IN VIVO–IN VITRO MODEL FOR THE ASSESSMENT OF CLINICALLY RELEVANT ANTIMALARIAL CROSS-RESISTANCE


Department of Specific Prophylaxis and Tropical Medicine, Institute of Pathophysiology, University of Vienna, Austria; Bangkok Hospital for Tropical Diseases, Faculty of Tropical Medicine, Mahidol University, Bangkok, Thailand

Abstract. Cross-resistance may be considered one of the most important factors leading to decreased drug susceptibility of Plasmodium falciparum. The study aimed to determine whether clinically relevant cross-sensitivity of P. falciparum existed between artemisinin and mefloquine. Seventy-six patients with falciparum malaria were admitted and treated with artemisinin derivatives. Treatment response parameters were assessed and in vitro drug sensitivity tests were performed with artemisinin, mefloquine, quinine, and chloroquine. Distinct in vitro cross-sensitivity between artemisinin and mefloquine was observed (p = 0.604; P < 0.001). To assess the relevance of this finding for clinical cross-resistance, we used an analytical model based on the relation of in vivo treatment response parameters (fever, parasite and symptom clearance) to a single reference drug with in vitro drug sensitivity data of several other drugs. Artemisinin (R = 0.554; P = 0.009) and mefloquine (R = 0.615; P = 0.002) in vitro drug sensitivities were equally well reflected in the in vivo treatment response to artemisinin, thereby suggesting the clinical relevance of in vitro cross-sensitivity.

INTRODUCTION

Ever since the discovery of the first cases of chloroquine resistance along the Thai-Cambodian border in the late 1950s, Southeast Asia has played an important role as a focus for the occurrence of drug-resistant strains of Plasmodium falciparum. The subsequent development of resistance to other antimalarials led to the introduction of mefloquine and finally its combination with artemesunate as the standard regimen for the treatment of falciparum malaria in Thailand. In recent years, however, several studies describe a close in vitro activity correlation and cross-sensitivity between these 2 substances, which are currently presumably the 2 most important drugs in the treatment of multidrug-resistant falciparum malaria.

Cross-resistance may be considered one of the most important factors leading to decreased drug susceptibility of P. falciparum. In part because of this phenomenon, there has been need to periodically replace outdated treatment regimens with new antimalarials. The determination of antimalarial cross-resistance is generally based on the correlation of in vitro drug sensitivity parameters. In vitro correlations, however, do not necessarily reflect clinical cross-resistance. The aim of the study was therefore to find a new model for the determination of the clinical relevance of cross-resistance between antimalarial drugs on the basis of the relation of therapeutic response parameters to the in vitro drug sensitivity of P. falciparum. Because of the importance of these drugs, special emphasis was put on artemisinin derivatives and their relation to mefloquine.

MATERIALS AND METHODS

The study was designed to use in vivo and in vitro data acquired from patients included in controlled clinical trials at the Bangkok Hospital for Tropical Diseases (Faculty of Tropical Medicine, Mahidol University) obtained from June 1999 to March 2000. Written informed consent was obtained from all adult participants or from parents or legal guardians of minors. The study protocols were approved by the ethical review board of the Faculty of Tropical Medicine, Mahidol University.

Seventy-six patients with a median age of 24.5 years of both sexes with microscopically confirmed P. falciparum infections were included in the study. All patients with plasmodial infections other than P. falciparum as well as women who were pregnant or lactating were excluded. Patients were excluded from the study if they had a history of antimalarial drug intake before admission: artemisinin within the past 7 days, 4-aminooquinolines within the past 14 days, pyrimethamine and sulfonamides within the past 28 days, or mefloquine within the past 56 days. History of drug intake before admission was taken, and Dill and Glazko's test for 4-aminooquinolines and the Lignin test for sulfonamides were performed to detect pretreatment.

In vivo test procedure. Patients were admitted to the Bangkok Hospital for Tropical Diseases and followed for 28 days to assess clinical findings, to eliminate the possibility of reinfection, and to observe cases of recrudescence. Patients were treated with a mean total dose of 11 mg/kg of artemisinin derivatives over a period of at least 3 days. To exclude a significant impact of the combination partners on the treatment response parameters, only drugs known to have a slow onset of action were used, and mefloquine was not administered before full parasite clearance. Body temperature, pulse, and respiration rates were recorded every 4 hr, and signs and symptoms were evaluated every day for the first 8 days.

