Inhibitory Effects of Pepstatin A and Mefloquine on the Growth of Babesia Parasites

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Abstract. We evaluated the inhibitory effects of pepstatin A and mefloquine on the in vitro and in vivo growths of Babesia parasites. The in vitro growth of Babesia bovis, B. bigemina, B. caballi, and B. equi was significantly inhibited (P < 0.05) by micromolar concentrations of pepstatin A (50% inhibitory concentrations = 38.5, 36.5, 17.6, and 18.1 μM, respectively) and mefloquine (50% inhibitory concentrations = 59.7, 56.7, 20.7, and 4 μM, respectively). Furthermore, both reagents either alone at a concentration of 5 mg/kg or in combinations (2.5/2.5 and 5/5 mg/kg) for 10 days significantly inhibited the in vivo growth of B. microti in mice. Mefloquine treatment was highly effective and the combination treatments were less effective than other treatments. Therefore, mefloquine may antagonize the actions of pepstatin A against babesiosis and aspartic proteases may play an important role in the asexual growth cycle of Babesia parasites.

INTRODUCTION

Babesiosis is an infectious disease caused by an intraerythrocytic protozoan of the genus Babesia; the parasites are transmitted by the bite of ticks of family Ixodidae such as Boophilus, Dermacentor, Rhizophagus, and Haemaphysalis.1 The main clinical symptoms of babesiosis in infected animals include fever, hemolytic anemia, jaundice, hemoglobinuria, and edema.2 A well-recognized disease of veterinary importance in cattle, horses, and dogs, babesiosis has also received increased attention as a globally distributed zoonosis in humans. In addition, serious economic losses have been caused by Babesia infections in the livestock and other industries.3 5

Although some anti-babesial agents have been used to control the disease, continuous searches for the development of new drugs against Babesia are caused by toxic side effects, repeated relapse of parasite infections, and the possibility of emerging drug-resistant parasites.6 Several novel anti-babesial drugs, such as triclosan,6 artesunate, pyrimethamine, pamaquine,7 hepiran,8 imidazole derivatives, staurosporine,9 and cysteine protease inhibitors,10 have been successfully studied by using in vitro and in vivo models. However, these drugs have not been evaluated for field application. Therefore, development of new compounds that have chemotherapeutic effects against babesiosis with high specificity for the parasite and no side effects in the host is desired.

Aspartic proteases (APs) are a widely distributed family of enzymes among protozoan parasites, and several APs, including those of Plasmodium falciparum (plasmepsin),11 Eimeria tenella (eimepsin),12,13 Cryptosporidium parvum (cryptompsin), and Trypanosoma cruzi (cruzipsin I and II),14 have been characterized. Among them, the P. falciparum (plasmepsin)11 enzyme of this class initiates the hemoglobin breakdown pathway that provides intraerythrocytic malaria parasites with nutritional resources. Inhibition of their activity results in the death of malaria parasites.15–17 Pepstatin A, a potent inhibitor of AP, binds to the active site of plasmepsins in food vacuoles of P. falciparum,18 prevents the degradation of hemoglobin, and kills malaria parasites. In in vitro studies, pepstatin A had a potent effect against cultured P. falciparum.19,20 In an in vivo study using a murine malaria model, pepstatin A cured P. vinckei-infected mice.20 Moreover, P. vivax AP is inhibited by pepstatin.21 Mefloquine is currently one of the recommended chemoprophylactic regimens for travelers visiting malaria-endemic areas.22 Recently, mefloquine has been used for treatment23,24 and prophylaxis25,26 against P. falciparum. Mefloquine works by attacking parasites once they have entered erythrocytes by killing the parasites and preventing them from further multiplications. However, its exact mechanism is unknown. A possible explanation is that mefloquine, which is similar to chloroquine and quinine, appears to interfere with the ability of the parasite to metabolize and use erythrocyte hemoglobin.26 Mefloquine might bind free heme, thus inhibiting the polymerization of heme or the swelling of food vacuoles. Conversely, mefloquine is believed to act by forming toxic heme complexes that damage parasitic food vacuoles. In addition, Mungthin and others27 reported that combination of plasmepsin I, the Ro40-3488 inhibitor, with a drug such as chloroquine, amodiaquine, quinine, or mefloquine, resulted in antagonism between plasmepsin I inhibitor and chloroquine and mefloquine.

