Dose selection for a phase III study evaluating gepotidacin (GSK2140944) in the treatment of uncomplicated urogenital gonorrhoea

Nicole E Scangarella-Oman, Mohammad Hossain, Caroline R Perry, Courtney Tiffany, Marcy Powell, Brandon Swift, Etienne F Dumont

ABSTRACT
Background Gepotidacin is a novel, first-in-class triazacacenaphthylene antibiotic that inhibits bacterial DNA replication by a distinct mechanism of action and is active against most strains of Neisseria gonorrhoeae (N. gonorrhoeae). Phase II data suggested higher exposures were needed for efficacy and to suppress resistance development. A translational approach using in vitro pharmacokinetic/pharmacodynamic (PK/PD) and clinical data was used to select a gepotidacin dose for a phase III study. In this narrative review of previously shown data, we summarise how a translational approach based on in vitro PK/PD and population PK modelling and simulation data was undertaken to select a dosing regimen for the ongoing phase III gepotidacin study in participants with uncomplicated urogenital gonorrhoea.

Methods For dose selection, prior in vitro minimum inhibitory concentrations (MICs) and PK/PD data were available. PK modelling was conducted to determine a dose that would limit plasma concentrations to less than 14 µg/mL (as concentrations above this are associated with QT prolongation and effects associated with acetylcholinesterase inhibition) while maintaining ≥90% probability of target attainment (PTA) for efficacy and resistance suppression against N. gonorrhoeae isolates with gepotidacin MICs ≤1 µg/mL.

Results Two 3000 mg gepotidacin doses, administered 10–12 hours apart, resulted in PTA of ≥97.5% and ≥91.7% for gepotidacin MICs ≤1 µg/mL for the ratio of the area under the free drug plasma concentration–time curve over 24 hours to the MIC (AUC0–24/MIC) efficacy, and resistance suppression targets of 40 and 46, respectively, but limited the occurrence of maximum plasma concentrations ≥14 µg/mL.

Conclusions Two gepotidacin 3000 mg oral doses 10–12 hours apart provide ~2-fold higher systemic exposures, increase efficacy for higher gepotidacin MIC N. gonorrhoeae isolates, reduce resistance potential and limit plasma concentrations of potential safety concern, compared with higher doses.

INTRODUCTION
Gonorrhoea is a common sexually transmitted disease caused by the bacterium Neisseria gonorrhoeae (N. gonorrhoeae). Gonorrhoea is increasingly prevalent across many regions of the world, including America, Asia and Europe. The World Health Organization (WHO) estimates that 82 million new cases of gonorrhoea are acquired each year in 15–49-year-olds worldwide. Gonococcal infections left untreated are a cause of serious sequelae including pelvic inflammatory disease which can lead to serious outcomes in women such as ectopic pregnancy and infertility. However, a major challenge in treating patients with gonorrhoea is the emergence of multidrug-resistant N. gonorrhoeae, prompting the US Centers for Disease Control and Prevention (CDC) and WHO to label drug-resistant N. gonorrhoeae as an ’urgent
gondor-while maximising the probability for efficacy against
sary from a safety perspective due to the plasma concentrations
of maximum plasma concentrations of ≥14 µg/mL (as is neces-
phase II clinical study had a gepotidacin MIC of 1 µg/mL and a pre-
or yet been established for this bacterium.
Gepotidacin is currently being evaluated for the treatment of
complicated urogenital gonorrhoea in adults and adolescents in a phase III clinical trial (NCT04010539). In this narrative
review, we summarise how a translational approach based on
in vitro PK/PD (from an in vitro hollow-fibre infection model and the phase II uncomplicated urogenital gonorrhoea clinical
trial) and population PK modelling and simulation data was
taken to select a dosing regimen for the ongoing phase III
gapotidacin study in participants with uncomplicated urogenital
gonorrhoea.