Parasitological examination was performed by counting the parasites on thick and thin blood films every 12 hr. Parasite clearance time was defined as the time from the start of treatment until blood films were negative for asexual parasites of P. falciparum for the first time and remained negative for the next 48 hr. Fever clearance time was defined as the time from the start of treatment until the oral temperature dropped to below 37.5°C and remained below this temperature during the next 48 hr. A score of 0 to 4 (0 = none, 1 = mild, 2 = requires treatment, 3 = requires bed rest, and
ASSSESSMENT OF ANTIMALARIAL CROSS-RESISTANCE

TABLE 1
Correlation of in vitro activity at various effective concentrations for 4 antimalarial drugs

<table>
<thead>
<tr>
<th>Drug</th>
<th>n</th>
<th>EC50</th>
<th>P</th>
<th>EC90</th>
<th>P</th>
<th>EC95</th>
<th>P</th>
</tr>
</thead>
<tbody>
<tr>
<td>ART-MEF</td>
<td>35</td>
<td>0.604</td>
<td>&lt;0.001†</td>
<td>0.580</td>
<td>&lt;0.001†</td>
<td>0.576</td>
<td>&lt;0.001†</td>
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<tr>
<td>ART-QNN</td>
<td>35</td>
<td>0.206</td>
<td>&gt;0.05</td>
<td>0.084</td>
<td>&gt;0.05</td>
<td>0.063</td>
<td>&gt;0.05</td>
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<tr>
<td>ART-CHL</td>
<td>35</td>
<td>0.211</td>
<td>&gt;0.05</td>
<td>0.174</td>
<td>&gt;0.05</td>
<td>0.241</td>
<td>&gt;0.05</td>
</tr>
<tr>
<td>MEF-QNN</td>
<td>35</td>
<td>0.485</td>
<td>&lt;0.003†</td>
<td>0.348</td>
<td>0.041†</td>
<td>0.272</td>
<td>&gt;0.05</td>
</tr>
<tr>
<td>MEF-CHL</td>
<td>35</td>
<td>0.212</td>
<td>&gt;0.05</td>
<td>0.102</td>
<td>&gt;0.05</td>
<td>0.062</td>
<td>&gt;0.05</td>
</tr>
<tr>
<td>QNN-CHL</td>
<td>35</td>
<td>0.288</td>
<td>&gt;0.05</td>
<td>0.282</td>
<td>&gt;0.05</td>
<td>0.361</td>
<td>0.03†</td>
</tr>
</tbody>
</table>

* ART = artemisinin, CHL = chloroquine, EC = effective concentration (at 50, 90 and 95%); MEF = mefloquine; ρ = correlation coefficient; QNN = quinine.
† Statistically significant as determined by Spearman’s rank correlation analysis.

4 = comatose) was assigned to the symptoms of all 76 patients, and the score was assessed every day within the first 8 days after the onset of treatment. An overall symptom score was calculated for every patient by adding daily scores, and the time was calculated until a complete clearance of symptoms was achieved (i.e., all scores were 0 and stayed at 0 for at least 48 hr).

In vitro test procedure. The in vitro tests for the measurement of the drug sensitivity of P. falciparum followed the standard methodology for the assessment of the inhibition of schizont maturation. Heparinized venous blood samples were drawn from every patient before the onset of treatment and mixed with RPMI 1640 medium in a dilution of 1:5% in 20. A total of 50 μL of the blood medium mixture was applied to each well of 96-well flat-bottomed microtiter plates predosed with ascending quantities of artemisinin (0.15–150 pmol/well), mefloquine (2–128 pmol/well), quinine (4–256 pmol/well), and chloroquine (1–64 pmol/well). After an incubation of 24 hr at 37.5°C (± 0.5°C), the samples were harvested, and the slides were microscopically counted and later reexamined for the correctness of the readings. The artemisinin plates were prepared at the Department of Specific Prophylaxis and Tropical Medicine, Institute of Pathophysiology, University of Vienna, Austria; the mefloquine, quinine, and chloroquine plates were supplied by the World Health Organization, Regional Office for the Western Pacific, Manila, Philippines.

Statistical evaluation. Log-probit analysis of regression (log-dose and probit-response) was used to evaluate in vitro drug sensitivity tests. Correlations of clinical treatment response and in vitro response parameters were studied by means of standard correlation analysis and multiple linear regression models at a significance level of α = 5% (P < 0.05). Principal parameters used for multiple regression analysis were parasite clearance times (PCT), fever clearance times (FCT), and symptom clearance times (SCT) for in vivo drug response and effective concentrations (50, 90, and 95% effective concentrations [EC50, EC90, and EC95]) for in vitro sensitivity. Nonparametric procedures were used for data that did not pass the Kolmogorov-Smirnov test for normal distribution.

