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Inhibitory Effect of TNF-α on Malaria Pre-Erythrocytic Stage Development: Influence of Host Hepatocyte/Parasite Combinations

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Abstract

Background: The liver stages of malaria parasites are inhibited by cytokines such as interferon-γ or Interleukin (IL)-6. Binding of these cytokines to their receptors at the surface of the infected hepatocytes leads to the production of nitric oxide (NO) and radical oxygen intermediates (ROI), which kill hepatic parasites. However, conflicting results were obtained with TNF- α possibly because of differences in the models used. We have reassessed the role of TNF-α in the different cellular systems used to study the Plasmodium pre-erythrocytic stages.

Methods and Findings: Human or mouse TNF-α were tested against human and rodent malaria parasites grown in vitro in human or rodent primary hepatocytes, or in hepatoma cell lines. Our data demonstrated that TNF- α treatment prevents the development of malaria pre-erythrocytic stages. This inhibitory effect however varies with the infecting parasite species and with the nature and origin of the cytokine and hepatocytes. Inhibition was only observed for all parasite species tested when hepatocytes were pre-incubated 24 or 48 hrs before infection and activity was directed only against early hepatic parasite. We further showed that TNF-α inhibition was mediated by a soluble factor present in the supernatant of TNF-α stimulated hepatocytes but it was not related to NO or ROI. Treatment TNF-α prevents the development of human and rodent malaria pre-erythrocytic stages through the activity of a mediator that remains to be identified.

Conclusions: Treatment TNF-α prevents the development of human and rodent malaria pre-erythrocytic stages through the activity of a mediator that remains to be identified. However, the nature of the cytokine-host cell-parasite combination must be carefully considered for extrapolation to the human infection.

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Introduction

Tumour necrosis factor (TNF)-α is a cytokine with pleiotropic effects including anti-microbial activities [1]. In malaria infections, it has been shown that TNF-α could have both beneficial and detrimental effects. TNF-α is detected in the circulation during the erythrocytic phase of the infection in humans [1–3] and in mice [4,5]. In both hosts, high levels of this cytokine have been associated with malarial pathology such as fever [6], and cerebral malaria [3,5]. On the other hand, TNF-α has also been shown to have a potent anti-parasitic activity. Administration of recombinant TNF-α protected against blood stage infection with Plasmodium chabaudi in mice [7], while mice deficient for TNF-α controlled P. chabaudi adami blood infections less efficiently [8]. In humans, sustained high levels of TNF-α were associated with rapid clearance of fever and parasites [9]. There are controversial observations concerning the role of TNF-α against the pre-erythrocytic (PE) stages of the malarial infection. Schofield et al. reported that recombinant human TNF-α directly inhibited P. berghei grown in vitro in the HepG2 human hepatoma cell line, and in vivo in rats and mice [10]. However, we have previously found that P. yoelii parasites grown in cultured purified mouse primary hepatocytes were unaffected by TNF-α, whereas this cytokine inhibited the hepatic development of this parasite in vivo [11]. We
then showed for this rodent malaria model that the inhibitory effect observed in vivo was actually mediated by the IL-6 secreted by non-parenchymal liver cells in response to TNF-α stimulation [11]. Thus depending on the host/parasite combination, different effects of TNF-α on Pl parasites were reported. In this study, we wished to reassess the role of some of the biological and experimental parameters on the inhibition of Plasmodium hepatic stages observed in in vitro assays of TNF-α activity.

Materials and Methods

Ethics

All experiments and procedures involving mice were approved by the “Direction Départementale des Service Vétérinaires de Paris, France” (Authorisation No 75-129) and performed in compliance with the French Ministry of Agriculture for animal experimentation (1987). Human liver fragments used to prepare primary hepatocyte cultures were collected after written informed consent from patients undergoing a partial hepatectomy. The experimentation (1987). Human liver fragments used to prepare primary hepatocytes were prepared as described, with minor modifications [19]. Briefly, cells were isolated by collagenase perfusion of liver fragments and were further purified over a 40% Percoll gradient. Human hepatocyte purity and viability were >99% as assessed by Trypan blue dye exclusion. Human primary hepatocyte cultures were prepared as described with minor modifications [19]. Briefly, cells were isolated by collagenase (Roche) perfusion of human liver fragments, which were collected and used in agreement with the French ethical regulations, and were further purified over a 40% Percoll gradient. Human hepatocyte purity and viability were >99% as assessed by Trypan blue dye exclusion. Mouse and human hepatocytes were seeded in eight-chamber plastic Lab-Tek slides (Nunc) coated with rat tail collagen I (Becton Dickinson) at a density of 1 x 10^5 cells per well for primary murine hepatocytes, and of 2 x 10^5 cells per well for primary human hepatocytes cells, and cultured at 37°C, 5% CO2, in DMEM medium as above supplemented with 10^{-7} M dexamethasone (Sigma) after complete cell adherence (12–24 hours).

