant maturation in vancomycin clearance, with 50% of maximal clearance being reached by 46.4 weeks PMA (PMA\(_{50}\)). After correcting for maturation, it became apparent that vancomycin clearance deteriorates with ageing. The sigmoidal function fitted to describe the declining clearance with age revealed that 50% of maximal clearance is lost by 61.6 years PMA (AGE\(_{50}\)). Figure 1 shows the typical-for-PMA standardised clearance (L h\(^{-1}\) 70 kg\(^{-1}\)) for all patients in our dataset. Figure 1 also shows the maturation–decline function as estimated by Lonsdale et al. [35] in a recent pooled analysis of three commonly used beta-lactam antibiotics.

After accounting for size- and age-related changes in vancomycin pharmacokinetics, we tested the influence of SCR on clearance according to Eq. 3. Table 2 provides an overview of the different model building steps and shows the different approaches taken to define SCR\(_{\text{std}}\). When the median observed SCR (0.80 mg dL\(^{-1}\) or 70.7 µmol L\(^{-1}\)) is used as SCR\(_{\text{std}}\), the lowest OFV is obtained \((\Delta\text{OFV} = -1810)\). However, this approach led to an increase in the estimates for PMA\(_{50}\) and AGE\(_{50}\). A fractional polynomial model relating SCR\(_{\text{std}}\) to PNA, gestational age, weight and sex performed less well \((\Delta\text{OFV} = -1692)\). However, standardisation of SCR values using this approach had no influence on the estimates for PMA\(_{50}\) and AGE\(_{50}\). Ultimately, we found that the empiric function producing the lowest OFV with the least influence on the estimates for PMA\(_{50}\) and AGE\(_{50}\) was a non-linear function relating SCR\(_{\text{std}}\) to PMA (Eq. 5).

\[
\text{SCR}_{\text{std}} = e^{-1.228+\log_{10}(\text{PMA}(\text{yr}))\times0.672+6.27e^{-3.11\times\text{PMA}(\text{yr})}}. \tag{5}
\]

A plot of the predicted SCR\(_{\text{std}}\) as a function of PMA is shown in Fig. S2 of the ESM. Figure S2 also shows the SCR\(_{\text{std}}\) used in the work of Johansson et al. [36] and Hennig et al. [37], which is based on the reference intervals reported by Ceriotti et al. [15] and Junge et al. [38] When we implemented the latter approach, we found a similar decrease in OFV compared to our best performing function \((\Delta\text{OFV} = -1790 \text{ vs. } -1805, \text{ respectively})\). However, as seen in Table 2, under this approach the estimates for PMA\(_{50}\) and AGE\(_{50}\) slightly increase (+1.8 weeks and +4.1 years, respectively). Furthermore, as seen in Fig. S2 of the ESM, the predicted SCR\(_{\text{std}}\) does not align well with the median of our observed SCR values. Therefore, we decided to include the empiric function described in Eq. 5 in our final model. The inclusion of SCR decreased in-sample MdAPEs for all subgroups ranging from –0.7% for children and adolescents.
Table 1  Details of the component datasets. The distribution of patient covariates is summarised by the median and the range; the percentage of missing values is shown in square brackets

