2040

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REPEATED INFECTION OF *AOTUS* MONKEYS WITH *PLASMODIUM FALCIPARUM* INDUCES PROTECTION AGAINST SUBSEQUENT CHALLENGE WITH HOMOLOGOUS AND HETEROLOGOUS STRAINS OF PARASITE

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Abstract. We evaluated repeated blood-stage infections with *Plasmodium falciparum* in eight *Aotus lemurinus lemurinus* monkeys. Over the course of seven infections with 10^2 *P. falciparum* (the Vietnam Oak Knoll [FVO] strain), the pre-patent period lengthened from 8.2 to 30.8 days; the peak parasitemia decreased from 4.5×10^5 to 0 parasites/μl (Challenges 6 and 7), and the requirement for treatment decreased from 100% to 0% (Challenges 3 to 7). Five weeks after the seventh FVO challenge, the eight immune and three naïve monkeys received 10^2 parasitized erythrocytes infected with *P. falciparum* (CAMP strain). The three control animals experienced uncontrolled parasitemias reaching between 4.8 and 7.7×10^5 parasites/μl (pre-patency = 6.3 days) and all required drug treatment; six of the eight immune monkeys became parasitemic (pre-patency = 8.8 days), but self-cured. Two of three of the monkeys having the greatest reductions in hematocrit (50–60%) also had the highest parasitemias ($\sim 10^4$ parasites/μl) before self-curing. Repeated homologous infections induced sterile immunity to homologous challenge; during heterologous challenge the monkeys developed clinically relevant, but not life-threatening, parasitemias and anemia.

INTRODUCTION

We believe that studying the response of *Aotus* monkeys to repeated infections with lethal strains of *Plasmodium falciparum* may provide important insights into the requirements of and potential for erythrocytic stage *P. falciparum* vaccines. We therefore studied the response to repeated infections with the highly virulent Vietnam Oak Knoll (FVO) strain of *P. falciparum*,[1] and the response of monkeys immune to repeated challenge with FVO to challenge with a different strain of *P. falciparum*, CAMP. Our goals were to determine 1) how many exposures were required before the monkeys were able to control the parasitemia, 2) if the monkeys developed sterile protective immunity, and 3) if monkeys immune to challenge with FVO were susceptible to challenge with CAMP. The results clearly demonstrate that by their third exposure to *P. falciparum*, the monkeys developed immunity which led to cure without treatment, and that by the sixth exposure they developed sterile protective immunity against a single strain of *P. falciparum*. Furthermore, when such completely immune monkeys were challenged with another strain of *P. falciparum*, they developed parasitemias at essentially the same rate as controls, developed a level of parasitemia that would cause illness in humans, and three of the eight monkeys experienced a decrease of ≥ 50% in their hematocrits. However, they then controlled the parasitemias and did not develop the level of parasitemia or anemia associated with severe disease in humans.

MATERIALS AND METHODS

Monkeys. Panamanian adult (male and female) *Aotus lemurinus lemurinus* (karyotype VIII or IX) monkeys[2] were maintained in the animal facility of the Gorgas Memorial Institute in Panama City, Republic of Panama. *Aotus l. lemurinus* monkeys were obtained in western Panama. Upon arrival at the laboratory, each animal was given a physical examination, weighed and sexed, identified by a metal neck tag with an accession number, administered thiabendazole orally for treatment of endoparasites (100 mg base/kg) and

vaccinated against *Herpes simplex*, *Herpes tamarinus* (New England Regional Primate Research Center, Southborough, MA) and *Klebsiella pneumoniae*[3]. The animals were housed and cared for as previously described.[3] About one month after arrival, each monkey was tattooed with its identification number and a thick blood film examined to exclude naturally occurring plasmodial infections. The animals remained in quarantine for a minimum of 90 days before being transferred to areas devoted to housing monkeys for malaria studies. The weight of the monkeys when inoculated ranged from 700 to 800g. All monkeys used in these experiments were wild caught adult monkeys and had no history of experimental infection with *Plasmodium*. None of monkeys was splenectomized.