METHODS
This narrative review drew on papers with prior in vitro minimum
inhibitory concentrations (MICs) data and PK/PD data available
from clinical data and the hollow-fibre infection model.19 21–24
Population PK modelling including phase II data and simulation
was conducted to determine a dose that would limit the occurrence of
maximum plasma concentrations of ≥14 µg/mL (as is neces-
sary from a safety perspective due to the plasma concentrations
above this threshold correlating with QT/corrected QT (QTc)
and adverse events associated with acetylcloheximiderase inhibition),
while maximising the probability for efficacy against N. gonor-hoeae isolates with gepotidacin MICs ≤1 µg/mL and preventing
the emergence of resistance. Probability of target attainment
(PTA) for efficacy and resistance suppression PK/PD targets
was determined using Monte Carlo simulations (200 trials of
50 subjects) that used a population PK model developed using
phase II data (NCT04079790).

Clinical efficacy and PK/PD data from the phase II gonorrhoea
clinical study
Of 69 participants in the phase II study, single oral doses of
1500 mg and 3000 mg gepotidacin were ≥95% efficacious for
bacterial eradication of N. gonorrhoeae in adults with urogenital
gonorhoea.19 Three participants failed therapy at the urogenital
body site (all with baseline N. gonorrhoeae isolate with a gopoti-
dacin MIC of 1 µg/mL and a pre-existing D86N substitution in the
parC gene).21,22 Post-treatment culture analysis identified 2
isolates with an additional substitution, A92T in the gyrA gene,
which resulted in reduced susceptibility to gepotidacin (gepoti-
dacin MICs ≥32 µg/mL).26 Resistance to gepotidacin is likely to
emerge if the combination of parC D86N and gyrA A92T muta-
tions occur.25 26 The highest reported prevalence of the parC
D86N mutation was 38.6% of ciprofloxacin-resistant N. gonorrho-
eae isolates.27 Currently, no published genomic databases
report frequencies for the gyrA A92T mutation.26
Bacterial eradication was 100% when the ratio of the area under
the unbound plasma concentration–time curve over 24 hours to the MIC (fAUC0–24/MIC) was ≥48, and all 3 of the
microbiological failures had an fAUC0–24/MIC of ≤24.21 In prior
studies, fAUC0–24/MIC has been shown to be the PK/PD index
most closely associated with gepotidacin efficacy against other
bacteria, specifically Escherichia coli, Staphylococcus aureus
and Streptococcus pneumoniae.22 23 Based on these phase II clin-
cal study results, the preliminary gepotidacin efficacy PK/PD
target for gonorrhoea in plasma was estimated to be an fAUC/
MIC between 24 (failure) and 48 (success, defined as culture-
confirmed eradication of N. gonorrhoeae).23 Due to the limited
number of isolates with a pre-existing single-step mutation, a
resistance suppression target could not be identified from the
phase II clinical study. In addition, 7% of the isolates from the
phase II clinical study had a gepotidacin MIC of 1 µg/mL,21
highlighting the importance of demonstrating efficacy against
N. gonorrhoeae isolates with higher gepotidacin MICs. There-
fore, the microbiological failures from this study demonstrated
the need to optimise the gepotidacin dose to increase efficacy
and prevent the emergence of bacterial resistance (table 1 and
table 2).

Previous research looking at body sites where gonorrhoea
infections have been identified evaluated the PK, safety and
exploratory efficacy of gepotidacin 1500 mg 2 times daily
for 5 days and found that urinary exposure over the dosing
interval (AUC0–24) increased from 3742 µg/mL/hour (day 1) to
5973 µg/mL/hour (day 4), with trough concentrations of 322 to
352 µg/mL from day 3 to day 5 and provided >600-fold higher
concentrations in urine than in free plasma at steady state.28
Previous research also investigated exploratory PK assessment
of the collection of cervical, rectal and pharyngeal swab spec-
imens on day 4 predose and 2 hours postdose, with blood

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<th>MIC (µg/mL)</th>
<th>n/N</th>
<th>Microbiological success (%)</th>
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<td>27/27</td>
<td>100</td>
</tr>
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FAUC/MIC, ratio of the area under the free-drug concentration–time curve to the
MIC; MIC, minimum inhibitory concentration; n/N, number of subjects with culture-
confirmed eradication of N. gonorrhoeae out of total microbiologically evaluable
subjects.
samples taken at these same timepoints as part of a study in patients with uncomplicated urinary tract infection following multiple oral doses of gepotidacin 1500 mg 2 times daily for 5 days. 