<table>
<thead>
<tr>
<th>Dataset</th>
<th>N</th>
<th>Patients Inclusion</th>
<th>% Male</th>
<th>PMA (y)a,e</th>
<th>PNA (d)c</th>
<th>Weight (kg)c</th>
<th>Height (m)</th>
<th>SCR (mg dL−1)f</th>
<th>No. of samples</th>
<th>No. of dosesb</th>
</tr>
</thead>
<tbody>
<tr>
<td>Allegaert et al. [11]</td>
<td>247</td>
<td>Premature neonates</td>
<td>2002–2006</td>
<td>54.7</td>
<td>0.60 (0.46–0.71)</td>
<td>11 (1–27)</td>
<td>1.20 (0.42–2.63)</td>
<td>0.37 (0.26–0.48)</td>
<td>0.73 (0.39–2.12)</td>
<td>2 (1–9)</td>
</tr>
<tr>
<td>Thomson et al. [12]</td>
<td>496</td>
<td>Adult patients</td>
<td>1991–2007</td>
<td>39.3</td>
<td>67.8 (16.8–97.8)</td>
<td>–</td>
<td>70.0 (35.0–159)</td>
<td>1.70 (1.42–1.98)</td>
<td>1.10 (0.34–6.48)</td>
<td>3 (1–19)</td>
</tr>
<tr>
<td>van der Meer et al. [13]</td>
<td>389</td>
<td>Paediatric, adult and elderly patients</td>
<td>2001–2010</td>
<td>55.8</td>
<td>65.9 (2.58–97.8)</td>
<td>–</td>
<td>70.0 (8.70–160)</td>
<td>1.70 (0.70–2.02)</td>
<td>0.79 (0.15–9.75)</td>
<td>2 (1–16)</td>
</tr>
<tr>
<td>Dolton et al. [14]</td>
<td>70</td>
<td>Adult patients with/without burn injuries</td>
<td>2000–2007</td>
<td>78.6</td>
<td>52.8 (15.8–95.8)</td>
<td>–</td>
<td>68.0 (42.5–116)</td>
<td>1.70 (1.55–1.80)</td>
<td>0.64 (0.24–6.11)</td>
<td>3 (1–32)</td>
</tr>
<tr>
<td>de Hoog et al. [15]</td>
<td>130</td>
<td>Premature neonates</td>
<td>1992–1997</td>
<td>54.6</td>
<td>0.60 (0.51–0.84)c</td>
<td>13 (3–27)</td>
<td>1.07 (0.51–4.41)</td>
<td>[100%]</td>
<td>0.57 (0.26–2.04)</td>
<td>2 (2–3)</td>
</tr>
<tr>
<td>Roberts et al. [16]</td>
<td>204</td>
<td>Adult septic critically ill patients</td>
<td>2008–2009</td>
<td>62.2</td>
<td>59.8 (18.8–86.8)</td>
<td>–</td>
<td>74.5 (35.0–140)</td>
<td>1.70 (1.53–1.90)</td>
<td>0.75 (0.20–4.4)</td>
<td>3 (1–3)</td>
</tr>
<tr>
<td>Adane et al. [17]</td>
<td>29</td>
<td>Extremely obese patients</td>
<td>2012–2013</td>
<td>65.5</td>
<td>46.8 (24.8–71.8)</td>
<td>–</td>
<td>148 (111–282)</td>
<td>1.78 (1.50–1.96)</td>
<td>1.00 (0.60–1.40)</td>
<td>3 (2–7)</td>
</tr>
<tr>
<td>Yamamoto et al. [18]</td>
<td>106</td>
<td>Adult Japanese patients and healthy controls</td>
<td>2004–2005</td>
<td>66.0</td>
<td>67.1 (20.8–100)</td>
<td>–</td>
<td>50.8 (28.6–97.0)</td>
<td>[100%]</td>
<td>0.70 (0.20–2.60)</td>
<td>2.5 (1–16)</td>
</tr>
<tr>
<td>Revilla et al. [19]</td>
<td>190</td>
<td>Adult Spanish ICU patients</td>
<td>1999–2004</td>
<td>65.8</td>
<td>65.8 (18.8–85.8)</td>
<td>–</td>
<td>70.5 (45.0–150)</td>
<td>1.67 (1.45–1.85)</td>
<td>1.00 (0.60–7.21)</td>
<td>2 (1–19)</td>
</tr>
<tr>
<td>Buelga et al. [20]</td>
<td>286</td>
<td>Adult Spanish patients with haematological malignancies</td>
<td>1989–1999</td>
<td>61.1</td>
<td>54.3 (15.8–84.8)</td>
<td>–</td>
<td>64.0 (41.0–100)</td>
<td>1.63 (1.44–1.85)</td>
<td>0.86 (0.40–3.00)</td>
<td>3 (1–12)</td>
</tr>
<tr>
<td>Oudin et al. [21]</td>
<td>67</td>
<td>Neonates and pediatric patients</td>
<td>2006–2008</td>
<td>61.1</td>
<td>0.60 (0.52–0.88)</td>
<td>13 (4–95)</td>
<td>1.06 (0.68–4.45)</td>
<td>[100%]</td>
<td>0.60 (0.20–3.12)</td>
<td>2 (1–6)</td>
</tr>
<tr>
<td>Cristallini et al. [22]</td>
<td>107</td>
<td>Adult critically ill patients</td>
<td>2012–2013</td>
<td>72.0</td>
<td>59.8 (18.8–89.8)</td>
<td>–</td>
<td>75.0 (40.0–142)</td>
<td>1.75 (1.50–1.92)</td>
<td>0.90 (0.20–4.70)</td>
<td>3 (2–3)</td>
</tr>
<tr>
<td>Lo et al. [23]</td>
<td>116</td>
<td>Premature Malaysian neonates</td>
<td>1999–2005</td>
<td>56.9</td>
<td>0.55 (0.45–0.65)</td>
<td>5 (1–39)</td>
<td>0.90 (0.50–2.00)</td>
<td>[100%]</td>
<td>0.88 (0.33–1.62)</td>
<td>6 (2–27)</td>
</tr>
<tr>
<td>Medellín-Garibay et al. [24]</td>
<td>117</td>
<td>Spanish trauma patients</td>
<td>2010–2013</td>
<td>44.4</td>
<td>77.8 (37.8–101)</td>
<td>–</td>
<td>71.0 (38.0–110)</td>
<td>1.60 (1.40–1.82)</td>
<td>0.74 (0.25–2.00)</td>
<td>2 (1–16)</td>
</tr>
</tbody>
</table>

