We investigated the efficacy of posaconazole prophylaxis in preventing invasive aspergillosis due to azole-resistant *Aspergillus fumigatus* isolates. Using a neutropenic murine model of pulmonary infection, posaconazole prophylaxis was evaluated using three isogenic clinical isolates, with posaconazole MICs of 0.063 mg/liter (wild type), 0.5 mg/liter (F219I mutation), and 16 mg/liter. A fourth isolate harboring TR34/L98H (MIC of 0.5 mg/liter) was also tested. Posaconazole prophylaxis was effective in *A. fumigatus* with posaconazole MICs of ≤0.5 mg/liter, where 100% survival was reached. However, breakthrough infection was observed in mice infected with the isolate for which the posaconazole MIC was >16 mg/liter.

Invasive aspergillosis (IA) is an important opportunistic fungal infection, especially among immunocompromised patients, with an overall mortality ranging between 30 and 88% and up to 95% in patients underlying azole-resistant *Aspergillus fumigatus* infections (1–5). Posaconazole (POS) is an extended-spectrum triazole recommended for salvage therapy and prophylaxis of aspergillus diseases in neutropenic patients with acute myeloid leukemia (AML) or myelodysplastic syndrome (MDS) and in patients with graft-versus-host disease (GVHD) (6–8). The incidence of invasive fungal diseases is significantly reduced in patients receiving POS prophylaxis (9, 10).

Over the past decade, acquired azole resistance in *Aspergillus fumigatus* is increasingly recognized as an emerging problem (11, 12). Animal models and clinical experience indicate that infection with an azole-resistant isolate is associated with azole treatment failure (4, 12–27). Although azole resistance may develop during azole therapy, the main route of resistance selection appears through environmental exposure of *A. fumigatus* toazole fungicides (28). Surveillance studies indicate that in areas of endemicity up to two-thirds of patients with azole-resistant aspergillus diseases have no history ofazole therapy (4). Therefore, in areas of environmental resistance, any patient at risk for IA can develop azole-resistant disease (29).

POS has been shown to be effective for preventing IA and is becoming a more common strategy to manage invasive fungal infection in high-risk patients (9, 10, 30–32). However, the efficacy of the drug in preventing IA due to azole-resistant isolates is unknown, and to date only one case of breakthrough IA due to azole-resistant *A. fumigatus* has been reported (18). In this study, the patient was diagnosed with AML and developed IA due to an *A. fumigatus* isolate with a TR34/L98H resistance mechanism and a POS MIC of 0.5 mg/liter. The breakthrough infection developed despite adequate POS plasma levels (2.01 mg/liter) (18).

We investigated the impact of azole resistance on the efficacy of POS prophylaxis in preventing IA using an immunosuppressed mouse model of pulmonary aspergillosis.

## MATERIALS AND METHODS

### Fungal isolates

Four clinical *A. fumigatus* isolates were studied in a neutropenic murine model of pulmonary infection. Three isolates were obtained sequentially from respiratory samples of a patient with aspergillosis (33). The first isolate exhibited a wild-type phenotype (POS MIC of 0.063 mg/liter) and harbored an A9T mutation in the CYP51A gene, which was not associated with azole resistance. The patient was treated with itraconazole, during which an F219I mutation was gained that corresponded with itraconazole resistance (MIC of >16 mg/liter) and low POS resistance (MIC of 0.5 mg/liter). The patient was then treated with POS, and a phenotype emerged which was POS highly resistant (MIC of >16 mg/liter) although no additional changes in the Cyp51A gene were found (10). Microsatellite typing indicated that these isolates were isogenic (10). A fourth genetically unrelated isolate harboring the highly prevalent TR34/L98H resistance mechanism with low POS resistance (MIC of 0.5 mg/liter) was also investigated. This isolate was obtained from a patient with proven IA and was previously evaluated in a nonneutropenic murine model of IA (24) (Table 1). Strain identification was confirmed by sequence-based analysis, as described previously (12). The isolates were stored in 10% glycerol broth at –80°C, and the inoculum was prepared as described before (34). An *in vitro* antifungal susceptibility test was performed based on the EUCAST guidelines using a broth microdilution format (35).