Parasite strains. Immunity to parasite challenge was established using the Vietnam Oak Knoll (FVO) strain of *P. falciparum*[1]. The heterologous strain challenge was performed using the CAMP strain of *P. falciparum* which was originally isolated in Malaysia.[4]

Challenge protocol. The monkeys described in this study received their first challenge with *P. falciparum* (FVO) either as naïve controls in other studies (n = 2) or after receiving one of three first generation monovalent malaria vaccines (n = 6). Once these studies were completed, the animals were reallocated to this study and re-challenged (Figure 1). None of the animals had been infected with *P. falciparum* prior to the first FVO challenge described here. The animals received their first FVO challenges between October 1994 and August 1995, and then six more FVO challenges approximately every five months until all had received seven FVO challenges. All animals received their seventh FVO challenge simultaneously. Five weeks after the seventh FVO challenge and two weeks prior to challenge with the heterologous CAMP, all animals were treated orally once a day for five days with 50 mg/kg quinine and 6 mg/kg doxycycline to eliminate any occult FVO parasitemia. All then received the heterologous CAMP strain challenge 10 days after treatment was concluded. All challenges described in this study were performed by the IV injection via the saphenous vein of 10^2 parasitized *Aotus* erythrocytes.
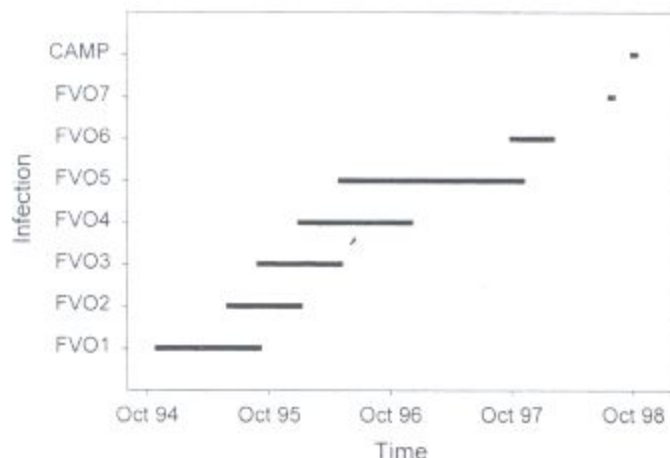
FIGURE 1. Eight *Aotus* monkeys were repeatedly challenged with *Plasmodium falciparum*, seven consecutive times with the Vietnam Oak Knoll (FVO) strain then once with CAMP strain. Time frames during which the repeated challenges occurred are shown below.

Blood films. During periods of surveillance, thick blood films were prepared with blood taken from a marginal ear vein by lancet venipuncture. The slides were Giemsa stained and the parasites enumerated using the method of Earle and Perez.[5] A negative parasitemia was recorded if no parasites were seen after 100 600x fields (approximately 0.65 µl of blood) were examined.

Hematocrit. Hematocrits were monitored on days 10, 14, 17 and 21 post-CAMP challenge. Fifty µl of blood was drawn into a heparinized capillary tube, then centrifuged in a microhematocrit centrifuge for five minutes prior to reading.

Treatment. Monkeys were treated if parasitemia reached 400,000 parasites/µl, or for clinical deterioration. Treatment was a single oral dose (20 mg/kg) of mefloquine.

Immunization status. As part of other studies conducted prior to this study, 6/8 of the monkeys received immunizations DNA plasmids prior to the first FVO infection. Three animals (monkeys 12756, 12759, 12757) received three doses of a *P. falciparum* (FVO strain) Merozoite Surface Antigen 1_{42} (PfMSP-1_{42}) DNA vaccine (Kumar S, unpublished data), an antigen expressed by blood stage parasites. Two other animals (monkeys 12765, 12763) received three doses of a *P. falciparum* Pfs25 DNA vaccine, an antigen expressed on parasite gametes. One animal (monkey 12730) received three doses of *P. falciparum* (FVO strain) Apical Merozoite Antigen-1 (PfAMA-1) DNA vaccine (Aguiar J, unpublished data). Table 1 outlines the immunization regimens.

Statistics. Statistical tests were performed using SPSS for Windows 8.0 (SPSS, Chicago, IL) and the STATCALC module in EpiInfo (Centers for Disease Control and Prevention, Atlanta, GA). Power calculations were performed in SamplePower 1.00 (SPSS).

Animal use. The experiments were conducted according to the principles set forth in the "Guide for the Care and Use of Laboratory Animals," Institute of Laboratory Animal Resources, National Research Council (Department of Health and Human Services, National Institutes of Health publication 86-23, 1985).