RESULTS

In vivo results. The median FCT for all 76 patients was 28.0 hr. Only 3 patients showed a FCT of >100 hr, whereas 3 patients never developed fever (i.e., an oral temperature of ≥37.5°C). The median PCT50 was 41.0 hr (range, 19.7–65.0 hr) and the mean clearance times for 50 and 90% of the parasites (PCT50 and PCT90) were 8.6 hr (1.6–21.5 hr) and 15.3 hr (2.9–28.6 hr), respectively. The median SCT was found to be 72 hr within a range of 0–192 hr, and the median overall symptom score was 10 points (range, 0–165 points). No significant differences were found for any of these variables between the means of the 35 isolates, which were successfully tested for their in vitro drug susceptibility, as compared with the whole sample of 76 patients. The overall cure rate was 89%. Eight patients showed recrudescences within the observation period. The mean duration of time until the parasites reappeared in blood films was 17.6 ± 2.1 days (range, 15–21 days). All 8 patients showed parasite clearance within 120 hr and were therefore classified as RI cases with late recrudescence.

In vitro results. Parallel to the assessment of clinical improvement, 35 isolates were successfully tested for their in vitro susceptibility to artemisinin, mefloquine, quinine, and chloroquine. The geometric mean parasite density for these blood samples before treatment was 13,542 asexual parasites per microliter of blood. Individual ECs for all drugs were obtained by applying log-probit regression analysis to the culture results. The geometric mean of the individual EC50, EC90, and EC95 values for artemisinin were 21.0, 78.2, and 112.4 nmol/L, respectively. The corresponding values for mefloquine were 704.5, 1,718.0, and 2,211.7 nmol/L; for quinine, 357.1, 862.2, and 1,106.9 nmol/L; and for chloroquine, 2,525.0, 6,878.4, and 9,826.3 nmol/L.

In vitro correlations. The same number of isolates (n = 35) was used to correlate the individual ECs of artemisinin, mefloquine, quinine, and chloroquine at the EC50, EC90, and EC95 level, by means of Spearman’s rank correlation analysis (Table 1). Highly significant correlations with coefficients (ρ) as high as 0.604 (P < 0.001) were found at all EC levels between the in vitro drug susceptibility to artemisinin and mefloquine, whereas no such relation was found with quinine (ρEC50 = 0.206; P > 0.05) and chloroquine (ρEC90 = 0.211; P > 0.05). Statistically significant activity correlations were also found between quinine and mefloquine at the lower EC levels (ρEC50 = 0.485; P < 0.005) and between quinine and chloroquine at EC90 (ρEC90 = 0.361; P < 0.05).

In vivo–in vitro correlations. In the course of the correlation analysis between the in vitro results of artemisinin and the in vivo clinical response parameters, a highly significant association was found between effective concentrations and the fever clearance times at EC50 (ρEC50 = 0.551; P = 0.001), EC90 (ρEC90 = 0.557; P = 0.001), and EC95 level (ρEC90 = 0.575; P < 0.001). Artemisinin EC values did not significantly correlate with parasite and symptom clearance. Nevertheless, both parameters were included in the multivariate
Table 2

<table>
<thead>
<tr>
<th>Drug</th>
<th>EC 90</th>
<th>n</th>
<th>df</th>
<th>R</th>
<th>Adjusted R²</th>
<th>P</th>
</tr>
</thead>
<tbody>
<tr>
<td>ART</td>
<td>EC 90</td>
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<td>0.554</td>
<td>0.240</td>
<td>0.009†</td>
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<td></td>
<td>EC 95</td>
<td>35</td>
<td>3+31</td>
<td>0.578</td>
<td>0.269</td>
<td>0.005†</td>
</tr>
<tr>
<td>MEF</td>
<td>EC 90</td>
<td>35</td>
<td>3+31</td>
<td>0.615</td>
<td>0.319</td>
<td>0.002†</td>
</tr>
<tr>
<td></td>
<td>EC 95</td>
<td>35</td>
<td>3+31</td>
<td>0.674</td>
<td>0.402</td>
<td>&lt;0.001†</td>
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<tr>
<td>QNN</td>
<td>EC 90</td>
<td>35</td>
<td>3+31</td>
<td>0.237</td>
<td>0.035</td>
<td>&gt;0.05</td>
</tr>
<tr>
<td></td>
<td>EC 95</td>
<td>35</td>
<td>3+31</td>
<td>0.238</td>
<td>0.034</td>
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<tr>
<td></td>
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<td></td>
<td>0.259</td>
<td>0.023</td>
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<tr>
<td></td>
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<td></td>
<td>0.462</td>
<td>0.137</td>
<td>&gt;0.05</td>
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<tr>
<td>CHL</td>
<td>EC 90</td>
<td>35</td>
<td>3+31</td>
<td>0.462</td>
<td>0.137</td>
<td>&gt;0.05</td>
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<tr>
<td></td>
<td>EC 95</td>
<td>35</td>
<td>3+31</td>
<td>0.406</td>
<td>0.086</td>
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<td></td>
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<td></td>
<td>0.387</td>
<td>0.131</td>
<td>&gt;0.05</td>
</tr>
</tbody>
</table>