Evaluation of TNF-α cytotoxicity

Toxicity of the cytokine to primary culture of hepatocytes or hepatoma cell lines in flat-bottom 96 wells (20 x 10^5 cells/well) was evaluated using a methylthiazolyltetrazolium bromide (MTT) assay. Briefly, cytokines were added in triplicate at decreasing concentrations. Medium was replaced 3 hours after sporozoite infection and every day thereafter up to day 4 (for rodent parasites) or 7 (for P. falciparum) with fresh medium containing the cytokine at the same concentration. Twenty-four hours after the last medium change, 110 μl of a solution containing 10 μl of MTT (Sigma) solution (5 mg/ml) and 100 μl of medium were added and the cultures incubated for a further 4 hours. The formazan crystals that were formed were dissolved using 100 μl of a 1:1 DMSO: ethanol solution. Optical density was read immediately at 570 nm with a reference wavelength at 630 nm [20].

In vitro assay of sporozoite invasion of and development in hepatocytes and HepG2 cells

After removal of medium from the culture chambers, ten thousands sporozoites were added in 100 μl of fresh supplemented medium with various quantities of TNF-α tested, and at different times during cultivation. Medium was replaced at −24, 0, 3, and 24 h after rodent malaria sporozoite inoculation, and at −24, 0, 3, 24 h and then every day up to day 5 after P. falciparum sporozoite inoculation of primary human hepatocytes with fresh medium containing or not the cytokine. In one experiment, supernatant was collected from wells containing human hepatocytes treated with TNF-α (100 ng/ml) of for 2 days. Plasmodium sporozoites (10^5 in a 50 μl) were added to this supernatant (50 μl) or to fresh medium (50 μl). The final solution (100 μl) containing the sporozoite was added to the culture. Medium was replaced after 3 h, 24 h, and then every day up to day 5 after sporozoite inoculation. Experimental determination of the number of liver stage parasites was performed in triplicate or quadruplicate. Cultures were stopped 48 h (for rodent malaria species) or 5 days (for P. falciparum) after sporozoite infection, fixed with cold methanol and schizont numbers were assessed by immunofluorescence using antibodies recognizing Plasmodium liver stages as previously described [21,22] and were quantified by microscopic examination or using the Odyssey infra red imaging system (LI-COR Biosciences) [23]. Percentage of inhibition of the development is calculated by comparing the numbers of parasitic forms in the experimental wells versus control wells.

Results

Effect of human TNF-α on HepG2-CD81 cells infected with murine Plasmodium species

HepG2 is a hepatoma cell line easily propagated in vitro [24] that has been shown to sustain the development of the P. berghei [25]
but not the *P. yoelii* [26] liver stages. Recently Silvie *et al.* [17] showed that HepG2 cells transduced with CD81 are thereby made permissive to *P. yoelii* development, providing a good system to study *P. yoelii* liver stage biology, thus reducing the need for the more tedious primary murine hepatocyte cultures. We employed this cell line to assess the role of TNF-α against the hepatic stages of malaria parasites.

When human TNF-α was added to HepG2-CD81 cultures over a four-day period centered on the time of sporozoite inoculation, Pyy265BY hepatic parasite development was inhibited in a dose dependent manner (Figure 1A). Significant inhibition was observed even at a low dose of 10 ng/ml. Only minor increases in the level of inhibition were observed at doses above 100 ng/ml (Figure 1A). We then tested the influence of the timing of TNF-α...
addition on the level of inhibition observed. HepG2-CD81 cultures where the cytokine was added only 1 day before sporozoite inoculation were also significantly inhibited by 100 ng/ml of TNF-α (Figure 1B). However, no inhibition of parasite development could be observed when TNF-α was first added starting at the time of sporozoite inoculation or thereafter (Figure 1B). The inhibitory activity of TNF-α was specific to the parasites because TNF-α had no cytotoxic effect on infected or normal HepG2 cells as measured by the MTT assay, even when added at the highest doses used. Indeed, the optical density values obtained in wells containing untreated cells [0.953±0.2 arbitrary units (A.U.)] or cells treated for 4 days with 100 ng/ml TNF-α and infected with P. yoelii sporozoites (1.29±0.03 A.U.) did not differ significantly.