RESULTS

Parasitemia. After the first and second challenge with FVO, all monkeys became parasitemic. After the third, fourth and fifth challenges, 6/8, 2/8 and 4/8 respectively became parasitemic. None of the animals became parasitemic

TABLE 1

Highest recorded parasitemia (parasites/µl blood) and length of pre-patent period (days) for each monkey repeatedly challenged with the Vietnam Oak Knoll (FVO) strain of *Plasmodium falciparum* then challenged with the CAMP strain of *P. falciparum*. Three naïve control animals challenged with CAMP strain only are included. Antigens used in any immunizations given prior to the start of the challenges are noted

Monkey no	Sex	Immune status	FVO1 challenge		FVO2 challenge		FVO3 challenge		FVO4 challenge		FVO5 challenge		FVO6 challenge		FVO7 challenge		CAMP challenge	
			PC	PP	PC	PP	PC	PP	PC	PP	PC	PP	PC	PP	PC	PP	PC	PP
Challenged																		
12765	M	Pfs25	840*	8	79*	13	0.8	13	0	–	0.002	20	0	–	0	–	9.9	8
12763	M	Pfs25	227*	8	140*	13	31	15	0	–	0.002	64	0	–	0	–	10.9	7
12730	M	PfAMA-1	1232*	8	79*	10	0	–	0	–	0	–	0	–	0	–	0.12	14
12756	M	PfMSP-1_{42}	277*	8	151*	13	0.9	14	0	–	0.002	21	0	–	0	–	0.38	9
12757	M	PfMSP-1_{42}	465*	8	382*	11	0.002	15	0	–	0.002	18	0	–	0	–	2.4	7
12759	M	PfMSP-1_{42}	326*	8	181	13	0.002	13	0	–	0	–	0	–	0	–	2.5	8
12739	M	naïve	762*	8	20	15	0.002	44	0.002	24	0	–	0	–	0	–	0	–
12749	F	naïve	204*	10	92	13	0	–	0.002	20	0	–	0	–	0	–	0	–
GeoMean			445	8.2	106	12.6	0.22	19	0.002	22	0.002	30.8	0	–	0	–	1.83	8.8
Control																		
12910	M	naïve	nc	nc	nc	nc	nc	nc	nc	nc	nc	nc	nc	nc	nc	nc	485†	6
12911	F	naïve	nc	nc	nc	nc	nc	nc	nc	nc	nc	nc	nc	nc	nc	nc	519†	6
12943	F	naïve	nc	nc	nc	nc	nc	nc	nc	nc	nc	nc	nc	nc	nc	nc	768†	7
GeoMean																	578	6.3

Pfs25 = *P. falciparum* sexual stage antigen 25, 500 µg plasmid DNA ID administered on Weeks −8, −5, and −2 prior to the first FVO challenge.
PfAMA-1 = *P. falciparum* apical membrane antigen-1, 2 mg IM administered on Weeks −9, −6, and −3 prior to the first FVO challenge.
PfMSP-1_{42} = *P. falciparum* merozoite surface antigen-1_{42}, 500 µg ID administered on Weeks −8, −5, and −2 prior to the first FVO challenge.
PC = highest parasite count in parasites/µl blood × 10⁻³; means for parasite counts are geometric means.
PP = pre-patent period in days; means for lengths of pre-patency are arithmetic means.
nc = not challenged; GeoMean = geometric mean; M = male; F = female.
* treated with three doses of mefloquine daily for three days (20 mg/kg).
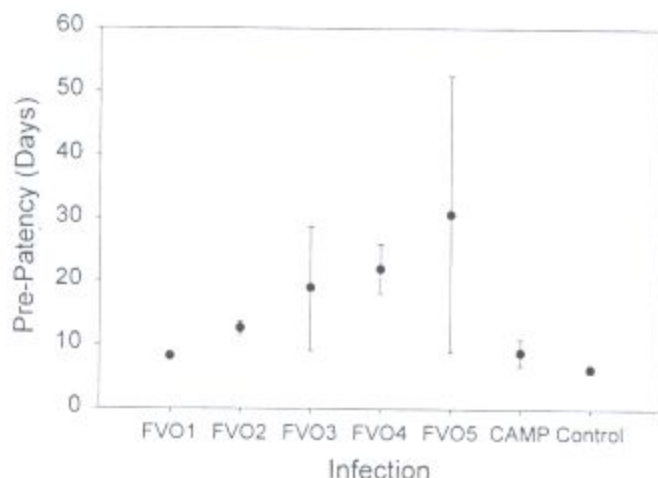† treated with a single dose of mefloquine (20 mg/kg).