The class of enzymes known as APs has not yet been characterized in Babesia parasites. Additionally, Babesia parasites have similarities to malaria parasites and the AP target genes present in the Babesia genome sequence database.28 Thus, the present study was conducted to evaluate possible inhibitory effects of pepstatin A and mefloquine, alone or combined, on the growth of bovine and equine Babesia parasites in vitro and in vivo experiments.

MATERIALS AND METHODS

Parasites. The Texas strain of B. bovis, the Argentina strain of B. bigemina, the U.S. Department of Agriculture strains of B. caballi and B. equi, and the Munich strain of B. microti were used in this study. Parasites were grown in bovine and equine erythrocytes by using a continuous micro-aerophilous stationary phase culture system.5 Medium M199 (for bovine Babesia and B. equi) and RPMI 1640 (for B. caballi) (both from Sigma-Aldrich, Tokyo, Japan) supplemented with 40% bovine serum (for bovine Babesia) or equine serum

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were prepared as described with some modifications. The Pepstatin A/mefloquine combinations (C1, C2, C3, and C4) were examined as described. Parasite-infected erythrocytes were used as models for bovine and equine parasites as a pH stabilizer (pH 7.2). Culture plates for parasites were incubated in atmospheres of 5% CO2 and 5% O2 at 37°C.

**Mice.** The Munich strain of *B. microti* was maintained by passage in blood of BALB/c mice. Twenty-four female BALB/c mice (8 weeks old) were obtained from CLEA Japan (Tokyo, Japan) and were used for in vivo studies.

**Chemical reagents.** Pepstatin A (Isovaleryl-L-Val-L-Val-hydroxymethyl) methyl-2-aminomethanesulfonic acid hemihydrate (229 mg/mL) was added to bovine *Babesia* parasite cultures in vivo Relating to the Care and Management of Experimental Animals set by the National Research Center for Protozoan Diseases, Obihiro University of Agriculture and Veterinary Medicine (Hokkaido, Japan).

Statistical analysis. Differences in percentages of parasitemia for in vitro cultures and among groups of in vivo studies were analyzed by using the independent Student’s *t*-test. *P* values < 0.05 was considered statistically significant for all tests.
RESULTS

In vitro inhibitory effect of pepstatin A on Babesia parasites. The in vitro growth of B. bovis (Figure 1A) and B. bigemina (Figure 1B) was significantly inhibited (P < 0.05) by 50 μM and 25 μM pepstatin A, respectively, and 5 μM pepstatin A significantly inhibited the growth of B. caballi (Figure 1C) and B. equi (Figure 1D). In the presence of 500 μM pepstatin A, growth of all parasites was completely suppressed. Complete suppression of parasites was observed with 2 μM diminazene aceturate (Figure 1A–C), and 100 μM tetracycline completely suppressed parasites (Figure 1C and D). Complete elimination of the growth of four species (B. bovis, B. bigemina, B. caballi, and B. equi) from pepstatin A-treated cultures was observed on day 3 (Figure 1A–D). Complete elimination of the three parasites from diminazene aceturate–treated cultures was observed on day 3 of the treatment for B. bovis, B. bigemina, and B. caballi (Figure 1A–C).

The IC₅₀ values of pepstatin A for growth inhibition of B. bovis, B. bigemina, B. caballi, and B. equi were 38.5, 36.5, 17.6, and 18.1 μM, respectively (Table 1). Subsequent viability tests showed that there was no re-growth of the four species with pepstatin A at a concentration of 500 μM. Moreover, pepstatin A affected the morphology of B. bovis (Figure 2B), B. bigemina (Figure 2D), B. caballi (Figure 2F), and B. equi (Figure 2H) parasites in treated cultures. The pepstatin-treated cultures showed a high number of degenerated