We next tested the effect of human TNF-α on Pba parasites, thus providing a reasonable comparison with the study of Schofield et al. where an inhibitory effect of human TNF-α against P. berghei NK65 strain was reported [10]. When human TNF-α at an inhibiting dose of 100 ng/ml was added to HepG2-CD81 cultures starting 48 h before sporozoite inoculation and over a four-day period until the end of the parasite cultivation period 48 h thereafter, Pba liver stage development was also inhibited in a dose dependent manner (Figure 2), though the magnitude of the inhibition was lesser than that observed for Pyy265BY.

Effect of TNF-α on mouse hepatoma cell line Hepa 1–6 and primary mouse hepatocytes infected with murine Plasmodium species

In order to test whether the findings obtained using HepG2-CD81 cells can be extended to other host cell/parasite combinations, we repeated the TNF-α treatment (100 ng/ml initiated at 48 h before sporozoite inoculation and maintained for the subsequent 48 h) with mouse hepatoma cells Hepa 1–6 and primary cultures of purified mouse hepatocytes, both of which sustain the growth of Plasmodium species that infect rodents [18,27]. Mouse TNFα significantly inhibited Pba in Hepa1-6 cells (Figure 3A) or in primary hepatocyte cultures (Figure 3B), whereas
for Py265BY, inhibition was only observed in primary hepatocytes (Figure 3).

We next tested the effect of human TNF-α on mouse cells since it was shown previously that in vivo treatment with this cytokine inhibited P. berghei NK65 liver stage development [10]. However, human TNF-α may have an indirect inhibitory effect on the liver stage in situ, for e.g. by inducing the production of another anti-liver stage cytokine such as IL-6 by nonparenchymal liver cells. We wished to ascertain whether the inhibition noted above was due to direct interaction with hepatocytes [11]. The liver stage development of parasites (Py265BY or PbA) grown in primary mouse hepatocytes was not inhibited by treatment with human TNF-α (Figure 3B). These results indicate that parasite species are differentially susceptible to the inhibitory activity of TNF-α, and that this is influenced by the origin of the TNF-α as well as the type and origin of the host cells in which the parasites develop. It is worth noting that treatment with TNF-α had no cytotoxic effect on infected or non-infected primary mouse cells as measured by the MTT assay. The difference in the optical density values obtained for wells containing untreated cells (0.47±0.09 A.U.) or cells treated for 4 days with 100 ng/ml TNF-α and infected with P. yoelii sporozoites (0.41±0.05 A.U.) were not significant.

**Effect of TNF-α on primary human hepatocytes infected with P. falciparum**

We then tested the effect of TNF-α on the development of P. falciparum in human primary hepatocytes, a host/parasite combination of direct clinical relevance. We used highly purified human hepatocytes to prevent indirect effect of TNF-α on contaminating nonparenchymal cells as shown previously [11]. P. falciparum liver stage development was inhibited when the cultures were treated with human TNF-α at 100 ng/ml, but not 1 ng/ml, 24 h or 48 h prior to sporozoite inoculation and until day 5 thereafter (Figure 4). Inhibition was more pronounced when the hepatocytes were pre-incubated with human TNF-α 48 h as compared to 24 h before sporozoite inoculation. As for the other hepatocyte cells, treatment with TNF-α had no cytotoxic effect on primary human hepatocytes as measured by the MTT assay. The optical density values obtained for wells containing untreated cells (0.70±0.005 A.U.) or cells treated with for 4 days with 100 ng/ml TNF-α and infected with P. yoelii sporozoites (0.793±0.03 A.U.) did not differ significantly.