FIGURE 2. The mean pre-patency period seen in *Plasmodium falciparum* strain the Vietnam Oak Knoll (FVO) challenge, CAMP strain challenge and CAMP control challenge. Bars are 95% confidence intervals. None of the monkeys became parasitemic at FVO challenge 6 or 7.
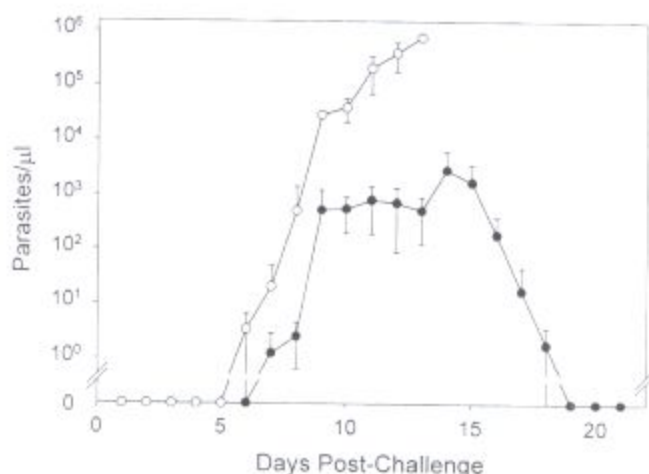

FIGURE 3. Mean *Plasmodium falciparum* CAMP strain parasitemia densities (parasites/μl blood) in monkeys previously infected seven times with *P. falciparum* the Vietnam Oak Knoll (FVO) strain (●), and in naïve monkeys (o). None of monkeys previously challenged with FVO strain required treatment for their CAMP infections. All three naïve monkeys required treatment on days 6 or 7. Bars are 95% confidence intervals. The two monkeys (12739, 12749) not developing parasitemias are not included here.

after the sixth and seventh FVO challenges. Six of eight of the monkeys became parasitemic after the CAMP challenge, as did all three naive monkeys challenged simultaneously with the CAMP strain (Table 1). The difference between the 100% protected from detectable parasitemia in the seventh FVO challenge and the 25% protected in the CAMP challenge was significant ($P = 0.007$, Fisher exact test two-tailed).

Pre-patency. The pre-patency lengthened after each FVO infection: 8.3 (95% CI: 7.8, 8.7) days after the first infection, 12.6 (11.6, 13.7) days after the second, 19 (9.2, 28.9) days after the third, 22 (18.1, 25.9) days after the fourth, and 31.8 (9.0, 52.5) days after the fifth infection ($P = 0.013$, one-way ANOVA). The mean pre-patency period after the CAMP challenge was 8.8 (6.7, 10.9) days for the immune monkeys, while the mean pre-patency in the naïve control monkeys infected at the same time was 6.3 (5.7, 7.0) days. The difference between the two pre-patency periods in the CAMP challenge (8.8 and 6.3 days) was not significant by t-test ($P = 0.160$). Our power to detect a true difference of that magnitude with our sample size (8 and 3) was 43%. The mean pre-patency periods for those infections in which animals became parasitemic are shown in Figure 2.

Peak parasitemia. Comparisons of peak parasitemia in the first two challenges are difficult because treatment was not instituted based solely on parasite density in the blood. All eight monkeys received treatment at first infection due to apparently uncontrolled parasitemias of between 2×10^5 and 1.2×10^6 parasites/μl (geometric mean = 445,409 parasites/μl). At second infection, 8/8 became parasitemic and 3/8 of those self-cured after developing parasitemias ranging from 2×10^4 to 1.8×10^5 parasites/μl (geometric mean = 106,621 parasites/μl). All monkeys that became parasitemic during FVO challenges 3, 4 and 5 self-cured (geometric mean peak parasitemias = 221, 2 and 2 parasites/μl respectively). Six of eight of the monkeys challenged with CAMP became parasitemic with a geometric mean of 1830 parasites/μl, and none higher than 10,920 parasites/μl. None of the monkeys challenged repeatedly with FVO required drug

treatment after the CAMP challenge (Fig 3), and none was parasitemic after day 18. All were followed for 100 days and did not become parasitemic again. On the other hand, all three naïve control animals challenged with CAMP required treatment on Day 12 or 13 (Table 1) due to parasitemias ranging between 4.8 and 7.7×10^5 parasites/μl.