In the cervical site, the distribution of gepotidacin was 1.30 \( \mu \)g/mL in predose samples and 1.03 \( \mu \)g/mL in postdose samples. In rectal samples, 6.04 \( \mu \)g/mL of gepotidacin was found in predose and 12.3 \( \mu \)g/mL postdose. In rectal samples, 6.04 \( \mu \)g/mL of gepotidacin was found in predose and 12.3 \( \mu \)g/mL postdose. In free plasma samples, 0.618 \( \mu \)g/mL of gepotidacin was found predose and 3.94 \( \mu \)g/mL postdose. 

Concentration-driven QT prolongation and acetylcholinesterase inhibition with gepotidacin

A potential for QT prolongation was identified during in vitro studies, and although in vitro prolongation potentials were not realised in in vivo dog studies, slight prolongations in QT interval observed in vitro showed that an infusion of gepotidacin at a dose of 1000 mg and 1800 mg over 2 hours caused a mild heart rate acceleration of approximately 7 bpm and 10 bpm, respectively, and QT prolongation measured as \( \Delta QT \) corrected by Fridericia’s formula (QTcF) of 12 ms to 22 ms, respectively. The QT prolongation evolved during the infusion and was reversed over 2 hours after the end of the infusion. Gepotidacin did not have a clinically relevant effect on cardiac conduction (PR and QRS intervals). A statistically significant effect on the QTcF interval was demonstrated with a slope of the relationship between gepotidacin plasma concentrations and \( \Delta QTcF \) of 1.45 ms/\( \mu \)g/mL (90% CI: 1.30 to 1.61). A gepotidacin plasma concentration was established to not exceed 14 \( \mu \)g/mL to decrease the occurrence of QTc prolongation, predicted to correlate to a 20 ms increase in the QT interval. 

In previous research, one instance of arrhythmia (1/13; 8%) was reported following a dose of 3000 mg 12 hours apart, which was mild in severity and did not related to gepotidacin. The plasma concentration ceiling also reduces the likelihood of adverse effects driven by acetylcholinesterase inhibition as observed in phase I and II studies, as in vitro studies have shown that gepotidacin is a rapidly reversible inhibitor of acetylcholinesterase (unpublished data).

In vitro hollow-fibre infection model

The predicted gepotidacin exposure necessary to prevent the amplification of gepotidacin-resistant N. gonorrhoeae was assessed using an in vitro hollow-fibre infection model. This in vitro model was undertaken to fill a gap in the phase II gonorrhoea study resistance development due to the lack of isolates with a pre-existing mutation and AUC/MIC between 24 and 96. A set of duplicate, 7-day, hollow-fibre infection model studies was completed using an N. gonorrhoeae isolate from the phase II clinical trial with a gepotidacin MIC of 1 \( \mu \)g/mL and a parC D86N mutation, to determine the AUC/MIC exposure of gepotidacin needed to prevent the amplification of a cephalosporin-resistant subpopulation when a pre-existing single-step mutation affecting cephalosporin activity was already present. The gepotidacin resistance suppression PK/PD target for N. gonorrhoeae in plasma was an AUC/MIC of 46, based on the data from the hollow-fibre infection model, which was able to replicate the efficacy and resistance development seen in the phase II gonorrhoea study. Using this approach, the hollow-fibre infection model confirmed that total daily doses of \( \geq 4500 \) mg (including 2 gepotidacin 3000 mg doses administered either 8 or 12 hours apart, as evaluated in the hollow-fibre infection model) prevented resistance amplification to gepotidacin in N. gonorrhoeae (figure 1). 