### In vitro kinetic growth assay

In order to rule out important fitness costs associated with the acquisition of resistance mechanisms, the growth characteristics of the four isolates were determined using a previously described microbroth kinetic system (36). Briefly, the inocula were prepared by diluting an overnight culture grown on agar plates with 0.9% NaCl to 1 × 10⁶ to 5 × 10⁶ CFU/ml. The fungal suspensions were then further diluted in RPMI 1640 medium (with l-glutamine, without sodium bicarbonate) (Sigma, USA) supplemented with 0.165 M morpholino propane sulfonic acid (MOPS) to give a final inoculum between 0.5 ×
TABLE 1 Characteristics of four A. fumigatus isolates used in the prophylaxis model

<table>
<thead>
<tr>
<th>Isolate no.</th>
<th>Strain</th>
<th>Prior azole exposure</th>
<th>Cyp51A substitution(s)</th>
<th>MIC (mg/liter)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>AMB</td>
</tr>
<tr>
<td>1</td>
<td>V74-61</td>
<td>ITC</td>
<td>A9T</td>
<td>1</td>
</tr>
<tr>
<td>2</td>
<td>V76-03</td>
<td>ITC</td>
<td>A9T, F219I</td>
<td>1</td>
</tr>
<tr>
<td>3</td>
<td>V79-63</td>
<td>POS</td>
<td>A9T, F219I</td>
<td>1</td>
</tr>
<tr>
<td>4</td>
<td>V52-35</td>
<td>No</td>
<td>TR2/L98H</td>
<td>1</td>
</tr>
</tbody>
</table>

a Isolates 1, 2, and 3 were isogenic and recovered from an aspergilloma patient (29).

b Isolates 1 to 3 harbored an A9T mutation in the Cyp51A gene, suggesting another, yet unknown, resistance mechanism. AMB, amphotericin B; ITC, itraconazole. The infected mice were then observed for signs of disease for 21 days, and all remaining surviving mice were humanely euthanized under isoflurane anesthesia, and blood and internal organs were collected.

PK analysis of POS prophylaxis in mice. The procedure and pharmacokinetic (PK) parameters for POS prophylaxis are described in our previous study (39). Briefly, a total of 96 outbred CD-1 (Charles River, the Netherlands) female mice, 4 to 5 weeks old, weighing 20 to 22 g, were used to establish immunosuppressed pulmonary infection, as described above. Blood and bronchoalveolar lavage (BAL) samples were drawn at eight predetermined time points postinfection (0, 0.5, 1, 2, 4, 8, 12, and 24 h; 3 mice per each time point) and stored at −80°C (39). POS concentrations in plasma and BAL fluid were measured by a validated (for human and mouse matrices) ultra-performance liquid chromatography (UPLC) method with fluorescence detection, as described elsewhere (41). Geometric mean concentrations of total POS in plasma were calculated for each time point (n = 3 mice). Peak concentrations in plasma (Cmax) were directly observed from the data. Pharmacokinetic parameters were derived using noncompartmental analysis with Phoenix, version 6.2 (Pharsight, Inc.). The area under the plasma concentration-time curve (AUC) from time zero to 24 h post infusion (AUC0–24) was determined by use of the log-linear trapezoidal rule. The elimination rate constant was determined by linear regression of the terminal points of the log-linear plasma concentration-time curve. The terminal half-life was defined as ln2 divided by the elimination rate constant. Clearance (CL) was calculated as dose/AUC0–24. Concentrations of total POS in BAL fluid from three mice per time point were determined as described previously (41). Urea in BAL aspirate and plasma was measured utilizing a modified enzymatic assay (QuantiChrom urea assay kit, DIUR-500; BioAssay Systems) (42, 43). The concentration of POS in epithelial lining fluid (ELF) was then determined by use of the ratio of the urea concentration in BAL fluid (ureaBAL) to that in plasma (ureaPL) as described previously (38, 39, 42–47): drug concentrationELF = drug concentrationBAL × (ureaBAL/ureaPL).