Hematocrit. After the CAMP challenge, mean hematocrits for the eight immunized monkeys decreased from 50.6% on Day 10 post-CAMP challenge to 36.5% on Day 17, then stabilized, averaging 36.7% on Day 21 and increasing to 48.5% by Day 31 post-CAMP challenge. The hematocrits of the three naïve monkeys also decreased to a low of 38.6% on Day 17 post-challenge, but increased to 47.3% on Day 21 (Table 2). All three of the naïve monkeys were treated with mefloquine on Day 12 or 13. The two immune monkeys with the highest parasitemias during the CAMP challenge (monkey 12765 at 9,890 parasites/μl and monkey 12763 at 10,920 parasites/μl) also had the largest decrease in hematocrit referent to the Day 10 baseline during the challenge (59.6% decrease and 51.8% decrease respectively). In spite of these decreases, the hematocrits in both these animals returned to normal by Day 35 (49% and 50% respectively).

Immunization status. The animals were divided into two groups based on their immunization status. Animals designated as "immunized" had received early generation AMA-1 or MSP-1 DNA vaccines while those designated as "not immunized" had received either no immunizations or a Pfs25 DNA vaccine, an antigen not known to be expressed by blood stage parasites. No association between immunization status and mean pre-patent period during FVO infections 1 and 2, and during the CAMP infection was noted (independent samples t test, $P = 0.36$, $P = 0.10$, $P = 0.3$, respectively). Calculations to determine our power to detect a difference between these two groups given that a true difference exists indicated that for the first FVO challenge, we had a 0.29 probability of detecting a true difference of 0.5

TABLE 2

Hematocrits in the CAMP-challenged immune *Aotus* (n = 8) and the naïve control *Aotus* (n = 3). Days cited are days post-CAMP challenge. The right column (% drop) shows the percent the hematocrit decreased from Day 10 to its lowest level on any subsequent day

| Monkey no | Parasitemia | | Hematocrit (%) | | | | | | | | |
	Maximum (parasites/µl)	Day*	Day 10	Day 14	Day 17	Day 21	Day 24	Day 28	Day 31	Day 35	% drop
12749	0	—	53	52	51	45†	51	49	60	55	15.1
12759	2520	14	55	48	40†	40	44	53	51	54	27.2
12739	0	—	35	38	44	38	31†	41	31	NA	11.4
12756	380	10	56	38	28†	40	42	43	47	50	50.0
12757	2980	9	42	39	27†	36	45	47	48	51	35.7
12765	9890	14	52	42	24	21†	23	43	53	49	59.6
12763	10920	14	54	41	27	26†	39	55	46	50	51.8
12730	120	14	58	57	51	45	44†	57	48	53	24.1
12910	484500	12‡	56	46†	52	52	50	50	52	52	21.4
12911	519000	12‡	49	29†	43	43	43	51	52	52	40.8
12943	767250	13‡	55	46	47	47	42†	47	57	57	23.6

* day upon which the maximum parasite density occurred.
† the lowest hematocrit recorded for that animal.
‡ treated, mefloquine 20 mg/kg on day noted.
NA = not available. Monkey 12739 died on Day 3. Necropsy revealed an enlarged spleen and liver, but no indication that the death was malaria-related.

day. Were the difference 1.2 days, we would have had a 0.5 probability of detecting that true difference. In the second FVO challenge, we had a 0.38 probability of detecting a true difference of 1.75 days. Were the difference 2.1 days, we would have had a 0.5 probability of detecting that true difference. In the CAMP challenge, we had a 0.15 probability of detecting a true difference of 2 days. Were the difference 4.5 days, we would have had a 0.5 probability of detecting that true difference. There was no association between immunization status and frequency of treatment in any of the infections (Chi square, P = non-calculable, P = 0.99, P = non-calculable, respectively).

