Phase I Safety and Immunogenicity Trial of *Plasmodium vivax* CS Derived Long Synthetic Peptides Adjuvanted with Montanide ISA 720 or Montanide ISA 51

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Abstract. We assessed the safety, tolerability, and immunogenicity of a mixture of three synthetic peptides derived from the *Plasmodium vivax* circumsporozoite protein formulated in Montanide ISA 720 or Montanide ISA 51. Forty healthy malaria-naive volunteers were allocated to five experimental groups (A–E): four groups (A–D) were immunized intramuscularly with 50 and 100 µg/dose injections of a mixture of N, R, and C peptides formulated in the two different adjuvants at 0, 2, and 4 months and one group was administered placebo. Vaccines were immunogenic, safe, well tolerated, and no serious adverse events related to the vaccine occurred. Seroconversion occurred in > 90% of the vaccines and antibodies recognized the sporozoite protein on immunofluorescent antibody test. Vaccines in Montanide ISA 51 showed a higher sporozoite protein recognition and interferon production. Results encourage further testing of the vaccine protective efficacy.

INTRODUCTION

A vaccine against pre-erythrocytic stages of malarial infection would be an ideal weapon to avoid clinical manifestations of disease because it would block the infection during the initial asymptomatic phase. Indeed, it has been extensively proven that animals[1,2] and humans[3,4] vaccinated with irradiated sporozoites become immune to experimental infections induced by sporozoites, and do not develop patent blood-stage infections or clinical malaria symptoms. Sera and cells from these individuals recognize proteins expressed on the sporozoites and the parasite liver forms[5–9] that have been incriminated in this protection and therefore have been proposed as malaria vaccine candidates.[10,11] Among them, the circumsporozoite (CS) protein that is abundantly expressed on the sporozoite surface has been shown to be involved in the process of parasite invasion to the hepatocyte[12,13] and its immunological blockage prevents the development of malaria infection.[6,7,14] The RTS-S vaccine based on a construct of the *Plasmodium falciparum* CS protein and the S antigen of human hepatitis B virus has proven to be immunogenic and partially protective in phase II studies conducted with human malaria-naive volunteers[15–18] and in adults and children from malaria-endemic areas of Africa.[19–22]

Regarding the *Plasmodium vivax* CS protein, three long synthetic peptides (LSP) homologous to the amino (N), central repeat (R), and carboxyl (C) regions were initially evaluated in preclinical studies and showed high immunogenicity in mice and *Aotus* monkeys.[23,24] On the basis of those studies the same LSPs were formulated in Montanide ISA 720 and assessed in phase Ia clinical trial conducted by the Malaria Vaccine and Drug Development Center (MVDC) in Cali, Colombia. Immunization with this formulation indicated to be safe, well tolerated, and immunogenic.[25] All three peptides induced production of high titers of specific antibodies that cross-reacted with the protein on the parasite and

production of interferon-gamma (IFN-γ) in most vaccinated subjects. Although the N peptide induced the highest antibody titers at three different doses tested (10, 30, and 100 µg/dose), peptides R and C were also immunogenic at high doses. In the search for an optimal vaccine formulation for human use we have conducted pre-clinical studies in mice, monkeys, and clinical trials in malaria-naive volunteers, and we performed a new series of studies to assess the safety and immunogenicity of a combination of the three peptides formulated either in Montanide ISA 720 or in Montanide ISA 51. The rationale for these mixtures was to determine the possibility of immunological interference among the different peptides or their potential synergism. These adjuvants were selected because they form stable water-in-oil emulsions and induced high antibody levels that lasted for up to 1 year in mice, rabbits, and monkeys in previous studies using recombinant malaria proteins.[23,26–32] More recently, a recombinant *P. vivax* CS protein produced in *Escherichia coli* and formulated in Montanide ISA 720 showed to be highly immunogenic in mice.[33] Several phase I clinical trials have been conducted using different malaria vaccine antigens in which these two adjuvants have been able to stimulate both humoral and cellular immune responses.[34–37]

We present here a phase I clinical trial conducted with the same *P. vivax* CS derived peptides formulated in two different adjuvants, and provide further safety and immunogenicity data as part of a clinical development plan that aims at developing vaccines to prevent malaria.