Notably, the gepotidacin isolates with reduced susceptibility recovered from the hollow-fibre infection model studies and contained target-site mutations consistent with those identified from the 2 cephalosporin-treated patients enrolled in the phase II study whose postbaseline N. gonorrhoeae isolates developed reduced the susceptibility to cephalosporins. The variable efficacy/resistance amplification of the 3000 mg dose seen in the hollow-fibre infection model studies was also consistent with the results for the 3000 mg single dose in the phase II clinical study, thereby providing confidence in this model’s ability to replicate the efficacy and resistance development seen in the clinical trial. These concurring findings were particularly useful for the selection of a dose which minimised resistance risk potential for the phase III clinical study in uncomplicated urogenital gonorrhoea.

Population PK modelling and simulation

A population PK model was developed using plasma PK data from a randomised, fixed-sequence, 3-period study of oral cephalosporin in 14 healthy adults, and a 2-period study in 13 healthy adolescent subjects (NCT04079790). Subjects received cephalosporin as a single 1500 mg dose, followed by 2×3000 mg doses given at a 12-hour interval (adults only) and 2×3000 mg doses given at a 6-hour interval (adults and adolescents). A 2-compartment model with first-order absorption and elimination containing transit compartments was used to describe the PK of cephalosporin. Based on this model, a Monte Carlo simulation approach was
used to simulate 10,000 virtual subjects for different gepotidacin dosing regimens (200 trials with 50 subjects in each trial). For each simulated plasma–concentration time profile, AUC0–24 was calculated using the linear-up log-down trapezoidal method. The individual AUC0–24 estimates were corrected for protein binding by multiplying by the unbound fraction (fu=0.67) and then dividing by the MIC values ranging from 0.125 to 4 µg/mL to calculate fAUC/MIC ratio, the PK/PD index for gepotidacin. The PTA was determined within each dose based on the proportion of the 10,000 virtual subjects above the PK/PD targets for efficacy (40) and resistance suppression (46) (figure 2). These simulations were conducted to evaluate doses that could maximise the probability of efficacy against Neisseria gonorrhoeae isolates with gepotidacin MICs ≤1 µg/mL, while minimising the potential for emergence of resistance. In addition, the simulations were used to identify a dose that would limit the occurrence of maximum plasma concentrations exceeding 14 µg/mL, which is necessary from a safety perspective due to the increased risk of QTc interval prolongation and acetylcholinesterase inhibition side effects.

**Figure 1** Gepotidacin exposure and change in log10 colony-forming unit per millilitre (CFU/mL) from baseline of the gepotidacin-resistant subpopulation. Figure adapted with permission from VanScoy et al., under the Creative Commons Attribution License. Full terms at: https://creativecommons.org/licenses/by/4.0/.

**Figure 2** Percentage probabilities of PK/PD target attainment by MIC for gepotidacin oral dosing regimen based on the evaluation of fAUC0–24/MIC targets associated with efficacy and resistance suppression, overlaid on the gepotidacin MIC distribution for Neisseria gonorrhoeae. Dashed line represents 90% PTA. Adapted with permission from Singh et al., fAUC0–24/MIC, ratio of the area under the free-drug plasma concentration–time curve over 24 hours to the MIC; MIC, minimum inhibitory concentration; PK/PD, pharmacokinetics/pharmacodynamics; PTA, probability of target attainment.