DISCUSSION

Aotus monkeys have been used successfully as one of the few animal models useful in the study of the biology of *P. falciparum* infection, having first been infected in 1967,[6] and subsequently used extensively in drug treatment and vaccine evaluation.[7-11] A small number of heterologous challenges have been performed in the past using *P. falciparum* strains in *Aotus* monkeys. These studies, performed in other species of *Aotus*, also showed that previous infection provided protection from subsequent challenge with the same strain. There was also demonstrations of varying degrees of protection to heterologous challenge, but a variety of differences between those studies and work reported here include different *Aotus* species, different *P. falciparum* strains, and the use of splenectomized animals.[12-15]

In this study, we have evaluated the ability of repeated blood stage infection with the FVO strain of *P. falciparum* to induce immunity to further FVO infections, and immunity to infections with a different strain of *P. falciparum*, the CAMP strain. Although FVO and CAMP were both originally isolated in Indochina, FVO in Vietnam[1] and CAMP in Malaysia,[4] we selected CAMP as the heterologous challenge strain because 1) it, like FVO, is adapted to *Aotus*, and 2) there is evidence that there are differences between the two strains in antigens thought to be important in immunity to blood stage infection. Specifically, a search of the National Center for Biotechnology Information (NCBI) at The Na-

tional Institutes of Health was conducted to identify *P. falciparum* antigens for which the amino acid sequences had been reported for both FVO and CAMP. In region II, which includes the glycophorin A binding domain, of erythrocyte binding protein 175 (EBA–175), four of 616 (0.65%) amino acids were non-identical[16,17] (accession X52524; accession AAU27390). The reported sequences for FVO and CAMP AMA–1 were 3.37% non-identical (21 of 622 residues)[18] (accession M58545, Aguiar and Hoffman, direct submission to NCBI, accession U84348). The FVO and CAMP strains possess different alleles of MSP-1; at the amino acid level, these alleles have 60% identity, 73% identity when including synonymous changes[19] (accession X03831; Louis-Wileman, Shi, Collins and Lal, direct submission to NCBI, accession L20092). In addition, RFLP analysis of FVO and CAMP showed length differences in ring-infected erythrocyte surface antigen (RESA).[20] Phenotypic differences between the two strains in infection pattern, gametocyte production, and auto-agglutination have also been reported.[20]

In our studies, repeated challenge with 10^4 blood stage *P. falciparum* FVO parasites induced complete resistance to subsequent FVO challenge after 2 (n = 1), 3 (n = 1), 4 (n = 2) or 5 (n = 4) homologous challenges. With the sixth challenge, all eight animals were resistant to infection with 10^4 infected *Aotus* erythrocytes to the extent that no parasites were found on thick blood film examination. Resistance to infection was also manifest by a lengthening in the pre-patency period, from an initial 8.25 days to 30 days at the fifth infection (Table 1, P = 0.013, one-way ANOVA). In addition, the frequency of treatment for parasitemia or clinical deterioration decreased from 100% during the first challenge to 63% during the second challenge, then to 0% in subsequent challenges (Table 1). Others have reported a similar ability to protect both *Aotus* and *Saimiri* monkeys from infection with *P. falciparum*.[15,18]

In our study, none of the animals required treatment beginning with the third infection. This capacity to self-cure is a significant development. If a vaccine based on a gene sequence from a single clone of *P. falciparum* led to the development of parasitemia like that found in the monkeys with the third infection, it would have an enormous impact

on the morbidity and mortality of malaria, especially if effective against a variety of strains. We therefore cross-challenged the monkeys with the CAMP strain. While all the monkeys controlled their CAMP parasitemias (unlike their first two FVO challenges, Table 1), six of eight did develop patent parasitemias (unlike their sixth and seventh FVO challenges). Furthermore, by fifth FVO infection, the mean pre-patent period had gone from 8.2 days with first infection to 30 days, but when these animals were challenged with CAMP the pre-patent period was reduced to 8.8 days. In addition, three of the animals had at least 50% decreases in hematocrit (Table 2). Nonetheless all CAMP-infected monkeys controlled their parasitemias. Geometric mean peak parasitemia after the first FVO infection was 445,000 parasites/μl compared with 1,825 parasites/μl for the CAMP infection ($P < 0.001$, t-test); the latter did not require treatment.