**Absence of effect of nitric oxide derivatives and radical oxygen intermediates inhibitors on TNF-α mediated pre-erythrocytic stage inhibition**

In order to determine how TNF-α inhibits liver stage parasite development, we used inhibitors that block the NO or the ROI pathways, both of which have been implicated previously in PE killing. First, we used S-methyl-thiourea (SMT), a competitive inhibitor of the inducible nitric oxide synthase [12]. Addition of SMT to cultures treated with 100 ng/ml of human TNF-α did not reverse the effect of the cytokine against Py265BY HepG2/CD81 (Figure 5A) or against P. falciparum in primary human hepatocytes (Figure 6A). We next tested whether inhibition was mediated via the ROI pathway by using N-acetyl-cysteine (NAC), the precursor of glutathione and a potent endogenous antioxidant [13]. Addition of NAC did not reverse TNF-α mediated inhibition of Py265BY in HepG2/CD81 (Figure 5B), or that of P. falciparum in primary human hepatocytes (Figure 6A). We also observed that SMT and NAC did not reverse the inhibitory effect of TNF-α on PbA-infected HepG2/CD81 hepatoma cells (data not shown).

![Figure 4. Human TNF-α inhibits the pre-erythrocytic stage of P. falciparum](https://example.com/figure4.png)

**A soluble mediator synthesized by human TNF-α-stimulated human hepatocytes prevents P. falciparum development**

Since inhibition was observed only when cells were treated 48 h or 24 h before sporozoite infection but not on the time of sporozoite inoculation, we hypothesized that TNF-α-treated hepatocytes might release a parasite-inhibitory soluble mediator as previously shown for IL-1 or other inflammatory stimuli [28,29]. P. falciparum sporozoites in normal medium were added to supernatant medium obtained from human hepatocytes treated for 48 h with TNF-α (1/1 volume). The mixture was then added to fresh human hepatocytes to initiate the infection. A strong significant inhibition of sporozoite development was observed, and it reached levels similar to those induced by direct TNF-α pre-treatment of the cultures (Figure 6B). This showed that an inhibitory soluble mediator was produced by TNF-α-stimulated hepatocytes.

**Discussion**

The in vitro experiments presented here were designed to assess parameters, such as the origin of the cytokine, the origin of the...
were treated 48 h (Figure 3) but not 24 h [11] before hepatocytes where an effect was observed only when the cultures 
These results differed from those obtained using primary mouse 
specific immune components against the malaria hepatic stages. 
makes it a good surrogate in future studies of the role of non-
from the 

Figure 5. The effect of human TNF-α against Py265BY is not 
mediated by NO or ROI. HepG2/CD81 hepatoma cells treated or not 
with 100 ng/ml of human TNF-α together with or without SMT (A) or 
NAC (B) 48 h before, at the time of, and then 3 h and 24 h after 
sporozoite inoculation. Cultures were stopped 48 h later. Data are 
presented as the mean (± SD) reduction in liver schizont numbers in 
triplicate wells compared to the mean number in 6 control wells. The 
numbers of Py265BY liver schizonts in the 6 control wells were 
145.5±9 (A), and 148±9 (B). The results are representative of three 
independent experiments. * p<0.05 versus control non-treated cultures 
(Kruskal-Wallis test, followed by Dunn test). 
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Inhibition of Py2 65BY PE development (%)