MATERIALS AND METHODS

Study design and population. This was a phase I double-blind, controlled vaccine trial, evaluating safety, tolerability, and immunogenicity of mixtures of N, R and C LSP derived from the *P. vivax* CS protein formulated in two adjuvants Montanide ISA 720 and Montanide ISA 51. The primary objective was to assess in malaria-naive adults, the safety and reactogenicity of these peptides formulated in the two adjuvants. Study protocol was approved by the Institutional Review Boards (IRB) of the Universidad del Valle and Centro Médico Imbanaco (CMI), and the study complied with Declaration of Helsinki principles, International Conference

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on Harmonization, Good Clinical Practices guidelines, and all pertinent Colombian regulations. We recruited 40 healthy men and women volunteers from Cali, Colombia, a city non-endemic for malaria. Volunteers were 19–41 years of age and had no history of malaria. During a period of 3 months a total of 100 volunteers were assessed for eligibility criteria to select a total of 40 volunteers willing to participate in the clinical trial. By consecutive allocation, eight participants were allocated to each of the five experimental groups (A–E): four groups (A–D) were immunized with the vaccine formulations at two different dose concentrations and formulated in two different adjuvants. A control group (E) was injected with placebo (saline solution) (Table 1). Volunteers and physicians responsible for immunization were kept blind using codes for volunteers and vaccine groups. Vaccines were prepared by individuals not involved with patient care. Syringes containing either vaccine or placebo were covered by opaque adhesive tape, precluding visualization of the contents by the study participants and clinical researchers.

All participants provided written informed consent and were notified that they were free to withdraw from the study at any time. Volunteers were excluded if they had diseases or medical conditions that would alter assessment of the vaccine, including infection by human immunodeficiency virus, hepatitis B, or hepatitis C; cardiac, hepatic, renal, or autoimmune disease; anemia, allergies, pregnancy, immunodeficiencies, existing antibodies to the *P. vivax* CS protein, history of splenectomy or any other condition that could increase the risk of an adverse outcome.

Intervention. To optimize the vaccine dose, eligible participants were enrolled to receive three doses of vaccine containing peptide mixtures at a dose of 50 or 100 μg of each individual peptide, for a final dose of 150 or 300 μg, respectively, in a volume of 0.5 mL. The previous clinical trial had indicated that doses between 30 and 100 μg produced better responses than lower doses. The first immunization dose (given at Month 0) contained the peptides N and C only, whereas the two boosting doses (given at Months 2 and 4) contained all three (N, R, and C) peptides (Table 1). Vaccination was performed by intramuscular injection in the deltoid muscle, alternating arms with each injection. For safety reasons, participants assigned to the low vaccine dose groups were immunized first and only 2 weeks after initiation when no serious adverse events (SAE) had occurred, immunization of participants in the high dose was started. Half of the participants assigned to receive placebo were immunized along with each dose level group. Clinical monitors and the institutional review boards (IRBs) of the Universidad del Valle and IMC, evaluated the

occurrence and severity of adverse events (AE) associated with immunization. The occurrence of more than three AE (severity grade 2 or higher) or one SAE related to the vaccine would have led to study termination. Participants who left the study were not replaced.

Vaccines. The N polypeptide comprises amino acids 20–96 of CS protein and constitutes a 77-mer peptide, the R peptide is a hybrid 48-mer peptide, type I or common sequence (VK210) contains repeats of the GDRADGQPA motif, and the 72-mer C peptide is composed of amino-acid residues 301–372 of the CS protein. We synthesized the peptides under good laboratory practices (GLP) conditions at the Biochemistry Institute, University of Lausanne, Switzerland, and using solid-phase fluorenylmethoxycarbonyl (F-moc) chemistry.[38] The C-terminal peptide containing 4-Cys was oxidized according to Verdini and others.[39] Mass and purity of the peptides were assessed by high performance liquid chromatography and mass spectrometry and was higher than 90%.[25] Peptides were lyophilized, packaged, and both sterility and pyrogenicity were tested. We mixed peptides N, R, and C in concentrations of 50 and 100 μg for each peptide for a final concentration of 150 or 300 μg/dose, and then 24 hrs before each immunization, the mixture was emulsified in either of the two adjuvants: Montanide ISA 51 or Montanide ISA 720 (Seppic Inc., Paris, France) and stored at 4°C according to manufacturer recommendations. Vaccine stability at this temperature is long lasting. Saline solution (Baxter, Deerfield, IL) was emulsified with the same adjuvants and used as placebo. Both vaccine and placebo were emulsified as described earlier.[23] An independent monitor assessed peptide integrity at the beginning and the end of the study.

