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Assessment of the growth inhibitory effect of gellan sulfate in rodent malaria in vivo

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Abstract
In our effort to discover novel antimalarials, we previously synthesized gellan sulfate, a novel anticoagulant derivative of gellan gum and showed that it inhibits the growth and invasion of erythrocytes by Plasmodium falciparum parasites in vitro (Recuenco et al. 2014. Sci Rep. 4:4723.). Gellan sulfate was also found to have low cytotoxicity and low anticoagulant activities in vitro. Here, we assessed gellan sulfate for its antimalarial effects in vivo. Despite its effectiveness in vitro, gellan sulfate inhibited the growth of both P. berghei ANKA and P. yoelii 17XL poorly in C57BL/6 and BALB/c mice, respectively. To our knowledge, this is the first work that uses gellan gum and gellan sulfate for intraperitoneal injection in mice.

Key Words: Gellan sulfate, in vivo, rodent malaria

Current antimalarial drugs act on intra-erythrocytic Plasmodium parasites. Quinine and artemisinin, two of the more widely used antimalarials, are both derived from plant sources. Both have synthetic derivatives that make them readily available commercially, and both act on malaria parasites by interfering with the uptake and digestion of hemoglobin. Artemisinins are currently the preferred treatment for severe malaria and artemisinin-based combination therapies (ACTs) are recommended for uncomplicated malaria. However, the development of resistance against antimalarials is hindering efforts to eradicate malaria worldwide. Hence, the continuous effort to develop new vaccines and novel drugs is needed.

Heparin is a highly sulfated polysaccharide that binds to several proteins of malaria...
parasites, inhibiting parasite entry into red blood cells in vitro\textsuperscript{21}. Heparin can also inhibit cytoadherence and sequestration of infected red blood cells to the vascular endothelium\textsuperscript{22} and its low molecular weight derivatives have been shown to prevent rosetting in vitro\textsuperscript{17}. Other sulfated polysaccharides, including dextran sulfate\textsuperscript{22}, carrageenans\textsuperscript{1}, and fucoidan\textsuperscript{4} have been found to inhibit parasite entry into red blood cell in vitro; but, their effectiveness in vivo is still questionable\textsuperscript{2,4,7}. In this case, heparin derivatives may represent a clinically safer alternative to heparin. Depolymerized heparin glycans that lack anticoagulant activity have been shown to release sequestered \textit{P. falciparum}-infected red blood cells in the non-human primate model, \textit{Macaca fascicularis}\textsuperscript{19}. For prevention of parasite entry into red blood cells, blood-stage antimalaria vaccines are still currently being designed and developed\textsuperscript{11}. We previously showed that gellan sulfate, a derivative of the microbial polysaccharide gellan gum, effectively inhibits malaria parasite entry into red blood cells and growth in vitro\textsuperscript{14}. Here, we assessed the in vivo effect of gellan sulfate using mouse models of severe and cerebral malaria. C57BL/6 mice were infected with \textit{Plasmodium berghei} ANKA while BALB/c mice were infected with \textit{P. yoelii} 17XL. Infected mice were treated intraperitoneally with 1×10\textsuperscript{6} parasitized red blood cells from cryopreserved stock. \textit{P. berghei} ANKA-infected blood from the C57BL/6 donor mice were collected at 6% parasitemia before the presumed onset of cerebral malaria. \textit{P. yoelii} 17XL-infected blood from donor BALB/c mice were collected at 15% parasitemia.

Artesunate (SIGMA) was dissolved in 1% sodium bicarbonate in PBS (2 mg/ml) and filter-sterilized by passage through a 0.45-μm filter. Gellan gum (WAKO) and gellan sulfate were both dissolved in PBS (2 mg/ml) and similarly filter-sterilized. Since gellan gum gels in solution, it was first heated to 65°C before filtration. Gellan sulfate was prepared by mixing 1% (w/v) gellan gum with 0.1 M HCl to pH 3.0 and confirming successful sulfation by nuclear magnetic resonance analysis, as described previously\textsuperscript{14}.

Experimental mice were infected intraperitoneally with 1×10\textsuperscript{6} parasitized red blood cells and were divided into four treatment groups: untreated control, artesunate-treated (ART), gellan gum-treated (GG), and gellan sulfate-treated (SGG). Treatment and monitoring were performed by following the four-day suppressive test protocol. GG and SGG were given intraperitoneally at doses of 20 mg/kg for C57BL/6 mice and 25 mg/kg for BALB/c mice. Artesunate was given at 20 mg/kg. Parasitemias
were monitored from day 4 until day 10 post-infection (p.i.) by examining Giemsa-stained thin blood smears. Ten oil immersion fields with 200–300 cells were counted, except for parasitemias approaching zero, in which cases, 100 fields were examined. Mice were observed for changes in appearance and behavior for possible signs of adverse reactions to treatment. We performed one-tailed t-tests for samples with unequal variances to compare the parasitemias of the treated groups to the untreated control groups with significance levels, \( p < 0.05 \) and \( p < 0.01 \).