ICU intensive care unit, PMA postmenstrual age, PNA postnatal age, SCR serum creatinine

aPMA in years was derived from the datasets or assumed to be PNA plus gestational age with a default of 40 wk for subjects with missing gestational age

bNumber of doses prior to the first plasma sample

cPMA in this study was missing but was assumed to be equal to postconceptual age

dIn this study, all patients received a loading dose followed by a continuous infusion

eCovariate values at the time of inclusion into the study are shown, during the modelling these covariates were considered to be time varying and their entire time course was taken into account
to $-10.2\%$ in elderly patients. Inclusion of SCR as a baseline covariate rather than a time-varying covariate was significantly worse ($\Delta$OFV = +876).

At this step in model development, we tested compartmental allometry for clearance and $Q_2$, scaling them allometrically to the estimated size of the corresponding compartment ($V_1$ and $V_2$). In line with earlier work on propofol [8], remifentanil [9] and dexmedetomidine [39], compartmental allometry improved the goodness of fit ($\Delta$OFV = −212) without disturbing the interpretation of the fixed-effect parameters in the models.

Altered pharmacokinetics was observed in two composite datasets. On the one hand, in the study by Buelga and co-workers on patients with haematological malignancies [29], clearance was significantly higher (+29.4%). On the other hand, the study by Lo and co-workers [32], who used heel-prick sampling as opposed to arterial/venous sampling, we found a lower $V_1$ ($-31.2\%$) and $Q_2$ ($-59.7\%$). Accounting for these subgroup-specific effects resulted in a better fit ($\Delta$OFV = −184 and −115, respectively).

To achieve adequate numeric stability of the model, i.e. smooth gradient minimisation and acceptable likelihood profiles, we removed the estimate for the population variability on $Q_2$ ($\Delta$OFV = +5.0).

The final population-PK model is shown in Eqs. 6–13 and Table 3, the NONMEM output for the final model is shown in the ESM.

$$
\text{CL} (\text{L h}^{-1} \text{70 kg}^{-1}) = \theta_{\text{CL}} \times \left( \frac{V_1}{\theta_{v_1}} \right)^{0.75} \times F_{\text{Mat}} \times F_{\text{Decline}} \\
	imes F_{\text{SCR}} \times (1 + \theta_{\text{STDY10}}) \times e^{\eta_i} \tag{6}
$$

$$
V_1 (L) = \theta_{v_1} \times (F_{\text{Size}})^{1} \times (1 - \theta_{\text{STDY13}, V1}) \times e^{\eta_i} \tag{7}
$$

$$
V_2 (L) = \theta_{v_2} \times (F_{\text{Size}})^{1} \times e^{\eta_i} \tag{8}
$$

$$
Q_2 (\text{L h}^{-1}) = \theta_{q2} \times \left( \frac{V_2}{\theta_{v_2}} \right)^{0.75} \times (1 - \theta_{\text{STDY13}, Q2}) \tag{9}
$$

$$
F_{\text{Size}} = \frac{\text{WGT} (\text{kg})}{70} \tag{10}
$$
### Table 2 Model building hierarchy

