Proveblue (Methylene Blue) as an Antimalarial Agent: In Vitro Synergy with Dihydroartemisinin and Atorvastatin

Proveblue (international patent PCT/FR/2007/001193), which is a methylene blue preparation that complies with the European Pharmacopoeia and contains limited organic impurities and heavy metals of recognized toxicity, has previously been demonstrated to possess in vitro antimalarial activity (at a geometric mean 50% inhibitory concentration [IC50] of 3.62 nM) against 23 Plasmodium falciparum strains that are resistant to various other antimalarials (11). No significant association was found between Proveblue IC50s and polymorphisms in the genes that are involved in quinoline resistance, such as pfcr, pfmdr1, pfmdr2, pfnr1, and pfnhe-1; furthermore, there was no significant association between Proveblue IC50s and the copy numbers of pfmdr1 and pfmdr2 (11).

In the present study, we tested the effects of Proveblue in combination with the standard antimalarial drugs chloroquine (CQ), monodesethylamodiaquine (MDAQ; the active metabolite of amodiaquine), quinine (QN), mefloquine (MQ), and dihydroartemisinin (DHA) and with atorvastatin (AVA), a potential antimalarial drug (9, 12).

The methodology of the in vitro potentiating test was previously described (7). We used nine well-established Plasmodium falciparum strains that had different phenotypic profiles: 3D7, W2, Palo Alto, FCR3, FCM29, ImtVol, ImtK2, ImtL1, and Imt10500 (3). Each strain was assessed once in triplicate for eight W2, Palo Alto, FCR3, FCM29, ImtVol, ImtK2, ImtL1, and falciparum strains that had different phenotypic profiles: 3D7, MDAQ against the nine combination with CQ and additive effects in combination with concentrations of standard drugs in combination with 10 concentrations of Proveblue ranging from 0.004 to 10 nM.

Proveblue was shown to have antagonistic effects in combination with CQ and additive effects in combination with MDAQ against the nine P. falciparum strains (Fig. 1). Proveblue exhibited noticeable synergistic effects in combination with MQ and QN but high synergistic effects in combination with DHA and AVA. CQ IC50s were not significantly reduced in combination with Proveblue (Table 1). MQ and DHA IC50s were significantly reduced from 12.6% to 31.54% and from 18.9% to 48%, respectively, when Proveblue was added at concentrations ranging from 0.04 to 0.63 nM (9- to 140-fold less than the mean Proveblue IC50).

In a previous study, we demonstrated that there was no significant correlation between DHA and Proveblue IC50s (r² = 0.056; P = 0.275) (11). All of these data suggest that Proveblue could be effective as a good partner with artemisinin derivatives. Recent trials using artesunate provided evidence that Nep MB (despite not complying with the European Pharmacopoeia) is safe and relatively effective in uncomplicated falciparum malaria (4, 15). In addition, Nep MB has a gametocytocidal effect both in vitro and in vivo (1, 4). As suggested by in vitro combination data, the combination of Nep MB and CQ is not sufficiently effective against malaria in vivo (8).

Proveblue demonstrated synergistic effects in combination with AVA, a synthetic inhibitor of 3-hydroxy-3-methylglutaryl-coenzyme A. AVA IC50s were significantly reduced from 24.6% to 63.1% when Proveblue was added at concentrations ranging from 0.04 to 0.63 nM (9- to 140-fold less than the mean Proveblue IC50).

These results were in agreement with the previous data on methylene blue noncompliant with the European Pharmacopoeia (Nep MB) that presented an antagonistic effect of Nep MB in combination with CQ against a CQ-resistant K1 strain but additive effects in combination with MQ and QN (2). More interestingly, the combination of Nep MB with artemisinin, artesunate, or artemether was found to act synergistically on the K1 strain (2). Garavito et al. found antagonism of Nep MB in combination with amodiaquine; additive effects in combination with CQ, MQ, and artemether; and synergy in combination with QN (5). Artemisinin induces a synergistic interaction with methylene blue; i.e., artemisinin reoxidizes leucomethylene blue, which is produced by reduction of methylene blue in parasites by the NADPH-flavin reductase system, in methylene blue, which both together oxidize FADH2 (6). This oxidation is inhibited by CQ, which interferes with redox processes.

In Table 1, the reduction of the in vitro IC50 of CQ, MDAQ, QN, MQ, DHA, and AVA in combination with Proveblue is shown. The data show that Proveblue demonstrated synergistic effects in combination with AVA, a synthetic inhibitor of 3-hydroxy-3-methylglutaryl-coenzyme A. AVA IC50s were significantly reduced from 24.6% to 63.1% when Proveblue was added at concentrations ranging from 0.04 to 0.63 nM (9- to 140-fold less than the mean Proveblue IC50).

<table>
<thead>
<tr>
<th>Antimalarials</th>
<th>Avg % IC50 reduction [95% CI] (P value) with Proveblue at:</th>
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<tr>
<td></td>
<td>0.04 nMb</td>
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<tr>
<td>CQ</td>
<td>4.3 (0.9–7.7) (0.250)</td>
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<tr>
<td>MDAQ</td>
<td>6.2 (0.5–17.6) (0.889)</td>
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<tr>
<td>QN</td>
<td>3.0 (0.8–6.3) (0.820)</td>
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<tr>
<td>MQ</td>
<td>12.6 (5.0–20.1) (0.027)</td>
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<tr>
<td>DHA</td>
<td>18.9 (8.3–29.4) (0.012)</td>
</tr>
<tr>
<td>AVA</td>
<td>24.6 (11.3–35.4) (0.020)</td>
</tr>
</tbody>
</table>

*Means IC50/40. **Mean IC50/70. **Mean IC50/35. *bMean IC50/18. *cMean IC50/9.
0.04 to 0.63 nM. Like Proveblue, AVA improved the in vitro activity of MQ (14), QN (10), or DHA (13) and the IC50s of AVA were unrelated to the mutations that occurred in the transport protein genes that are involved in quinoline resistance (9). The synergistic effect of AVA on MQ was significantly associated with the *pfmdr1* copy number (14). However, there was no association between Proveblue activity and the *pfmdr1* copy number (11). Even if we cannot explain the synergy between Proveblue and AVA, this observation supports the calls for in vivo evaluations in the murine malaria model.

These results confirm the therapeutic potential of Proveblue, which is a new methylene blue that contains limited organic im-
purities and heavy metals of recognized toxicity and could be integrated into new, low-cost antimalarial combination therapies.

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REFERENCES