Figure 6. A soluble mediator but not NO or RO intermediates 
synthesized by human TNF-α-stimulated human hepatocytes 
inhibits *P. falciparum* development. A. Primary human hepatocytes 
were treated or not with 100 ng/ml of human TNF-α together with or 
without SMT or NAC at 48 h before, at the time and every day for day 1 
to day 5 after sporozoite inoculation. B. In the same experiment, 
supernatants from cells treated previously for 48 h with human TNF-α 
were added together with *P. falciparum* sporozoites to fresh human 
primary hepatocytes. Medium was changed after 3 h and every day 
after sporozoite inoculation. In both experimental settings, cultures 
were stopped 5 days later. Data are presented as the mean (± SD) 
reduction in liver schizont numbers in triplicate wells to the mean 
number in 6 control wells and are derived from one of two experiments. 
The numbers of *P. falciparum* 5 day-liver schizonts in the 6 control wells 
were 179.2±26.1. * p<0.05 versus control non-treated cultures 
(Kruskal-Wallis test, followed by Dunn test). 
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host cells, the parasite species, or the schedule of application that 
might affect the anti-liver stage activity of TNF-α. Different types 
of hepatocytes and hepatoma cell lines together with 3 *Plasmodium* 
species were used. Our main finding is that human TNF-α was 
able to inhibit the hepatic development of two rodent malaria 
species, *P. yoelii* and to a lesser extent *P. berghei* (Figure 1), and most 
importantly that of *P. falciparum* (Figure 4). We showed that this 
activity of TNF-α was dependent on the host cell type and on the 
schedule of this cytokine’s administration. Maximal inhibition 
could be obtained when human TNF-α was administered 48 h 
before sporozoite inoculation to HepG2-CD81 cells (Figure 1). 
Significant inhibition was still observed when cells were treated 
24 h before sporozoite inoculation both in HepG2-CD81 infected 
with *P. yoelii* and in highly purified primary human hepatocytes 
infecte with *P. falciparum*. The good concordance between the 
data derived from *P. yoelii/HepG2-CD81* combination and that 
from the *P. falciparum/human primary hepatocyte combination makes it a good surrogate in future studies of the role of non-specific immune components against the malaria hepatic stages. These results differed from those obtained using primary mouse hepatocytes where an effect was observed only when the cultures were treated 48 h (Figure 3) but not 24 h [11] before *P. yoelii* sporozoite inoculation. Of the different parameters that might account for this difference we favour those related to the TNF-α mechanism of action. Murine TNF-α and human TNF-α differ 
in their affinity to the various host TNF receptors. Human TNF-α 
signals only through TNFR1 in mouse cells [30] and, as shown 
here, it had no effect on primary mouse hepatocytes infected with 
*P. yoelii* or with *P. berghei* (Figure 3). Signalling by TNF-R1 signals is 
effected through the TRAD/NEMO pathway to NF-kB or 
through FAD to activate caspase for apoptosis. TNF-R2 also 
mediates NF-kB activation through the TRAF pathway [31], 
however, in hepatocytes only TNFR1 mediates activation of NF- 
kB [32]. The NF-kB pathway is necessary for the induction of the 
NO or ROI in hepatocytes [33]. These two mediators have been 
shown to inhibit the *Plasmodium* liver stage [34,35]. We did not 
observe the induction of NO and ROI, which strongly suggests 
that it was TNFR2 but not TNFR1 that was involved in TNF-α 
signalling in infected hepatocytes. It has been proposed recently 
that malaria parasites manipulate their host hepatocytes to make 
them resistant to the apoptosis induced by TNF-α in *vivo* or *in vitro* 
[36] through interference with the NF-kB pathway [37] and 
consequently allowing them to escape the TNFR1-signaled 
cytotoxic effect of TNF-α. In addition, since signalling through 
TNF-R2 has also been involved in the necrotic effect of TNF-α
The fact that the inhibitory effect of TNF-α was observed only when cells were pre-incubated with the cytokine suggested that stimulated hepatocytes secrete an inhibitory factor and/or that the TNF-α treatment makes them refractory to infection. Host cell refractoriness is unlikely because addition of the supernatant from TNF-α-stimulated hepatocytes to the cultures was sufficient to obtain hepatic parasite inhibition. TNF-α alone or together with IL-6 and IL-1, is known to induce the synthesis of acute phase response proteins by hepatocytes. Although the acute phase response to inflammatory stimuli is evolutionarily conserved, species-specific differences exist [39,40]. IL-1 was previously shown to prevent sporozoite development in human or rat primary hepatocytes in vitro through the action of an acute phase protein, the C-reactive protein (CRP) [11,29]. Human or rat C-reactive proteins can bind sporozoite and prevent their invasion and further development in hepatocytes [12,30]. However, Yap et al. [41] have shown that CRP is not produced by human hepatocytes after TNF-α stimulation. They also showed that TNF-α treatment blocks the induction of CRP stimulated by IL-1 or IL-6 treatment of human hepatocytes. This suggest strongly that this acute phase protein does not mediate the TNF-α effect. It has been reported previously that two other acute phase proteins, the protease inhibitors α1-antitrypsin and α2 macroglobulin, were also able to prevent sporozoite infection and development [42]. Parasite proteases are necessary for sporozoite invasion in hepatocytes [43] and thus may be targeted by these two protease inhibitors. However, although TNF-α has been shown to increase the synthesis of α1-antitrypsin [44] or α2 macroglobulin [45] in HepG2 cells, it does not induce these molecules in human hepatocytes [40]. Thus, the nature of the inhibitory mediator secreted by human hepatocytes is still unknown and deserves further study. In the mouse liver the profile of acute phase proteins induced by inflammatory stimuli is different, for example mouse hepatocytes do not synthesize CRP. Serum Amyloid A is induced by TNF-α in mouse hepatocytes [46] and it might be responsible for the inhibition that is consequent to TNF-α-stimulation of mouse primary hepatocytes or mouse hepatoma cell lines. However, Serum Amyloid A is not induced in human hepatocytes by TNF-α stimulation [47] suggesting that other mediators might be involved.