**Summarising dose regimen selection for the phase III gonorrhoea study**

Based on the phase II clinical study results, when all isolates were considered, the preliminary gepotidacin efficacy PK/PD target for N. gonorrhoeae in plasma was an fAUC/MIC between 24 (failure) and 48 (success, defined as culture-confirmed eradication of N. gonorrhoeae). However, for the purposes of modelling, an fAUC/MIC target of 40 was chosen, for a total daily dose of 6000 mg (3000 mg given twice). The gepotidacin resistance suppression PK/PD target for N. gonorrhoeae in plasma was determined to be an fAUC/MIC of 46, based on the in vitro hollow-fibre model. This in vitro model was specifically undertaken to fill a gap in the phase II gonorrhoea study with regards to resistance development, due to a limited subset of isolates with a pre-existing single-step mutation. Results of the PK modelling and simulation demonstrated that a dosing strategy of 2 gepotidacin 3000 mg oral doses administered 12 hours apart resulted in PTA of approximately 97.5% and 91.7% for gepotidacin MICs ≤1 µg/mL for the efficacy and resistance suppression PK/PD targets of an fAUC/MIC of 40 and 46, respectively. Furthermore, 2 gepotidacin 3000 mg doses resulted in a limited occurrence of exceeding the QTc threshold of 14 µg/mL. In previous research that studied the dose of 3000 mg 12 hours apart (mean observed maximum concentrations of 10–11 µg/mL; less than the 14 µg/mL), 77% experienced an adverse event, 62% experienced diarrhoea and 31% had abdominal discomfort.

**CONCLUDING REMARKS**

The overarching aim of the studies described herein was to evaluate gepotidacin-dosing regimens to support dose selection for a pivotal phase III clinical study of gepotidacin in patients with uncomplicated urogenital gonorrhoea. The gepotidacin dose and dosing regimen was guided by modelling and simulation, using a population PK model and applying efficacy and resistance suppression PK/PD targets determined from an in vitro hollow-fibre infection model and phase II clinical data,
while also limiting plasma concentrations of potential safety concern.\textsuperscript{19} Despite a lack of validated preclinical models for \textit{N. gonorrhoeae}, the use of this translational approach permitted informed selection of an appropriate gepotidacin dose likely to provide safe and effective exposure, and overcome resistance development in the pivotal phase III clinical trial. It was through this evaluation that we found the optimal regimen to be 2 oral 3000 mg doses of gepotidacin 10–12 hours apart, rather than the single 3000 mg oral dose used in a phase II trial.\textsuperscript{19} In terms of gepotidacin systemic exposure, 2 oral 3000 mg doses 10–12 hours apart provided approximately twice the systemic exposure of the single 3000 mg dose, allowing more reliable efficacy coverage of \textit{N. gonorrhoeae} isolates with gepotidacin MICs of 1 \textmu g/mL and resistance suppression.\textsuperscript{19} PK modelling and simulation demonstrated that for the 2 oral gepotidacin 3000 mg doses, taken 12 hours apart, the PTA was \( \geq 97.5\% \) when applying the efficacy PK/PD target of an \( \text{AUC/MIC of 40} \) (based on the preliminary target from the phase II clinical trial and achievable PK levels for a total daily dose of 6000 mg (3000 mg given twice)), and \( \geq 97.1\% \) when applying the resistance suppression PK/PD target of an \( \text{AUC/MIC of 46} \) (based on the in vitro hollow-fibre infection model) for gepotidacin MICs \( \leq 1 \text{ \textmu g/mL} \). The second 3000 mg dose given 10–12 hours later as compared with the single dose used in phase II trials provided reliable efficacy while simultaneously preventing the development of resistance. PK modelling and simulation with the selected dosing regimen also predicted maximum plasma concentrations that would limit exceeding the exposure threshold of 14 \textmu g/mL, which correlates with a potential to increase the QTc interval and acetylcarninesterase inhibitory effects.\textsuperscript{24} On the basis of these results, the ongoing phase III randomised, open-label study is currently evaluating gepotidacin administered as an initial 3000 mg oral dose followed by another 3000 mg oral dose 10–12 hours later. The original protocol designated an interval of 6–12 hours for the second dose. Subsequent data from the completion of a phase I study in adults and adolescents\textsuperscript{40} resulted in lengthening the second-dose interval via a protocol amendment to 10–12 hours to mitigate any potential safety concerns from plasma concentrations exceeding the exposure threshold of \( \geq 14 \text{ \textmu g/mL} \). Gepotidacin will be compared with ceftriaxone plus azithromycin in individuals (planned sample size of 600) with urogenital gonorrhoea; the study is currently recruiting.\textsuperscript{31} Of note, the study started prior to the CDC-recommended change in the standard of care, and as such uses ceftriaxone plus azithromycin, rather than ceftriaxone alone.\textsuperscript{34}