<table>
<thead>
<tr>
<th>No.</th>
<th>Ref.</th>
<th>Description</th>
<th>OFV</th>
<th>ΔOFV</th>
<th>PMA50 (wk)</th>
<th>γ1</th>
<th>AGE50 (y)</th>
<th>γ2</th>
<th>IIV CL (%)</th>
<th>IIV V1 (%)</th>
<th>IIV Q2 (%)</th>
<th>IIV V2 (%)</th>
<th>MdAPE (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Allometry + maturation</td>
<td>36,846</td>
<td>–</td>
<td>32.8</td>
<td>4.44</td>
<td>–</td>
<td>–</td>
<td>58.0</td>
<td>34.6</td>
<td>66.3</td>
<td>151</td>
<td>39.0</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>1</td>
<td>PMA as a covariate on CL (F_{\text{Decline}}); Eq. 12</td>
<td>36,150</td>
<td>–</td>
<td>696</td>
<td>44.2</td>
<td>3.29</td>
<td>66.0</td>
<td>2.66</td>
<td>47.7</td>
<td>33.9</td>
<td>65.3</td>
<td>146</td>
</tr>
<tr>
<td>3</td>
<td>2</td>
<td>SCR on CL (Eq. 13) with SCR(_{\text{std}})=0.80 mg dL(^{-1}) ((70.7 \mu\text{mol L}^{-1}))</td>
<td>34,340</td>
<td>–</td>
<td>1810</td>
<td>52.5</td>
<td>2.28</td>
<td>79.8</td>
<td>3.22</td>
<td>34.6</td>
<td>34.3</td>
<td>66.5</td>
<td>122</td>
</tr>
<tr>
<td>4</td>
<td>2</td>
<td>SCR on CL (Eq. 13) with SCR(_{\text{std}}) as a nonlinear function of PMA</td>
<td>34,345</td>
<td>–</td>
<td>1805</td>
<td>44.7</td>
<td>3.32</td>
<td>67.4</td>
<td>2.77</td>
<td>34.7</td>
<td>34.7</td>
<td>62.2</td>
<td>123</td>
</tr>
<tr>
<td>5</td>
<td>2</td>
<td>SCR on CL (Eq. 13) with SCR(_{\text{std}}) according to Johansson et al.(^\text{36})</td>
<td>34,360</td>
<td>–</td>
<td>1790</td>
<td>46.5</td>
<td>2.77</td>
<td>71.5</td>
<td>2.34</td>
<td>34.9</td>
<td>34.1</td>
<td>67.9</td>
<td>121</td>
</tr>
<tr>
<td>6</td>
<td>2</td>
<td>SCR on CL (Eq. 13) with SCR(_{\text{std}}) as a fractional polynomial equation of PNA, GA, WGT, M1F2</td>
<td>34,458</td>
<td>–</td>
<td>1692</td>
<td>45.2</td>
<td>3.16</td>
<td>67.4</td>
<td>2.94</td>
<td>35.9</td>
<td>33.4</td>
<td>54.3</td>
<td>119</td>
</tr>
<tr>
<td>7</td>
<td>4</td>
<td>Compart mental allometry</td>
<td>34,133</td>
<td>–</td>
<td>212</td>
<td>47.6</td>
<td>2.91</td>
<td>62.8</td>
<td>2.58</td>
<td>27.3</td>
<td>32.6</td>
<td>72.3</td>
<td>92.1</td>
</tr>
<tr>
<td>8</td>
<td>7</td>
<td>STDY13 as a covariate on V1, Q2</td>
<td>33,949</td>
<td>–</td>
<td>184</td>
<td>46.5</td>
<td>2.86</td>
<td>64.1</td>
<td>2.69</td>
<td>28.8</td>
<td>28.2</td>
<td>31.9</td>
<td>96.6</td>
</tr>
<tr>
<td>9</td>
<td>8</td>
<td>STDY10 as a covariate on CL</td>
<td>33,834</td>
<td>–</td>
<td>115</td>
<td>46.6</td>
<td>2.86</td>
<td>61.6</td>
<td>2.24</td>
<td>27.6</td>
<td>27.7</td>
<td>32.9</td>
<td>95.4</td>
</tr>
<tr>
<td>10</td>
<td>9</td>
<td>Removal of IIV on Q2</td>
<td>33,839</td>
<td>+</td>
<td>5</td>
<td>46.4</td>
<td>2.89</td>
<td>61.6</td>
<td>2.24</td>
<td>27.9</td>
<td>27.3</td>
<td>–</td>
<td>97.9</td>
</tr>
</tbody>
</table>