<table>
<thead>
<tr>
<th>Organism</th>
<th>IC₅₀ (μM)</th>
<th>References</th>
</tr>
</thead>
<tbody>
<tr>
<td>B. bovis</td>
<td>59.7</td>
<td>Present study</td>
</tr>
<tr>
<td>B. bigemina</td>
<td>56.9</td>
<td></td>
</tr>
<tr>
<td>B. caballi</td>
<td>20.7</td>
<td></td>
</tr>
<tr>
<td>B. equi</td>
<td>4</td>
<td></td>
</tr>
<tr>
<td>Plasmodium falciparum</td>
<td>0.028–0.13</td>
<td>19, 27, 34, and 35</td>
</tr>
</tbody>
</table>

*IC₅₀* values of mefloquine and pepstatin A for growth inhibition of different Babesia species

Table 1

IC₅₀ values of mefloquine and pepstatin A for growth inhibition of different Babesia species

### Table 1

<table>
<thead>
<tr>
<th>Organism</th>
<th>Mefloquine</th>
<th>Pepstatin A</th>
<th>References</th>
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<tr>
<td>B. bovis</td>
<td>59.7</td>
<td>38.5</td>
<td>Present study</td>
</tr>
<tr>
<td>B. bigemina</td>
<td>56.9</td>
<td>36.5</td>
<td></td>
</tr>
<tr>
<td>B. caballi</td>
<td>20.7</td>
<td>17.6</td>
<td></td>
</tr>
<tr>
<td>B. equi</td>
<td>4</td>
<td>18.1</td>
<td></td>
</tr>
<tr>
<td>Plasmodium falciparum</td>
<td>0.028–0.13</td>
<td>19, 27, 34, and 35</td>
<td></td>
</tr>
</tbody>
</table>

* *50% inhibitory concentration (IC₅₀) values are expressed as mefloquine and pepstatin A concentrations and are in micromolars of the growth medium and were determined on the day of maximum growth of the dimethylsulfoxide control in vitro culture by using a curve-fitting technique from three separate experiments. ND = not determined.

![Figure 1](image-url)
parasites, which appeared to be dot-shaped when compared with those in control cultures. Some parasites appeared as abnormally multidividing forms.

**In vitro inhibitory effect of mefloquine on Babesia parasites.** The growth of *B. bovis* (Figure 3A), *B. bigemina* (Figure 3B), *B. caballi* (Figure 3C), and *B. equi* (Figure 3D) was significantly inhibited (*P < 0.05*) by 1 μM mefloquine. In the presence of 100 μM of mefloquine, growth of all parasites was completely suppressed. In addition, *B. caballi* and *B. equi* were completely suppressed at concentrations of 50 and 25 μM, respectively. Complete suppression of diminazene aceturate–treated parasites was observed at a concentration of 2 μM (Figure 3A–C), and 100 μM tetracycline completely suppressed parasites (Figure 3C). After the mefloquine-treatment regimen, *Babesia* parasites were completely eliminated as early as day 1 (*B. caballi* and *B. equi*) and day 3 (*B. bovis* and *B. bigemina*) (Figure 3A–D). Complete elimination of the three parasites from diminazene aceturate–treated cultures was observed on day 1 (for *B. bovis*, *B. bigemina*, *B. caballi*, and *B. equi*) of treatment (Figure 3A–D), and tetracycline hydrochloride eliminated equine *Babesia* parasites on days 3 and 4 of treatment (Figure 3C and D). The IC_{50} values of mefloquine were 59.7, 56.9, 20.7, and 4 μM for *B. bovis*, *B. bigemina*, *B. caballi*, and *B. equi*, respectively (Table 1). Notably, *B. equi* was the most susceptible to mefloquine. Subsequent viability tests showed that there was no re-growth of bovine and equine *Babesia* parasites for all drug combinations used (Table 2).

**In vitro effects of pepstatin A and mefloquine on *B. microti* infection.** To examine the effects of pepstatin A and mefloquine on rodent *Babesia*, infected mice were treated with pepstatin A and mefloquine either alone or in combinations. In the pepstatin A-, mefloquine-, and combination-treated groups, levels of parasitemia were significantly lower than those in the control group (*P < 0.05*). Peak parasitemia reached an mean of 23.5% and 26.1% when treated with pepstatin A/mefloquine combinations of 5 mg/kg/5 mg/kg and 2.5 mg/kg/2.5 mg/kg, respectively, and 22.8% in treatment with 5 mg/kg pepstatin A 8 days after inoculation (Figure 5). The mean for the mefloquine-treated (5 mg/kg) group was 17.1%, and the mean for the control group was 67.3% (DMSO) 9 days after inoculation (Figure 5). Parasites were completely eliminated on day 23 post-infection in the treated groups. Conversely, parasites were completely cleared on day 30 post-infection in the control group. There were significant differences (*P < 0.05*) between the control and treatment groups on days 5–14 post-infection (Figure 5).