Statistical analysis. All data analyses were performed using GraphPad Prism, version 5.0, software for Windows (GraphPad Software, San Diego, CA). The significance of the differences between the geometric means of the four isolates, including lag phase, first transition phase, log phase, and second transition phase, was determined using one-way analysis of variance (ANOVA), followed by Bonferroni’s multiple-comparison test. Mortality data were analyzed by a log rank test. Dose/MIC and AUC0–24/MIC ratios were calculated by dividing the dose (in milligrams per kilogram of body weight) by the AUC of the MIC. The dose, CLmax and AUC0–24/MIC ratio data were log10 transformed to approximate a normal distribution prior to statistical analysis. The relationship between the log10 survival rate and the log10 dose was modeled using a log10-log10 plot. A chi-square test was used to compare mortality rates for the different groups. Comparison of two groups was performed using a Student’s t test. Statistical significance was defined as a P value of <0.05. The fits were performed for survival data of each strain and all strains simultaneously. The goodness of fit was checked by use of the R2 value and visual inspection. Statistical significance was defined as a P value of <0.05 (two-tailed). The probability of expected pharmacodynamic (PD) target attainment (AUC/MIC) of POS prophylaxis versus treatment was determined for a range of A. fumigatus MICs, as described previously (48). In addition, the 50, 90, and 90% effective pharmacodynamic indices (EI50, EI90, and EI90, respectively) of the 24-h area under the concentration-time curve (AUC) of POS best correlating with efficacy were determined. For comparison, an F test was performed to define whether the best-fit values (log 50% effective dose [ED50]) differed between the four groups.

The treatment data used in Fig. 4 was obtained from our previously published study (24), for which an EI50 of 184.2 (95% confidence interval [CI]; 33.21 to 1,022) was shown to be the optimal pharmacodynamic index to treat disseminated infection caused by the A. fumigatus isolate (V52-35) for which the POS MIC was 0.5 mg/liter.
RESULTS

\textit{In vitro} susceptibility and fitness. The characteristics and \textit{in vitro} susceptibilities of the four \textit{A. fumigatus} isolates are shown in Table 1. All isolates grew well after 48 h of incubation at 35 to 37°C. The three isolates showed increasing POS MICs although the increase from 0.5 mg/liter to 16 mg/liter was not associated with additional mutations in the \textit{cyp51A} gene. Growth curves did not differ in shape and growth rates between the wild-type and two POS-resistant isogenic \textit{A. fumigatus} isolates. Similar growth characteristics were also observed for the nonisogenic isolate harboring the TR34/L98H resistance mechanism (data not shown).

\begin{table}[h]
\centering
\begin{tabular}{|c|c|c|c|c|}
\hline
POS dose & \(C_{\text{max}}\) & \(AUC_{0-24}\) & \(C_{\text{max}}\) & \(AUC_{0-24}\) \\
(mg/kg) & (mg/liter) & (mg · h/liter) & in ELF/C\text{max} & in ELF/AUC_{0-24} \\
Plasma & Plasma & ELF & (\%) & (\%) \\
\hline
4 & 5.51 & 1.58 & 72.69 & 14.69 & 28.68 & 20.21 \\
8 & 8.7 & 2.83 & 149.80 & 42.14 & 32.53 & 28.13 \\
16 & 10.92 & 3.62 & 198.90 & 62.23 & 33.15 & 31.29 \\
32 & 15.04 & 5.32 & 290.50 & 78.78 & 35.37 & 27.12 \\
\hline
\end{tabular}
\caption{Pharmacokinetic parameters of POS in plasma and ELF following 3 days of once-daily oral administration of 4, 8, 16, and 32 mg/kg in immunosuppressed mice\textsuperscript{a}}
\end{table}

\textsuperscript{a}For comparison, in humans the \(C_{\text{max}}\) and AUC\(_{0-24}\) values were 0.58 mg/liter and 15.06 mg · h/liter, respectively, with a dosing regimen of 200 mg three times daily (6).

\textbf{PK of POS.} The PK parameters of POS prophylaxis are shown in Table 2. The penetration of POS in ELF based on total drug was between 20.21 and 31.39%. At the range of 4 to 32 mg/kg dosing regimens, the total AUC\(_{0-24}\)/MIC was 145.4 to 581 in plasma and 29.38 to 157.56 in ELF for the isolates with MICs of \(\leq 0.5\) mg/liter.

As a comparison, the recommended dose of the oral suspension of POS is 200 mg three times a day for the prophylaxis of invasive fungal infections, which corresponds to an AUC of 115.06 mg · h/liter and a \(C_{\text{max}}\) of 0.58 mg/liter in plasma (6).

\textbf{Efficacy of POS prophylaxis.} (i) Survival curves. Figure 1 shows the survival curves of POS-treated mice by dose. The survival curves for all control groups receiving 0.9% saline orally showed a mortality of 100%. The survival at day 10 postinfection was significantly better for POS-treated mice than for controls (Fig. 1). A dose-response relationship was observed for each isolate. The maximum effect (100% survival) was reached at a dose of 16 mg/kg for the isolates with MICs of \(\leq 0.5\) mg/liter, independent of the corresponding genotype. Yet for the isolate with the POS MIC of \(> 16\) mg/liter, maximum effect was lower (less than 70%) than for other isolates, even with the highest dose (32 mg/kg).