CL vancomycin clearance, FracPoly fractional polynomial regression, GA gestational age, IIV inter-individual variability, MdAPE in-sample median absolute relative prediction error, OFV objective function value, PMA postmenstrual age, PNA postnatal age, Q2 inter-compartmental clearance, Ref. reference, SCR serum creatinine, SCR\(_{\text{std}}\) standardised SCR, V1 central volume of distribution, V2 peripheral volume of distribution, WGT weight
In these equations, CL (L h\(^{-1}\)) is vancomycin clearance, \(V_1\) and \(V_2\) (L) are the central and peripheral volume of distribution and \(Q_2\) (L h\(^{-1}\)) is the inter-compartmental clearance.

\[ F_{\text{Size}} = PMA_{(wk)}^{\gamma_1} / (PMA_{(wk)}^{\gamma_1} + PMA_{50}^{\gamma_1}) \tag{11} \]

\[ F_{\text{Decline}} = PMA_{(yr)}^{\gamma_2} / (PMA_{(yr)}^{\gamma_2} + AGE_{50}^{\gamma_2}) \tag{12} \]

\[ F_{\text{SCR}} = e^{-\theta_{\text{SCR}} \times (\text{mgdL}^{-1} - \text{SCR}_{\text{adj}})} \]  

respectively. Overall, these diagnostics show that our final model is adequately developed.

### 3.3 Evaluation and Optimisation of Current Dosing Recommendations

The distribution of predicted steady-state vancomycin AUC\(_{24h}\) resulting from the dosing recommendations in the SmPC and the FDA label are shown in Fig. 3. The proportion of patients achieving an AUC\(_{24h}\) below 400 mg L\(^{-1}\) h (\(AUC<400\)), between 400 and 700 mg L\(^{-1}\) h (\(Target\)), and above 700 mg L\(^{-1}\) h (\(AUC>700\)) are shown in Tables S3 and S4 of the ESM.

Based on the dosing regimen in the SmPC, 19% of patients attain an AUC\(_{24h}\) below 400 mg L\(^{-1}\) h, whilst 46% of patients attain an AUC\(_{24h}\) above 700 mg L\(^{-1}\) h. Elderly (76%), very elderly (70%) and obese patients (81%) are mainly at risk for attaining a steady-state AUC\(_{24h}\) above 700 mg L\(^{-1}\) h, whereas for underweight adults (25%), newborns (43%), and children and adolescents (65%) a considerable proportion of patients is expected to attain an AUC\(_{24h}\) below 400 mg L\(^{-1}\) h.

The optimised daily doses for the SmPC and FDA label are shown in Table 4. In general, optimised daily doses are
higher. Exceptions are adults and children with an estimated glomerular filtration rate < 50 mL.min⁻¹, where the optimised daily doses for the SmPC are 14.5 and 28.5 mg kg⁻¹ instead of 15 and 30 mg kg⁻¹. For both the optimised SmPC and the FDA label, \( f_{\text{Target}} \) increases consistently across subgroups with the overall \( f_{\text{Target}} \) increasing from 35 to 46% and 37 to 60% for the SmPC and the FDA label, respectively. For the optimised label, \( f_{\text{Target}} \) is > 50% in all subgroups and the risk for over- or under-dosing is consistent (±20%) across subgroups. However, for the optimised SmPC, children and adolescents (30%) and underweight adults (46%) remain at risk for under-dosing, whereas elderly patients (46%), very elderly patients (53%) and obese patients (58%) are at risk for over-dosing.