Public health control of gonorrhoea relies on appropriate antimicrobial treatment, together with targeted prevention, and the use of effective diagnostics and surveillance. The aim of therapy should be to cure individual cases to reduce the risk of potentially severe complications and prevent transmission. The prospect of multidrug-resistant \textit{N. gonorrhoeae}, including resistance to ceftriaxone, the only remaining option for first-line therapy in many settings, is the cause for trepidation.\textsuperscript{3} There is some concern around adherence to antibiotic treatment regimens requiring >1 dose per day, which may result in poorer outcomes, emergence of drug-resistant strains and increased healthcare costs. Meta-analyses have shown that patients who received antibiotic treatment once daily had higher compliance than those who received antibiotic treatment multiple times daily.\textsuperscript{31} However, regimens, where treatment is received for a short period of time, may lead to a high overall compliance to treatment. Apart from the frequency of daily dosing, other factors such as patient age, gender, health literacy, therapy-related factors (treatment-related adverse events, taste or odour of medication), factors associated with healthcare (lack of accessibility, long waiting times, difficulty filling prescriptions) and disease severity can affect treatment compliance.\textsuperscript{36} Strategies to improve adherence should also consider the needs of the patient. For example, contact between patient and doctor during treatment may result in higher compliance.\textsuperscript{37}

The studies used to inform the phase III gepotidacin dosing regimen for evaluation in patients with urogenital gonorrhoea had several limitations. The phase II multicentre, open-label, dose-ranging study was limited by sample size (\( n=69 \) microbiologically evaluable) and did not include a comparator. Although both men and women were enrolled, only 3\% of the microbiologically evaluable samples were from women. An additional limitation of the phase II study was that microbiologically evaluable samples were from US participants only; therefore, the results may not reflect the global epidemiology of \textit{N. gonorrhoeae}, and different patterns of resistance may be observed in other geographic regions.\textsuperscript{39} A limitation of the in vitro hollow-fibre infection model was that only one isolate was evaluated, and it was therefore not possible to test interisolate variability in the gepotidacin exposure associated with resistance prevention.\textsuperscript{31} Another limitation was that the PK/PD target (ie, \( \text{AUC/MIC} \) for dose selection was based on unbound plasma exposures rather than local exposures in the infected tissues, such as the pharynx or rectum, and systemic exposures may not be reflective of these additional target tissue sites.\textsuperscript{31} Since the start of the phase III trial in uncomplicated urogenital gonorrhoea, an animal model has been developed that may be informative for future dose selection studies in gonorrhoea.\textsuperscript{11}

Using a translational approach, a regimen of 2 oral gepotidacin doses of 3000 mg administered 10–12 hours apart was selected for the treatment of individuals with gonorrhoea in the ongoing phase III clinical study in uncomplicated urogenital gonorrhoea (NCT04010539). This regimen is predicted to provide appropriate systemic exposure to achieve efficacy with consideration of QT prolongation safety limits while reducing the risk of resistance emergence to gepotidacin in \textit{N. gonorrhoeae} in the clinic. Additional data derived from this study will allow for further study of the gepotidacin dose regimen as it relates to a greater understanding of gepotidacin efficacy in a larger and more geographically diverse patient population.
REFERENCES