**DISCUSSION**

*Babesia*, an intraerythrocytic protozoan parasite, is similar to the malarial parasite *P. falciparum*. *Plasmodium* spp. use hemoglobin for reproduction in infected erythrocytes. Hemoglobin degradation takes place in an acidic food vacuole of
the parasite, and many current antimalarial drugs appear to disrupt important vacuolar functions.16

Aspartic protease inhibitors prevent degradation of hemoglobin and kill malaria parasites in vitro and in vivo.18–21 However, in the Babesia parasite, these processes require further investigations. In the current study, AP inhibitor and anti-malarial drug were demonstrated to significantly inhibit in vitro and in vivo growth of Babesia parasites. Exposure of parasites to higher concentrations of both reagents completely suppressed the growth of bovine and equine Babesia parasites tested. Because treatment with DMSO only had no effect on parasitic growth, if this growth inhibition was likely caused by effects of both reagents.

The IC50 values of pepstatin A against bovine Babesia parasites (B. bovis and B. bigemina) were 38.5 µM and 36.5 µM, respectively, and those of equine Babesia parasites (B. caballi and B. equi) were 17.6 µM and 18.1 µM, respectively. In malaria parasites, 4 µM pepstatin A (IC50) killed P. falciparum before trophozoite development and had a major effect on schizont maturation.19

The IC50 values of mefloquine against bovine Babesia parasites (B. bovis and B. bigemina) were 23 µM and 33.3 µM, respectively, and the values of mefloquine against equine Babesia parasites (B. caballi and B. equi) were 7.6 µM and 15 µM, respectively. Earlier studies showed that mefloquine was effective against P. falciparum in vitro, and showed low IC50 values of 28.7–130 nM.27,34,35 Mefloquine showed high IC50 values (272 µM) for mammalian cells (dog neurons).36

Doses of pepstatin A and mefloquine for bovine babesiosis most effectively suppressed parasite growth compared with other drugs that have been tested for the treatment of babesiosis.8,37 Conversely, effective doses of pepstatin A and mefloquine for bovine Babesia parasites were higher than those of other drugs tested in previous studies.10,29,38–41 For equine Babesia parasites, the IC50 values of pepstatin A and mefloquine were similar to those reported in previous studies40,42 but significantly lower than the IC50 values reported for equine Babesia.8

Moreover, the combination of pepstatin A and mefloquine produced antagonistic effects on in vitro-cultured parasites.
It was previously reported that the plasmepsin inhibitor Ro40-4388 and the antimalarial drug chloroquine interacted antagonistically against *P. falciparum.* Similar antagonistic actions between Ro40-4388 and mefloquine, quinine, amodiaquine, and halofantrine were found. Conversely, AP inhibitors reduce hemoglobin degradation and subsequent release of heme, thus antagonizing the antimalarial activity of these drugs. Furthermore, pepstatin A and mefloquine alone or in combination had inhibitory effects against *B. microti* infection in mice given single doses of 5 mg/kg, 5 mg/kg, or combinations of 2.5 mg/kg of each and 5 mg/kg of each during 6-day treatments. In the treated group, the parasitemia increased more slowly and achieved lower peaks compared with the parasitemia dynamics of the control group. In contrast, DMSO alone did not affect the growth of the parasites. Mefloquine was more effective than pepstatin A for treatment of infected mice, and pepstatin A/mefloquine combinations (2.5/2.5 mg/kg and 5/5 mg/kg) were less effective than each single treatment. The treated mice showed no signs of toxicity. As described in a previous study, *P. vinckei*-infected mice treated with 50 mg/kg of pepstatin A showed no toxic signs, and the *in vivo* effect was improved by combinations of AP and peptidyl cysteine inhibitors. Mefloquine was used for treatment of mice infected with *Schistosoma mansoni* and *S. japonicum* and of hamsters infected with *Opisthorchis viverrini* at concentrations of 100–400 mg/kg for 2–4 weeks. There were no signs of toxicity observed in the murine model. Thus, pepstatin A (5 mg/kg) and mefloquine (5 mg/kg) did not induce any signs of toxicity. These results are consistent with those of Seminov and others, who showed that 50 mg/kg of pepstatin A was used without any side effects. Therefore, mefloquine at this dose is not toxic to mice and might be used for treatment of babesiosis.