4 Discussion

In this population-PK modelling study, we showed that vancomycin pharmacokinetics undergoes significant changes throughout human life. Besides size-related changes in clearance, maturation is the main driver for clearance during early childhood with 90% of adult clearance being reached by 2 years PMA. Between 3 and 16 years PMA, size-corrected clearance is highest (> 5.05 L h⁻¹ 70 kg⁻¹). Afterwards, clearance deteriorates significantly, reaching 2.66 h⁻¹ 70 kg⁻¹ (i.e. 50% of maximum clearance) by 61.6 years PMA. Not surprisingly, we found that SCR is a significant covariate on clearance for both between- and within-subject variability. When SCR decreases or increases 0.20 mg dL⁻¹ (17.7 µmol L⁻¹) from the typical-for-PMA SCR std, clearance changes with +13.8 and −12.2%, respectively.

According to our model, typical vancomycin clearance in a 60-year-old, 65-kg patient with a SCR of 0.97 mg dL⁻¹ (85.7 µmol L⁻¹) is 2.55 L h⁻¹ (0.039 L h⁻¹ kg⁻¹). Vancomycin clearance in a 32-week, 1.5-kg neonate with a SCR of 0.64 mg dL⁻¹ (56.6 µmol L⁻¹) is 0.0756 L h⁻¹ (0.0504 L h⁻¹ kg⁻¹). Both values are in line with the range of clearance estimates reported by Marsot et al. ³ for adults (0.031–0.086 L h⁻¹ kg⁻¹) and paediatric patients (0.020–0.112 L h⁻¹ kg⁻¹). In contrast to Marsot et al. [3] who reported different estimates for vancomycin volume of distribution for adults (0.864 L kg⁻¹) and children (0.565 L kg⁻¹), we found that
the size-standardised volume of the distribution is constant throughout life at 0.61 L.kg⁻¹ for $V_1$ and 0.59 L kg⁻¹ for $V_2$.

Our estimate for PMA₅₀ of 46.4 weeks is in good agreement with earlier work by Rhodin et al. [41] who found that glomerular filtration function reaches 50% of adult values by 47.7 weeks PMA. This suggests, in line with previous reports [42], that vancomycin elimination depends predominantly on glomerular filtration. Moreover, our PMA₅₀ estimate is not significantly different from the findings of Anderson et al. [20] who reported a PMA₅₀ of 33.3 weeks (95% confidence interval 14.8–51.8) in a cohort of preterm neonates. It also inspires confidence that our conclusion of maturation being nearly complete at 2 years PMA is supported by a recent physiologically based PK simulation study by Calvier et al. [43].

Model building started out with an a priori model consisting of allometric scaling and a maturation function as advocated by Holford et al. [11] and more recently by Germovsek et al. [12]. By extending this standardised model with an additional sigmoidal decline function, we were able to describe the deterioration in vancomycin clearance with age. Recently, Lonsdale et al. [35] have used the same methodology to describe beta-lactam antimicrobial pharmacokinetics from early life to old age. Notwithstanding that tubular secretion and/or re-absorption are likely involved in beta-lactam elimination, these authors found a PMA₅₀ estimate of 49.7 weeks, which is in line with our findings. Their estimated AGE₅₀ of 86.8 years, however, is significantly higher than what we found for vancomycin (61.6 years). In addition to differences in elimination processes, the different handling of renal function in the study by Lonsdale et al. [35] compared with our analysis might explain the different AGE₅₀ estimates. Indeed, as seen from Table 2, during model building, AGE₅₀ ranged from 67.4 to 79.8 years depending on the method used to standardise SCR.

This is by far the largest population-PK modelling study on vancomycin pharmacokinetics. On the one hand, our findings confirm earlier fragmented findings on the influence of weight, kidney function and age on vancomycin pharmacokinetics by other groups [3] as well as the increased clearance in patients with haematological diseases [29]. On the other hand, we were able to negate some prior hypotheses.
Patient subgroup Renal function adjustments Daily dose Optimised daily dose

Neonates < 1 wk PNA – 20 mg kg⁻¹ 25.0 mg kg⁻¹
Neonates < 1 mo PNA – 30 mg kg⁻¹ 34.0 mg kg⁻¹
1 mo PNA > children > 18 yr – 40 mg kg⁻¹ 61.0 mg kg⁻¹