During malaria blood stage infection, the production of TNF-α is increased [1,3], and these cytokine might modulate new liver stage infections [48,49]. By extension, any systemic inflammations or infections or more localized liver infections, of viral or bacterial origin, that induces high level of TNF-α might also have an inhibitory effect on the liver stages, which could consequently influence the outcome of a subsequent blood infection and its associated pathology [40,49].

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**Author Contributions**

Conceived and designed the experiments: ND JFF LR. Performed the experiments: ND JFF AGC MM GS LR. Analyzed the data: ND JFF DM GS LR. Contributed reagents/materials/analysis tools: JMC AJFL GJG RWS JMS LH. Wrote the paper: ND GS LR.

**References**

1. Grau GE, Taylor TE, Molyneux ME, Wirmia J, Vassali P, et al. (1989) Tumor necrosis factor and disease severity in children with *Plasmodium* Malaria. N Engl J Med 320: 1586–1591.

2. Kern P, Hemmer CJ, Vandamme J, Gross HJ, Dietrich M (1989) Elevated tumor necrosis factor-alpha and interleukin-6 serum levels as markers for complicated plasmodium-falciparum malaria. Am J Med 87: 139.

3. Kwiatkowski DP, Hill AVS, Sambou I, Twumasi PM, Gastracene J, et al. (1990) TNF concentration in fatal cerebral, non fatal cerebral, and uncomplicated *Plasmodium falciparum* malaria. Lancet 336: 1201–1205.

4. Amani V, Vigario AM, Belnoue E, Marussig M, Fonseca L, et al. (2000) Human primary hepatocytes have shown that CRP is not produced by human hepatocytes or mouse hepatoma cells. However, Serum Amyloid A is not induced in human hepatocytes by TNF-α stimulation [47] suggesting that other mediators might be involved.

5. Weigert et al. (1989) Elevated nitric oxide synthases with variable isoform selectivity. Br J Pharmacol 114: 1646–1655.

6. Grau GE, Fajardo LF, Piguet PF, Alllet B, et al. (1987) Tumor necrosis factor (cachectin) as an essential mediator in murine cerebral malaria. Science 237: 1210–1212.

7. Karunaseera ND, Grau GE, Gamage P, Cartier RL, Mendis KN (1992) Dynamics of fever and serum levels of tumor necrosis factor are closely associated during clinical paroxysms in *Plasmodium vivax* malaria. Proc Natl Acad Sci USA 89: 3290–3293.

8. Clark IA, Hunt NH, Butcher GA, Cowden WB (1987) Inhibition of murine *Plasmodium chabaudi adami* in vivo by recombinant interferon gamma or tumor necrosis factor-alpha. J Immunol 139: 3495–3498.

9. Hernandez-Valladares M, Naessens J, Musoke AJ, Sekikawa K, Rihet P, et al. (2006) Pathology of *Tnf-deficient mice infected with Plasmodium berghei*. J Immunol 170: 510–516.

10. Cortgeave IA (1997) N-acetylcysteine: pharmacological considerations and experimental and clinical applications. Adv Pharmacol 38: 205–227.

11. Franke-Fayard B, Trueman H, Ramesar J, Mendoza J, de la Veer M, et al. (2004) A *Plasmodium berghei* reference line that constitutively expresses GFP at a high level throughout the complete life cycle. Mol Biochem Parasitol 137: 23–33.

12. Nudelman S, Renia L, Charoevint Y, Yuan L, Milgten F, et al. (1989) Dual action of anti-sporozoite antibodies in vitro. J Immunol 143: 996–1000.

13. Silvio O, Greco C, Franetine JW, Dubart-Kupperschmitt A, Hannoun L, et al. (2006) Expression of human CD81 differently affects host cell susceptibility to malaria sporozoites depending on the *Plasmodium* species. Cell Microbiol 8: 1134–1146.