### Table 2

Percentages of actual parasitemia and growth inhibition of combined applications of pepstatin A and mefloquine for *Babesia bovis*, *B. bigemina*, *B. caballi*, and *B. equi*

<table>
<thead>
<tr>
<th>Peptatin A/mefloquine (μM)</th>
<th>B. bovis</th>
<th>B. bigemina</th>
<th>B. caballi</th>
<th>B. equi</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>P % †</td>
<td>I % ‡</td>
<td>V †</td>
<td>P % †</td>
</tr>
<tr>
<td>A (medium)</td>
<td>6 ± 2.8</td>
<td>0 +</td>
<td>5.6 ± 1.7</td>
<td>0 +</td>
</tr>
<tr>
<td>B (0.0002% DMSO)</td>
<td>5.2 ± 1.9</td>
<td>0 +</td>
<td>4.7 ± 1.6</td>
<td>0 +</td>
</tr>
<tr>
<td>P (high)</td>
<td>1.7 ± 1.1</td>
<td>67.3#</td>
<td>2.2 ± 1.2</td>
<td>53.2#</td>
</tr>
<tr>
<td>P (low)</td>
<td>2.3 ± 1.5</td>
<td>55.8#</td>
<td>2.7 ± 1.8</td>
<td>42.6#</td>
</tr>
<tr>
<td>M (high)</td>
<td>1.4 ± 0.8</td>
<td>73.1#</td>
<td>2 ± 0.7</td>
<td>57.7#</td>
</tr>
<tr>
<td>M (low)</td>
<td>2.1 ± 0.7</td>
<td>59.6#</td>
<td>2.5 ± 1.3</td>
<td>46.8#</td>
</tr>
<tr>
<td>C1</td>
<td>2.8 ± 1.1</td>
<td>46.2#</td>
<td>3 ± 1.5</td>
<td>36.2#</td>
</tr>
<tr>
<td>C2</td>
<td>2.2 ± 0.9</td>
<td>57.7#</td>
<td>2.3 ± 1.1</td>
<td>51.1#</td>
</tr>
<tr>
<td>C3</td>
<td>1.9 ± 0.8</td>
<td>63.5#</td>
<td>2 ± 0.9</td>
<td>57.5#</td>
</tr>
<tr>
<td>C4</td>
<td>1.3 ± 0.5</td>
<td>75#</td>
<td>1.9 ± 0.5</td>
<td>59.6#</td>
</tr>
</tbody>
</table>

†Percentage actual parasitemia is mean ± SD at day 3 of culture.
‡Percentage growth inhibition was determined at day 3 of culture by compared with the control parasitemia.
§Viability test indicates viability after 10 days of subsequent drug-free culture. + = viable.
#Significant difference (P < 0.05) between treated and control groups.
The gene sequences of APs can be found in the \textit{B. bovis} genome sequence database.\textsuperscript{28} Therefore, \textit{in vitro} and \textit{in vivo} inhibition of these enzymes indicates an important role of APs in the growth cycle of \textit{Babesia} parasites.

In conclusion, results of the present study showed that pepstatin A and mefloquine potently inhibit \textit{Babesia} parasites \textit{in vitro} and \textit{in vivo}. Furthermore, pepstatin A might antagonize actions of mefloquine on the inhibitory effects of \textit{in vitro} and \textit{in vivo} combinations. This study also shows that AP has an important role in the growth cycle of \textit{Babesia} parasites. Therefore, characterization, enzymatic activity, and effect of APs on hemoglobin degradation are needed.

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REFERENCES