Adults – 2000 mg 3000 mg
Adults with impaired renal function eGFR<sub>adult</sub> < 100 eGFR<sub>adult</sub> < 90 eGFR<sub>adult</sub> < 80 eGFR<sub>adult</sub> < 70 eGFR<sub>adult</sub> < 60 eGFR<sub>adult</sub> < 50 eGFR<sub>adult</sub> < 40 eGFR<sub>adult</sub> < 30 eGFR<sub>adult</sub> < 20 eGFR<sub>adult</sub> < 10 1545 mg 1390 mg 1235 mg 1080 mg 925 mg 770 mg 620 mg 465 mg 310 mg 155 mg

We found that after correcting for age, body size and kidney function, PK parameters were not different between patients with or without burns [23], between critically ill or non-critically ill patients [25], or between patients treated with intermittent or continuous dosing [44]. In addition, we found no differences in PK parameters with respect to the different vancomycin assay methods used (i.e. assays based on fluorescence polarisation or turbidimetric inhibition principles) [45]. Supportive evidence for these findings is provided in Figs. S6–S9 of the ESM.

Patients from two studies differed significantly from the rest of the population, thereby forcing us to include two study-specific parameters. First, patients in the Buelga et al. study [29] had a significantly higher clearance. This finding is in line with earlier work by Jarkowski et al. [46] and Zhao et al. [47] who found higher clearance in adult and paediatric patients with malignant haematological diseases. Second, the concentration–time profile for patients in the Lo et al. study [32] was different from other studies. This is likely owing to the heel pricking that was used in the Lo et al. study as opposed to venous or arterial blood sampling in the other studies. This reasoning is in line with earlier work by Chiou who showed that drug concentrations depend on the sampling site [48].

Using the post hoc PK parameters derived from our model, we evaluated two currently used dosing regimens for vancomycin and showed that these dosing regimens do not consistently result in efficacious and safe steady-state vancomycin exposure across patient populations. The optimised daily doses increase the proportion of patients attaining a C<sub>24</sub> between 400 and 700 mg L⁻¹ h for both the European Medicines Agency-approved SmPC and the FDA-approved label. From these simulations, we see that weight-based dosing for neonates is acceptable, yet the dose-per-kilogram should be increased. For adults, weight-based dosing is inappropriate and results in under-dosing of underweight adult patients whilst obese adult patients are generally overdosed. Moreover, age- or kidney function-adjusted dosing is necessary to avoid over-dosing in elderly patients and very elderly patients. The optimised FDA label, which defines kidney function-adjusted doses for patients aged older than 18 years and weight-based dosing otherwise, performs well...
with consistent target attainment and minimal (± 20%) risk of under- and over-dosing across patient subgroups.

These recommendations should be interpreted by taking into account that: (1) further optimisation of these dosing regimens could be achieved by further stratifying patient subgroups based on age and/or weight; (2) the thresholds used for defining adequate and or excessive AUC_{24h} are still under debate and regional differences exist in minimum inhibitory concentration distributions; and (3) TDM is still necessary to further optimise the treatment of individual patients. Furthermore, our study excluded specific patient categories (patients receiving renal replacement therapy, haemodialysis, haemodiafiltration and extra-corporeal membrane oxygenation) and in the pooled dataset some patient categories were only sparsely populated (e.g. the group of children and adolescents). As such, the generalisability of our results and the predictive performance of the final model should be validated in a prospective study prior to implementation of the model or derived recommendations in clinical practice.

5 Conclusion

In this article, we show that vancomycin pharmacokinetics changes dramatically throughout human life and a single population-PK model is able to capture these changes. Through simulations, we showed that current dosing regimens do not succeed in providing similar steady-state exposure across patient subgroups and as such the probability for therapeutic success or vancomycin-induced toxicity is not constant throughout life. As illustrated in this work, this new model has the potential to overcome these limitations and could be used to further develop age- and renal function-specific dosing regimens for vancomycin. Furthermore, this model could facilitate individualised vancomycin dosing through Bayesian forecasting based on therapeutic drug monitoring.