For the BALB/c mice infected with \( P. \) yoelii 17XL, we pooled data from two independent experiments. Deaths were recorded promptly. Statistically significant differences in mouse survival of ART-, GG-, or SGG-treated groups compared with untreated group were determined by using Log-rank test; values were considered to be significantly different when the P value was less than 0.05.

The parasitemias of the C57BL/6 mice infected with \( P. \) berghei ANKA and BALB/c mice infected with \( P. \) yoelii 17XL treated with GG and SGG were not significantly different from those of the untreated control groups (Fig. 1A and B) based on one-tailed t-tests. By contrast, there were significant differences between the parasitemias of the untreated control and the artesunate-treated mice (Fig. 1A and 1B).

All \( P. \) berghei ANKA infected control mice died by day 6 p.i., compared to just one death in each of the SGG- and GG-treated groups on day 7 p.i. (Fig. 1C). Artesunate-treated mice also succumbed to the infection by day 26–28 p.i. and the last SGG- and GG- treated mice died on days 35 and 38 p.i., respectively (Fig. 1C). There was 50% mortality for the \( P. \) yoelii 17XL infected control mice by Day 15 p.i (Fig. 1D). At Day 25 p.i., all control mice have died and about 50% of both GG and SGG treated mice (Fig. 1D). From this point, the surviving mice from the GG, SGG, and ART treatment groups were eventually sacrificed on Day 60. Parasitemias at the time of deaths were not collected and...
pathological tests were also not done this time. We statistically analyzed the mouse survival using Kaplan-Meier method followed by Log-Rank test. In both mouse malaria models, we found statistically significant differences ($P < 0.05$) in the survival of mouse treated with ART, GG, or SGG compared with those untreated (UN), indicating that GG and SGG have life-prolonging effects in these murine malaria models.

Several factors can affect the effectiveness of drugs in animals. The animal’s immune response to the disease itself is a major determinant of the course of the disease and response to treatment. In addition, the method of administration and the delivery system can affect the absorption and metabolism of drugs. The deaths in the *P. berghesi* ANKA- and *P. yoelii* 17XL-infected groups treated with artesunate may have been due to the limited time of treatment. Oral artesunate given at 10 mg/kg/day for 7 days has been shown to prevent parasitemia but with the likelihood of recrudescence of parasitemia and development of cerebral malaria\(^\text{6}\). A 14-day treatment course of oral artesunate at 100 mg/kg/day completely prevented the development of parasitemia and cerebral malaria\(^\text{6}\). In this case, artesunate did indeed effectively inhibit the growth and proliferation of the parasites during the early stages of the infection under drug pressure. However, when treatment ended and the parasites were allowed to proliferate and the disease was allowed to run its course, some artesunate-treated mice died within 30 days of infection.

Gellan gum is currently used as drug delivery system, and is said to be safe when given orally. When mixed in the diet of Swiss Crl mice for 96–98 weeks, gellan gum has no effect on the body weight or food consumption of the animals, and no neoplastic or non-neoplastic changes associated with feeding gellan gum were observed\(^\text{16}\). When implanted in the dorsal region of BALB/c mice for 21 days, 1% gellan gum discs causes no significant lesions\(^\text{13}\). However, the nutritive or therapeutic benefits of gellan gum have not been reported. Gellan sulfate, the sulfated derivative of gellan gum, was originally developed as a novel anticoagulant\(^\text{12}\). To our knowledge, this is the first study where gellan gum and gellan sulfate were administered intraperitoneally in mice. We tried to administer gellan gum and gellan sulfate at 50 mg/kg to C67BL/6 mice but observed signs of probable adverse reactions, such as hunching and huddling after injection. Mice given this dose appeared smaller in size and unkempt based on visual assessment. Although some of these changes may have been due to the ongoing disease, these signs were only observed during the four-day treatment period. In contrast, these signs were not evident in mice given lower doses of SGG and GG, suggesting that the dose of 50 mg/kg for intraperitoneal injection in mice may not be suitable; accordingly, it was discontinued and not used on BALB/c mice.

Despite the effective inhibition of growth and invasion of *P. falciparum* 3D7 and Dd2 *in vitro*, gellan sulfate appears to be less effective in inhibiting the *in vivo* growth of the rodent malaria parasites, *P. berghesi* ANKA and *P. yoelii* 17XL, based on the parasitemia levels after treatment. Although statistical analyses indicate life-prolonging effects in both murine malaria models with SGG and GG treatments, the reasons for these results remain unclear. It is important to consider the small sample size used in this study and be cautious with the conclusions. We can hypothesize that SGG or GG may have effects on immunity or on sequestration\(^\text{19}\) of *P. berghesi* ANKA in the brain microvessels. In order to understand this, however, the mechanisms how gellan sulfate and gellan gum behave in the animal body after systemic administration must be further investigated.

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