(ii) Dose-response analysis. The dose-response curves for dosing regimens and control groups of POS prophylaxis are shown in Fig. 2. POS prophylaxis improved the survival of the mice in a dose-dependent manner. A dose-response relationship was observed that depended on the POS dose level but was inde-
dependent of the genotypes and azole resistance mechanisms. The Hill equation with a variable slope fitted the relationship between the dose and 10-day survival data well, with \( R^2 \) values of 0.96 (V74-61, wild type; MIC of 0.63 mg/liter POS), 0.98 (V76-03, F219I mutation; MIC of 0.5 mg/liter POS), 0.95 (V79-63, F219I mutation; MIC of >16 mg/liter POS), and 0.97 (V52-35, TR34/L98H mutation; MIC of 0.5 mg/liter POS), respectively. The 50% effective dose (ED\(_{50}\)) was 3.35 mg/kg (95% confidence interval [CI], 2.19 to 5.12 mg/kg), 2.83 mg/kg (95% CI, 1.81 to 4.43 mg/kg), and 14.08 mg/kg (95% CI, 9.06 to 21.90 mg/kg) for three genetically identical isolates with wild type phenotype and low and high POS resistance, respectively, and 3.03 mg/kg (95% CI, 1.91 to 4.80 mg/kg) for the isolate with different genotype and low resistance to POS.

(iii) Exposure-response analysis. The AUC for each dose, determined from PK experiments (Table 2), was used to calculate the AUC\(_{0-24}\)/MIC ratio for each isolate, as shown in Fig. 3. The exposure-response relationship had a sigmoidal shape. Increased POS exposure was required to obtain maximum efficacy in mice infected with the isolate with a MIC of >16 mg/liter compared to those infected with the isolate with a MIC of ≤0.5 mg/liter.

The Hill-type model with a variable slope fitted the relationship between the 24-h AUC/MIC ratio and 14-day survival well, with an \( R^2 \) value of 0.77 (P < 0.05). The 50% effective AUC for POS prophylaxis was 37.38 (95% confidence interval [CI], 7.130 to 196). We also determined the relationship between the in vivo efficacy and the peak level C\(_{\text{max}}\)/MIC (50% effective concentration [EC\(_{50}\)] of 1.74; CI, 0.073 to 41.28; \( R^2 \) value of 0.76). However, the
AUC$_{0-24}$/MIC appeared to be the most important pharmacodynamic index correlating with prophylaxis, which was significantly different between *A. fumigatus* isolates with POS MICs of $0.5 \text{ mg/liter}$ and the isolate with a POS MIC of $16 \text{ mg/liter}$ ($P = 0.05$).

Notably, in the current prophylaxis study, the 50% effective total AUC$_{0-24}$/MIC was 93.58 (95% CI, 13.90 to 629.9) in order to prevent invasive pulmonary infection caused by the *A. fumigatus* isolate (V 52-35) with the POS MIC of $0.5 \text{ mg/liter}$. However, in preclinical treatment studies, we have previously shown that a two-times-higher exposure was required to treat infection caused by this isolate (EI$_{50}$ of 184.2 [95% CI, 33.21 to 1,022]) (Fig. 4).

(iv) **Comparative efficacy of POS prophylaxis against the four isolates.** In order to compare the efficacy of POS prophylaxis in preventing infection caused by the different isolates, the best-fit values for the curves were defined based on the EI$_{50}$, EI$_{80}$, and EI$_{90}$ of the AUC of POS and compared to each other (Table 3). The efficacy of POS prophylaxis was significantly different between *A. fumigatus* isolates with POS MICs of $\leq 0.5 \text{ mg/liter}$ and the isolate with a POS MIC of $>16 \text{ mg/liter}$ ($P < 0.05$). The null hypothesis was rejected in an $F$ test ($P = 0.0014$, $F = 10.72$, degrees of freedom, numerator $[df_n] = 3$; degrees of freedom, denominator $[df_d] = 11$), indicating that EI$_{50}$ was significantly different (Table 3).