Author Contributions  Peter J. Colin: idea generation, data analysis and first draft of the paper; Karel Allegaert, Alison H. Thomson, Daan J. Touw, Michael Dolton, Matthijs de Hoog, Jason A. Roberts, Eyob D. Adane, Masato Yamamoto, Dolores Santos-Buelga, Ana Martín-Suarez, Nicolas Simon, Fabio S. Taccone, Yoke-Lin Lo, Emilia Barcia and Douglas J. Eleveld have no conflicts of interest that are directly relevant to the contents of this article. Daan J. Touw reports funding outside the submitted work from: ZONMW, Chiesi and Astellas. Douglas J. Touw is a member of Sanquin Blood Bank Medical Advisory Board, an honorary member of the editorial board of Clinical Pharmacokinetics and a member of the editorial board of the Journal of Cystic Fibrosis. Jason A. Roberts has received funding from the Australian National Health and Medical Research Council for a Centre of Research Excellence (APP1099452) and a Practitioner Fellowship (APP1048652); has consultancies with Astellas, Biomerieux, Accelerate Diagnostics and Bayer as well as investigator-initiated studies with MSD, Cardeas and The Medicines Company, all outside the submitted work. Michel M. R. F. Struys research group/department received grants and funding from The Medicines Company (Parsippany, NJ, USA), Masimo (Irvine, CA, USA), Fresenius (Bad Homburg, Germany), Acacia Design (Maasricht, the Netherlands) and Medtronic (Dublin, Ireland) and received honoraria from The Medicines Company, Masimo, Fresenius, Baxter (Deerfield, IL, USA), Medtronic and Demed Medical (Tense, Belgium). He is an editorial board member of the British Journal of Anaesthesia and a senior editor of Anesthesiology and Analgesia.

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Affiliations

Pieter J. Colin1,2 · Karel Allegaert3,4,5 · Alison H. Thomson6 · Daan J. Touw7,8 · Michael Dolton9 · Matthijs de Hoog10 · Jason A. Roberts11 · Eyob D. Adane12 · Masato Yamamoto13 · Dolores Santos-Buelga14 · Ana Martín-Suarez14 · Nicolas Simon15 · Fabio S. Taccone16 · Yoke-Lin Lo17,18 · Emilia Barcia19 · Michel M. R. F. Struys1,20 · Douglas J. Eleveld1

1 Department of Anesthesiology, University Medical Center Groningen, University of Groningen, P.O. Box 30001, 9700 RB Groningen, The Netherlands
2 Laboratory of Medical Biochemistry and Clinical Analysis, Faculty of Pharmaceutical Sciences, Ghent University, Ghent, Belgium
3 Pediatric Intensive Care, Erasmus MC, Sophia Children’s Hospital, Rotterdam, The Netherlands
4 Department of Neonatology, Erasmus MC, Sophia Children’s Hospital, Rotterdam, The Netherlands
5 Department of Development and Regeneration, KU Leuven, Louvain, Belgium
6 Strathclyde Institute of Pharmacy and Biomedical Sciences, University of Strathclyde, Glasgow, UK
7 Department of Clinical Pharmacy and Pharmacology, University Medical Center Groningen, University of Groningen, Groningen, The Netherlands
8 Department of Pharmacy, Section Pharmacokinetics, Toxicology and Targeting, University of Groningen, Groningen, The Netherlands
9 Faculty of Pharmacy, University of Sydney, Sydney, NSW, Australia
10 Department of Pediatrics, Erasmus University and University Hospital Rotterdam/Sophia Children’s Hospital, Rotterdam, The Netherlands
11 University of Queensland Centre for Clinical Research and School of Pharmacy, The University of Queensland, Brisbane, QLD, Australia
12 Raabe College of Pharmacy, Ohio Northern University, Ada, OH, USA
13 Department of Neuropsychopharmacology and Hospital Pharmacy, Nagoya University Graduate School of Medicine, Nagoya, Japan
14 Department of Pharmacy and Pharmaceutical Technology, University of Salamanca, Salamanca, Spain
15 Aix-Marseille University, INSERM, IRD, SESSTIM, Hop Sainte Marguerite, Service de Pharmacologie Clinique, CAP, Marseille, France
16 Department of Intensive Care, Erasme Hospital, Université Libre de Bruxelles, Brussels, Belgium
17 Department of Pharmacy, Faculty of Medicine, University of Malaya, Kuala Lumpur, Malaysia
18 Department of Pharmacy Practice, School of Pharmacy, International Medical University, Kuala Lumpur, Malaysia
19 Department of Pharmaceutics and Food Technology, School of Pharmacy, Universidad Complutense de Madrid, Madrid, Spain
20 Department of Anesthesia and Peri-operative Medicine, Ghent University, Ghent, Belgium