*ART = artemisinin; CHL = chloroquine; df = degrees of freedom; EC = effective concentration (at 50, 90, and 95%); MEF = mefloquine; QNN = quinine; R = correlation coefficient. ART treatment response parameters (fever, parasitic, and symptoms clearance times) were used as independent variables and in vitro drug sensitivity data (effective concentrations of ART, MEF, QNN, and CHL were used as dependent variables).
†Statistically significant.

As compared with clinical trials, in vitro drug sensitivity tests offer comparatively objective results. In vitro drug sensitivity tests are not influenced by the patient’s immune system or the formulation, absorption, or distribution of the drug, and they offer a simple way to assess cross-resistance between different antimalarials. However, relatively little is known about their clinical relevance. In this study, a combined in vivo–in vitro model was therefore used to assess the clinical relevance of in vitro cross-reactivity.

Because each of the individual treatment response parameters was found to be of limited value for the predictability of drug sensitivity, a more complex system was used, one based on a combination of FCT, PCT, and SCT. The aim was to find a quantitative measure to reflect in vivo drug sensitivity on a more comprehensive basis than individual clinical parameters. Effective concentrations were used as quantitative parameters of in vitro drug sensitivity. At the same time, the system should permit the correlation of in vivo and in vitro findings for a number of drugs other than the one tested in vivo. This rationale aimed to determine whether cross-sensitivities, which are found between in vitro results of 2 different drugs (such as between effective concentrations of artemisinin and mefloquine), are reflected in treatment response data and may therefore be of relevance for the development of clinical cross-resistance.

The naturally close correlation between artemisinin in vivo and in vitro results, which was found in the course of this analysis, reflects the dependence of treatment response on the drug sensitivity of P. falciparum. The similarly close relation of artemisinin in vivo findings with ECs of mefloquine, on the other hand, which were an almost perfect match for the close in vitro correlation of these substances, may only be explained by a distinct, clinically relevant cross-sensitivity. The fact that neither quinine nor chloroquine ECs showed any significant correlation with artemisinin treatment response indicates that in these cases, no clinical cross-resistance would have to be expected. The complex relation between the individual drugs and their relation to artemisinin treatment response is shown in Figure 1.

Some authors have suggested that the short half-life of artemisinin derivatives as well as their novel chemical structure would protect this class of antimalarials from the development of drug resistance. This study suggests, however, that future development of resistance of P. falciparum to artemisinin derivatives may not merely depend on the pharmacokinetic properties of artemisinin, but also on the future development of mefloquine resistance. The reason for the close relationship between artemisinin and mefloquine may possibly be found in parallels in their mode of action. This assumption is also supported by the fact that these drugs are synergistic when used in combination. Furthermore, the role of the pfmde1 gene as a possible factor for the development of multidrug resistance, especially to mefloquine and artemisinin, has recently been proposed.

The findings from this study indicate a clinically relevant (in vivo) cross-sensitivity between artemisinin and mefloquine, similar to the one previously found in vitro. Such a relationship could have a significant impact on the future development of the artemisinin drug sensitivity of P. falciparum, especially if mefloquine is employed in highly malaria-endemic areas.

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Authors’ addresses: H. Noedl, W. H. Wernsdorfer, H. Kollaritsch,
Figure 1. Model for the correlation of in vitro drug sensitivity of individual drugs with each other and with artemisinin treatment response parameters (arrows represent correlations, crossed-out arrows the lack of a correlation). The upper part displays the clinically relevant in vivo correlation between artemisinin and mefloquine. ECs = effective concentrations; FCT = fever clearance time; PCT = parasite clearance time; SCT = symptom clearance time.

and G. Wiedermann, Department of Specific Prophylaxis and Tropical Medicine, Institute of Pathophysiology, University of Vienna, Kinderspitalgasse 15, A-1095, Vienna, Austria. S. Krudsood, P. Wilairatana, P. Viriyavejakul, and S. Looareesuwan, Faculty of Tropical Medicine, Mahidol University, 420/6 Rajvithi Road, Bangkok 10400, Thailand.

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