**DISCUSSION**

Our model indicated that the efficacy of POS prophylaxis in low-resistant isolates (MIC of $0.5 \text{ mg/liter}$) was similar to that of mice infected with the isolate with the wild-type phenotype. In a previous study that investigated the efficacy of POS treatment of azole-resistant isolates, we observed that the efficacy of POS was reduced in mice infected with the isolate harboring the TR34/L98H resistance mechanism (MIC of $0.5 \text{ mg/liter}$) compared to that of mice infected with a wild-type isolate, indicating that higher doses of POS were required to achieve efficacy similar to that for the wild-type-infected mice (24). Our current model indicates that when...
POS is given as prophylaxis, the efficacy against isolates with a POS MIC of 0.5 mg/liter is similar to that of the wild-type isolate. It has been reported that the POS levels in the lung, at the site of infection/colonization, are relatively high (49, 50), which is consistent with the drug’s lipophilic characteristics and its increased intracellular permeability (51, 52). In our model we previously reported high POS levels in epithelial lining fluid, which might explain the high efficacy against low-POS-resistant isolates (38, 39). However, reduced efficacy was observed in isolates with high POS resistance (MIC of >16 mg/liter).

It is unlikely that differences in POS efficacies were due to differences in *A. fumigatus* fitness levels. Although the acquisition of resistance mechanisms during azole therapy has been associated with a fitness cost (33), isolates with resistance mechanisms in the cyp51A gene were shown to be as virulent as wild-type controls (54). In our current study we selected three isogenic isolates with increasing POS MICs and demonstrated similar in vitro growth characteristics, which indicates that the acquisition of a resistance mechanism was not associated with a fitness cost.

The exposure-response relationships of POS have been defined previously in experimental models of aspergillosis infections (24, 25, 55), for which a total AUC$_{0–24}$/MIC ratio between 167 and 178 was predictive of half-maximal efficacy, given that only the unbound fraction of a drug in serum/plasma is pharmacologically active. Considering the high degree of POS protein binding in plasma (98 to 99%) and negligible protein binding in ELF, the results of the current study indicated that effective local concentrations (less than 50% survival) might be achieved even at the lowest dose (4 mg/kg), with a free AUC$_{0–24}$/MIC ratio of 1.45 in plasma and 14.69 in ELF. Our model indicates that this level is high enough to prevent infection with *A. fumigatus* isolates with MICs of ≤0.5 mg/liter (Fig. 4). However, for the isolates with higher POS MICs (≥16 mg/liter), the obtained free AUC$_{0–24}$/MIC was ≤0.18 in plasma and ≤4.92 in ELF at highest dose (32 mg/liter), which indicates the possibility of breakthrough 1A. Given that a significant proportion of isolates harboring an azole resistance mechanism exhibit a POS MIC of <0.5 mg/liter (36), the effective exposure is highly probable to be achieved with the recommended dose of POS.

In a recent large international surveillance study, including 22 centers from 19 countries, the proportion of azole-resistant clinical *A. fumigatus* isolates was 3.4% (range, 0 to 26.1% per center) (J. W. M. van der Linden, M. C. Arendrup, A. Warris, K. Lagrou, H. Pelloux, P. M. Hauser, E. Chryssanthou, E. Mellado, S. E. Kidd, A. M. Tortorano, E. Dannaoui, P. Gaustad, J. W. Baddley, A. Uekötter, C. Lass-Flörl, N. Klimko, C. B. Moore, D. W. Denning, A. A. Pasiqalotto, C. Kübbler, S. Arikian-Akdagli, D. Andes, J. Meletiadis, L. Naumiuk, M. Nucci, W. J. G. Melchers, and P. E. Verweij, submitted for publication). Among the isolates with an azole-resistant phenotype, 50% exhibited a POS MIC of ≤0.5 mg/liter which according to our model could be prevented with POS prophylaxis. Given the above-mentioned epidemiology, in centers that choose to give POS prophylaxis to high-risk patients, the probability of breakthrough infection due to azole-resistant *A. fumigatus* appears to be very low.

Notably, the size of inoculum used for infection in the current preclinical study may not seem to represent human infections. However, the concordance of PK/PD index magnitudes obtained from this model and humans has been demonstrated in terms of efficacy and pharmacokinetics of antifungals against *A. fumigatus* infections, using survival as primary endpoint (22–24, 34, 39, 57). Thus, the results of our study can be useful in a human setting.

We conclude that POS is effective in preventing invasive pulmonary aspergillosis in our immunocompromised mouse model. However, our model indicates that treatment does not prevent the full range of POS resistance phenotypes. Possibly higher exposure can be obtained using the new formulations, i.e., a POS tablet, which may then also enable prevention of infection due to *A. fumigatus* isolates highly resistant to POS.

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