14. Mosmann TR (1983) Rapid colorimetric assay for cellular growth and survival: Application to proliferation and cytotoxicity assays. J Immunol Methods 65: 55–63.

15. Renia L, Mattei DM, Goma J, Perea, Duhoux P, et al. (1990) A malaria heat shock like protein epitope expressed on the infected hepatocyte surface is the target of antibody-dependent cell-mediated cytotoxic mechanisms by non-paranchymal liver cells. Eur J Immunol 20: 1445–1449.

16. Tsuij M, Mattei D, Nussenzweig RS, Eihinger D, Zacala F (1994) Demonstration of heat-shock protein 70 in the sporozoite stage of malaria parasites. Parasitol Res 80: 16–21.

17. Grego A, Silvio O, Franetine JF, Farhati K, Hannoun L, et al. (2006) New approach for high-throughput screening of drug activity on *Plasmodium* liver stages. Antimicrob Agents Chemother 50: 1564–1569.

18. Knowles BB, Howe C, Aden D (1980) Human hepatocellular carcinoma cell line. Am J Trop Med Hyg 32: 682–684.

19. Regamey IA (1996) Dual action of anti-sporozoite antibodies in vitro. J Immunol 143: 996–1000.

20. Mosmann TR (1983) Rapid colorimetric assay for cellular growth and survival: Application to proliferation and cytotoxicity assays. J Immunol Methods 65: 55–63.

21. Renia L, Mattei DM, Goma J, Perea, Duhoux P, et al. (1990) A malaria heat shock like protein epitope expressed on the infected hepatocyte surface is the target of antibody-dependent cell-mediated cytotoxic mechanisms by non-paranchymal liver cells. Eur J Immunol 20: 1445–1449.

22. Tsuij M, Mattei D, Nussenzweig RS, Eihinger D, Zacala F (1994) Demonstration of heat-shock protein 70 in the sporozoite stage of malaria parasites. Parasitol Res 80: 16–21.

23. Grego A, Silvio O, Franetine JF, Farhati K, Hannoun L, et al. (2006) New approach for high-throughput screening of drug activity on *Plasmodium* liver stages. Antimicrob Agents Chemother 50: 1564–1569.

24. Knowles BB, Howe C, Aden D (1980) Human hepatocellular carcinoma cell line. Am J Trop Med Hyg 32: 682–684.

25. Hollingdale MR, Leland P, Schwartz AL (1983) In vitro cultivation of the erythrocytic stage of *Plasmodium berghei* in a hepatoma cell line. Am J Trop Med Hyg 32: 682–684.

26. Molyneux ME, Wirmia J, Vassali P, et al. (1989) Tumor necrosis factor and disease severity in children with *Plasmodium* Malaria. N Engl J Med 320: 1586–1591.
26. Calvo-Calle JM, Moreno A, Eling WMC, Nardin EH (1994) In vitro development of infectious liver stages of *Plasmodium yoelii* and *P. berghei* malaria in human cell lines. Exp Parasitol 79: 362–373.

27. Mota MM, Rodriguez A (2000) *Plasmodium yoelii*: Efficient in Vitro invasion and complete development of sporozoites in mouse hepatic cell lines. Exp Parasitol 96: 257–259.

28. Nussler AK, Pied S, Pontet M, Miltgen F, Renia L, et al. (1991) Inflammatory status and pre-erythrocytic stages of malaria. Role of the C-reactive protein. Exp Parasitol 72: 1–7.

29. Pied S, Nussler AK, Pontet M, Miltgen F, Maille H, et al. (1989) C-reactive protein protects against pre-erythrocytic stages of malaria. Infect Immun 57: 278–282.

30. Tartaglia LA, Weber RF, Figari IS, Reynolds C, Palladino MA, Jr., et al. (1991) The two different receptors for tumor necrosis factor mediate distinct cellular responses. Proc Natl Acad Sci USA 88: 9292–9296.

31. Bradley JR, Pober JS (2001) Tumor necrosis factor receptor-associated factors (TRAFs). Oncogene 20: 6482–6491.

32. Yamada Y, Webber EM, Kirillova I, Peschon JJ, Fausto N (1998) Analysis of liver regeneration in mice lacking type 1 or type 2 tumor necrosis factor receptor: requirement for type 1 but not type 2 receptor. Hepatology 28: 959–970.

