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 to azole fungicides (28). Surveillance studies indicate that in areas of endemicity up to two-thirds of patients with azole-resistant aspergillus diseases have no history of azole 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).

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 morpholinepropanesulfonic 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>Priorazole 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>TR49/L98H</td>
<td>1</td>
</tr>
</tbody>
</table>

* Isolates 1, 2, and 3 were isogenic and recovered from an aspergilloma patient (29). Isolate number 4 was unrelated to isolates 1 to 3 and was obtained from a patient with proven invasive aspergillosis.

The animal studies were conducted in accordance with the recommendations of the European Community (Directive 2010/63/EU revising Directive 86/609/EEC on the protection of animals used for scientific purposes adopted on 22 September 2010), and all animal procedures were approved by the Animal Welfare Committee of Radboud University (RUC 2011-174).

Survival in days postinfection was recorded for each mouse in each group and was considered the primary outcome effect measure to assess the therapeutic efficacy of POS prophylaxis (40). The infected mice were examined at least three times daily. These clinical inspections were carried out in order to ensure that there were no cases of dehydration, torticollis, staggering, high weight loss (a decrease of 15% within 48 h or 20% within 24 h), or drop in body temperature to below 33°C. Mice demonstrating these signs of disease were humanely terminated. On day 15 postinfection, 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 predefined 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) ultrasensitive 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 (Phar- sight, 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 urea concentration in BAL fluid (ureaBAL) to that in plasma (ureaPlasma) as described previously (38, 39, 42–47): drug concentrationELF = drug concentrationBAL × ureaPlasma/ureaBAL.

Statistical analysis. All data analyses were performed using GraphPad Prism, version 5.0, software for Windows (GraphPad Software, San Di- ego, CA). The significance of the differences between growth characteristics of 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 MIC of the MIC. The dose, Cmax, and AUC0–24/MIC ratio data were log10 transformed to approximate a normal distribution prior to statistical analysis. The relationship between the in vivo prophylaxis (survival), dose, and AUC0–24/MIC was determined by nonlinear regression analysis and the Hill equation, with a variable slope fitted to the data both for each individual isolate and for pooled survival data, with the maximum effect (maximum survival) constrained at ≤100%. 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, 80, and 90% effective pharmacodynamic indices (E50, E80 and E90, 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 ED50 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

In vitro susceptibility and fitness. The characteristics and in vitro susceptibilities of the four *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 *cyp51A* gene. Growth curves did not differ in shape and growth rates between the wild-type and two POS-resistant isogenic *A. fumigatus* isolates. Similar growth characteristics were also observed for the nonisogenic isolate harboring the TR34/L98H resistance mechanism (data not shown).

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 AUC₀–₂₄/MIC was 145.4 to 581 in plasma and 29.38 to 157.56 in ELF for the isolates with MICs of ≤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 Cₘₐₓ of 0.58 mg/liter in plasma (6).

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 ≤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-

### TABLE 2 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

<table>
<thead>
<tr>
<th>POS dose (mg/kg)</th>
<th>Cₘₐₓ (mg/liter)</th>
<th>AUC₀–₂₄ (mg · h/liter)</th>
<th>Cₘₐₓ in ELF/Cₘₐₓ in plasma ratio (%)</th>
<th>AUC₀–₂₄ in ELF/AUC₀–₂₄ in plasma ratio (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Plasma ELF</td>
<td>Plasma ELF</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>5.51</td>
<td>1.58</td>
<td>72.69</td>
<td>14.69</td>
</tr>
<tr>
<td>8</td>
<td>8.73</td>
<td>2.83</td>
<td>149.80</td>
<td>42.14</td>
</tr>
<tr>
<td>16</td>
<td>10.92</td>
<td>3.62</td>
<td>198.90</td>
<td>62.23</td>
</tr>
<tr>
<td>32</td>
<td>15.04</td>
<td>5.32</td>
<td>290.50</td>
<td>78.78</td>
</tr>
</tbody>
</table>

For comparison, in humans the Cₘₐₓ and AUC₀–₂₄ values were 0.58 mg/liter and 15.06 mg · h/liter, respectively, with a dosing regimen of 200 mg three times daily (6).
pendent 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 \( \text{AUC}_{0-24}/\text{MIC} \) 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 \( C_{\text{max}}/\text{MIC} \) (50% effective concentration \( [\text{EC}_{50}] \) of 1.74; CI, 0.073 to 41.28; \( R^2 \) value of 0.76). However, the

![FIG 2 Fourteen-day survival as a function of posaconazole dose against four A. fumigatus isolates. Shown are data for the three isogenic isolates harboring A9T and F219I point mutations in the \( \text{cyp51A} \) gene with POS MICs of 0.063 mg/liter (V 74-61), 0.5 mg/liter (V 76-03), and >16 mg/liter (V 79-63) and for a genetically different isolate with a POS MIC of 0.5 mg/liter (V52-35) harboring the TR34/L98H resistance mechanism. POS prophylaxis improved the survival of the infected mice in a dose-dependent manner for all four isolates. The curves indicate fits with the Hill equation for each isolate. ED\(_{50}\), 50% effective dose.](aac.asm.org/content/59/3/1490/F2.large.jpg)

![FIG 3 Percent survival as a function of the POS AUC\(_{0-24}/\text{MIC} \). The curve is the model fit with the Hill equation for each datum.](aac.asm.org/content/59/3/1490/F3.large.jpg)
AUC₀−₂⁴/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 mg/liter and the isolate with a POS MIC of 16 mg/liter (*P* < 0.05).

Notably, in the current prophylaxis study, the 50% effective total AUC₀−₂⁴/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) for which the POS MIC was 0.5 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 (EI₅₀ 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 EI₅₀, EI₈₀, and EI₉₀ 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 ≤0.5 mg/liter and the isolate with a POS MIC of >16 mg/liter (*P* < 0.05). The null hypothesis was rejected in an *F* test (*P* = 0.0014, *F* = 10.72, degrees of freedom, numerator [dfₙ] = 3; degrees of freedom, denominator [df_d] = 11), indicating that EI₅₀ was significantly different (Table 3).

**DISCUSSION**

Our model indicated that the efficacy of POS prophylaxis in low-resistant isolates (MIC of 0.5 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 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

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**TABLE 3** The comparison of efficacy of POS prophylaxis between four *A. fumigatus* isolates based on the EI₅₀, EI₈₀, and EI₉₀ values of the 24-h AUCₕ."
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 _cytP51A_ 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 AUC0–24/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 AUC0–24/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 AUC0–24/MIC was ≤0.18 in plasma and ≤4.92 in ELF at highest dose (32 mg/ liter), which indicates the possibility of breakthrough IA. 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. C. Pasqualotto, C. Kibbler, S. Arikana-Akdağlı, D. Andes, J. Melletiadis, L. Naumuki, 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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