The fact that all of the animals developed sterile protective immunity to homologous challenge, and controlled the heterologous challenge parasitemia without treatment provides an important yardstick for vaccine developers. As stated above, if a vaccine did this, it would eliminate much of the severe morbidity and mortality of malaria. However, such a vaccine would not be optimal for non-immune travelers. If they developed parasite densities like those seen in monkeys 12765 and 12763 (10,000 parasites/μl or greater), the travelers would become ill,[22] and a 50% decrease in their hematocrits, even if not to life-threatening levels, would certainly have a clinical impact.

The fact that the pre-patent period after the heterologous CAMP challenge was similar to the pre-patent period following the first FVO infection (not significantly different, $P = 0.6$, t-test) suggests to us that immediately after the CAMP infection, the anti-FVO immune responses had only a modest effect, if any, on controlling the infection. However, the antigens presented at the beginning of the CAMP infection must have led to rapid boosting of cross-reacting anti-CAMP immune responses primed by repeated FVO infections, and these immune responses controlled the parasitemia.

The rapid reduction of hematocrit in some of the FVO-immune animals challenged with CAMP is disturbing. The dramatic decrease in hematocrit in monkeys 12765, 12763, and 12756 (Table 2) cannot be ascribed to destruction of infected erythrocytes, since peak parasitemias were only 10,920 parasites/μl. If one assumes 3.3×10^6 erythrocytes/μl blood, then this level of parasitemia would translate into only 0.33% of erythrocytes being infected. Destruction of these cells cannot account for a decrease in hematocrit of over 50%. Ineffective erythropoeisis cannot be invoked for this drop which occurred over 7 to 11 days. We believe that only hemolysis of non-infected erythrocytes can explain the rapid decrease in hematocrit that we observed, and we are currently evaluating the anemia from this perspective.

Although some of the monkeys received DNA immunizations prior to the start of this study, we were unable to document any effect associated with immunization status. Although the two naïve animals (12739 and 12749) were the only animals that did not become parasitemic upon CAMP challenge, it should be remembered that the two others immunized with Pfs25 are, for the purposes of this study, also naïve because Pfs25 is not expressed by asexual parasites.[23]

These two animals (12765 and 12763) had the densest CAMP parasitemias. Attemping to draw conclusions about the effect of prior immunization is unwise because of the statistical non-significance of the differences, and the lack of statistical power to resolve meaningful differences.

In summary, repeated infection with one strain of *P. falciparum* (FVO) led to sterile protective immunity against the same strain, and provided significant protection from overwhelming parasitemia in a subsequent challenge with another strain (CAMP). This protection did not, however, extend to protection from anemia. Those animals with the highest parasitemias after CAMP challenge, while self-curing their infections, experienced very significant decreases in hematocrit. Further characterization of the pathogenesis of the anemia will be important.

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REFERENCES

1. Siddiqui WA, Schnell JV, Geiman QM, 1972. A model *in vitro* system to test the susceptibility of human malarial parasites to antimalarial drugs. *Amer J Trop Med Hyg 21:* 393–399.
2. Ma NS, Rossan RN, Kelley ST, Harper JS, Bedard MT, Jones TC, 1978. Banding patterns of the chromosomes of two new karyotypes of the owl monkey, *Aotus*, captured in Panama. *J Med Primatol 7:* 146–155.
3. Obaldia N, 1991. Detection of *Klebsiella pneumonia* in *Aotus l. lemurinus* (Panamanian owl monkey) using an enzyme-linked immunosorbent assay (ELISA) test. *Lab Anim 25:* 133–141.
4. Wellde BT, Johnson AJ, Williams JS, Sadun EH, 1972. Experimental infection with *Plasmodium falciparum* in *Aotus* monkeys 1. Parasitologic, hematologic, and serum biochemical determinations. *Amer J Trop Med Hyg 21:* 260–271.
5. Earle WC, Perez M, 1932. Enumeration of parasites in the blood of malarial patients. *J Lab Clin Med 17:* 1124–1130.
6. Geiman QM, Meagher MJ, 1967. Susceptibility of a New World monkey to *Plasmodium falciparum* from man. *Nature 215:* 437–439.
7. Schmidt LH, 1973. Infections with *Plasmodium falciparum* and *Plasmodium vivax* in the Owl monkey—model systems for

basic biological and chemotherapeutic studies. *Trans Roy Soc Trop Med Hyg 67*: 446–474.