33. Lee HJ, Oh YK, Rhee M, Lim JY, Hwang JY, et al. (2007) The role of STAT1/IRF-1 on synergistic ROS production and loss of mitochondrial transmembrane potential during hepatic cell death induced by LPS/d-GalN. J Mol Biol 369: 967–984.

34. Nussler AK, Drapier JC, Renia L, Pied S, Miltgen F, et al. (1991) L-arginine dependent destruction of intrahepatic malaria parasite in response to tumor necrosis factor and/or interleukin 6 stimulation. Eur J Immunol 21: 227–230.

35. Pied S, Renia L, Nussler AK, Miltgen F, Mazier D (1991) Inhibitory activity of IL-6 on malaria hepatic stages. Parasite Immunol 13: 211–217.

36. Van De Sand C, Horstmann S, Schmidt A, Sturm A, Bolte S, et al. (2005) The liver stage of *Plasmodium berghei* inhibits host cell apoptosis. Mol Microbiol 58: 731–742.

37. Singh AP, Buscaglia CA, Wang Q, Levay A, Nauenreuther DR, et al. (2007) *Plasmodium circumsporozoite* protein promotes the development of the liver stages of the parasite. Cell 131: 492–504.

38. Erickson SL, de Sauvage FJ, Kibdy K, Carver-Moore K, Pitts-Meek S, et al. (1994) Decreased sensitivity to tumour-necrosis factor but normal T-cell development in TNF receptor-2-deficient mice. Nature 372: 560–563.

39. Fry GH, Gauldie J (1999) The acute phase response of the liver in inflammation. Prog Liver Dis 9: 89–116.

40. Heinrich PC, Castell JV, Andus T (1990) Interleukin-6 and the acute phase response. Biochem J 265: 621–636.

41. Yap SH, Moshage HJ, Hazenberg BPC, Roelofs HMJ, Rijpma J, et al. (1991) Tumor necrosis factor (TNF) inhibits interleukin IL-1 and/or IL-6 stimulated synthesis of C-reactive protein (CRP) and serum amyloid A (SAA) in primary cultures of human hepatocytes. Biochem Biophys Acta 1091: 405–408.

42. Pied S, Tahone MD, Chateller G, Marussig M, Jardel C, et al. (1993) Non specific resistance against malaria pre-erythrocytic stages: involvement of acute phase proteins. Parasite 2: 263–268.

43. Coppi A, Pinzon-Ortiz C, Hutter C, Sinnis P (2005) The *Plasmodium* circumsporozoite protein is proteosyntetically processed during cell invasion. J Exp Med 201: 27–33.

44. Baumann H, Richards C, Gauldie J (1987) Interaction among hepatocyte-stimulating factors, interleukin 1, and glucocorticoids for regulation of acute phase plasma proteins in human hepatoma HepG2 cells. J Immunol 139: 4122–4128.

45. Magielska-Zero D, Bereta J, Czuba-Pelech B, Pajdlak W, Gauldie J, et al. (1988) Inhibitory effect of human recombinant interferon gamma on synthesis of acute phase protein in human hepatoma Hep G2 cells stimulated by leukocyte cytokines, TNF alpha and IFN-beta 2/BSF-2/IL-6. Biochem Int 17: 17–23.

46. Ghezzi P, Sipe JD (1988) Dexamethasone modulation of LPS, IL-1, and TNF stimulated serum amyloid A synthesis in mice. Lymphokine Res 7: 157–166.

47. Castell JV, Gomez-Lechon MJ, David M, Andus T, Geiger T, et al. (1989) Interleukin-6 is the major regulator of acute phase protein synthesis in adult human hepatocytes. FEMS Lett 242: 237–239.

48. Mazier D, Goma J, Pied S, Renia L, Nussler AK, et al. (1990) Hepatic phase of *Malaria*. A crucial role as “go-between” with other stages. Bull World Health Organ 68: 126–131.

49. Mazier D, Renia L, Nussler AK, Pied S, Goma J, et al. (1990) Hepatic phase of malaria parasite is the target of cellular mechanisms induced by the previous and the subsequent stage. A crucial role for the liver nonparenchymal cells. Immunol Lett 25: 63–70.