8. Collins WE, 1994. The owl monkey as a model for malaria. Baer JF, Weller RE, Kakoma I, eds. *Aotus: The Owl Monkey.* San Diego, CA: Academic Press, 217–244.

9. Kumar S, Yadava A, Keister DB, Tian JH, Ohl M, Perdue-Greenfield KA, Miller LH, Kaslow DC, 1995. Immunogenicity and *in vivo* efficacy of recombinant *Plasmodium falciparum* merozoite surface protein-1 in *Aotus* monkeys. *Mol Med 1*: 325–332.

10. Chang SP, Case SE, Gosnell WL, Hashimoto A, Kramer KJ, Tam LQ, Hashiro CQ, Nikaido CM, Gibson HL, Lee-Ng CT, Barr PJ, Yokota BT, Hui GSN, 1996. A recombinant baculovirus 42-kilodalton C-terminal fragment of *Plasmodium falciparum* merozoite surface protein 1 protects *Aotus* monkeys against malaria. *Infect Immunity 64*: 253–261.

11. Oduola AM, Sowunmi A, Milhous WK, Brewer TG, Kyle DE, Gerena L, Rossan RN, Salako LA, Schuster BG, 1998. *In vitro* and *in vivo* reversal of chloroquine resistance in *Plasmodium falciparum* with promethazine. *Amer J Trop Med Hyg 58*: 625–629.

12. Voller A, Richards WHG, 1970. Immunity to *Plasmodium falciparum* in owl monkeys (*Aotus trivirgatus*). *Z Tropenmed Parasit 21*: 159–166.

13. Voller A, Green DI, Richards WHG, 1973. Cross immunity studies with East and West African strains of *Plasmodium falciparum* in owl monkeys (*Aotus trivirgatus*). *J Trop Med Hyg 76*: 135–139.

14. Mitchell GH, Richards WHG, Butcher GA, Cohen S, 1977. Merozoite vaccinations of Douroucouli monkeys against falciparum malaria. Lancet I: 1335–1338.

15. Siddiqui WA, Taylor DA, Kan S-C, Kramer K, Richmond-Crum S, 1978. Partial protection of *Plasmodium falciparum*-vacci-nated *Aotus trivirgatus* against a challenge of heterologous strain. *Amer J Trop Med Hyg 27*: 1277–1278.

16. Sim BKL, 1990. Sequence conservation of a functional domain of erythrocyte binding antigen 175 in *Plasmodium falciparum*. *Mol Biochem Parasitol 41*: 293–295.

17. Liang H and Sim BKL, 1997. Conservation of structure and function of the erythrocyte-binding domain of *Plasmodium falciparum* EBA-175. *Mol Biochem Parasitol 84*: 241–245.

18. Thomas AW, Waters AP, Carr D, 1990. Analysis of variation in PF83, an erythrocytic merozoite vaccine candidate antigen of *Plasmodium falciparum. Mol Biochem Parasitol 42*: 285–287.

19. Weber JL, Leininger WM, Lyon JA, 1986. Variation in the gene encoding a major merozoite surface antigen of the human malaria parasite *Plasmodium falciparum. Nucleic Acid Res 14*: 3311–3323.

20. Fandeur T, Mercereau-Puijalon O, Bonnemains B, 1996. *Plasmodium falciparum*: genetic diversity of several strains infectious for the squirrel monkey (*Saimiri sciureus*). *Exp Parasitol 84*: 1–15.

21. Fandeur T, Chalvet W, 1998. Variant- and strain-specific immunity in *Saimiri* infected with *Plasmodium falciparum. Amer J Trop Med Hyg 58*: 225–231.

22. Church LWP, Le TP, Bryan JP, Gordon DM, Edelman R, Fries L, Davis JR, Herrington DA, Clyde DF, Shmurklarsky MJ, Schneider I, McGovern TW, Chulay JD, Ballou WR, Hoffman SL, 1997. Clinical manifestations of *Plasmodium falciparum* malaria experimentally induced by mosquito challenge. *J Infect Dis 175*: 915–920.

23. Kaslow DC, Quakyi IA, Syin C, Raum MG, Keister DB, Coligan JE, McCutchan TF, Miller LH, 1988. A vaccine candidate from the sexual stage of human malaria that contains EGF-like domains. *Nature 333*: 74–76.