Safety. The primary endpoints were the occurrence of solicited signs and symptoms during an 8-day period after each vaccination. Volunteers were encouraged to maintain contact with the research team by phone and whenever needed personally, at any time of the day, to inform the occurrence of any symptom during the 1-year study period. Volunteers were observed for 60 minutes after injection and evaluated by the study team at 8 and 24 hrs after injection and again on Day 7 after vaccination. Safety was assessed by a complete physical examination and clinical laboratory tests on all study participants during monthly visits up to Month 5 post immunization and followed up by phone between months 5 and 12. Blood samples were collected for complete blood count, sedimentation rate, prothrombin time, partial thromboplastin time, blood urea nitrogen, and serum glucose, total protein, albumin, alanine aminotransferase, aspartate aminotransferase, alkaline phosphatase, and bilirubin. Immediately before each

TABLE 1
Volunteer recruitment and immunization schedule

Recruitment process		Volunteers asked to participate	Refused to participate	Not meet inclusion criteria	Reserved if needed	Volunteers briefed
Number of volunteers (n)		100	51	7	2	40
		Consecutive allocation				
		A	B	C	D	E
Montanide adjuvant	Immunogen	ISA 51	ISA 720	ISA 51	ISA 720	Placebo
1st dose	N + C	100* (N = 8)	100 (N = 8)	200 (N = 8)	200 (N = 8)	SS† (N = 8)
2nd dose	N + R + C	150 (N = 8)	150 (N = 7)	300 (N = 7)	300 (N = 8)	SS (N = 8)
3rd dose	N + R + C	150 (N = 8)	150 (N = 7)	300 (N = 6)	300 (N = 8)	SS (N = 8)

*μg/dose.
†Saline solution.

vaccination, we tested female volunteers for pregnancy using a beta human chorionic gonadotropin test. Solicited symptoms were grouped by local and systemic. Local symptoms included pain, swelling, and erythema, whereas systemic symptoms were fever, flu-like symptoms, headache, dizziness, nausea, emesis, and abdominal pain. Signs and symptoms were graded from mild to serious with a four level score. The AE were recorded throughout the study and were defined as any new or worsening sign or symptom of illness or an abnormal laboratory test during the protocol specified follow-up. Each AE was evaluated by the study clinician for its severity,[40] and relatedness to vaccination and SAE were reported as required by the World Health Organization (WHO).[41] The data safety monitoring board was constituted by an external clinical monitor and an internal clinical monitor who met three times during the study.

Measurement of humoral responses. The immunological assays were performed using samples collected during the monthly visits. Antibody response was measured by enzyme-linked immunosorbent assay (ELISA) using as antigen the N, R, or C peptides (1 µg/mL), as described previously.[42] The final reaction was read at 405 nm in a microplate reader (MRX; Dynex Technologies, Inc., Chantilly, VA). Cut-off points were calculated as three SD above the mean absorbance value at 405 nm of sera from healthy volunteers who had never been exposed to malaria. Controls were selected from a pool of sera from semi-immune blood donors (positive controls) and a pool of sera from malaria-naive donors (negative controls). Peptide-specific IgG isotypes were determined by modified ELISA using sera collected at Months 0 and 5 from immunized volunteers. Briefly, 1 µg/mL of peptide was used as antigen to coat microplates. Wells were blocked with phosphate buffer saline (PBS)-Tween 20 plus fat free milk and then incubated with the serum sample dilutions for 1 hr. Plates were washed with PBS-Tween 20 and then incubated with mouse anti-human IgG isotype antisera. The ELISA titers of < 1:200 were considered negative.

Anti-IgG1, IgG3, and IgG4 (Skibio, Bedfordshire, England) and anti-IgG2 (Sigma, St. Louis, MO) isotypes were used and a peroxidase conjugated goat anti-mouse IgG antibody (Kirkegaard and Perry Laboratories, Gaithersburg, MD) was added and the reaction read at 630 nm ($OD_{630)}$. Data were reported as ratio (OD mean of the sample, positive or negative controls divided by the cut-off point).

Parasite recognition by anti-peptide antibodies was determined by indirect immunofluorescent antibody test (IFAT) at 0, 3, and 5 months after enrollment using *P. vivax* sporozoites produced in *Anopheles albimanus* mosquitoes. Antibody titers were determined as the reciprocal of the end-point dilution that showed positive fluorescence as described previously.[25] In addition, 50 sera from individuals naturally exposed to malaria were also evaluated for the presence of anti-*P. vivax* sporozoite and comparison with antibodies induced by vaccinations.

Enzyme-linked immunosorbent spot (ELISpot) assay for single cell release of IFN-γ. Peripheral blood mononuclear cells (PBMC) collected after last immunization (Month 5) were separated from whole blood using Ficoll Histopaque (Sigma-Aldrich, St. Louis, MO) density gradients, and were resuspended in RPMI medium 1640 (Gibco, Grand Island, NY). The IFN-γ-producing cells were identified using a commercial IFN-γ ELISpot human kit (Mabtech AB, Stockholm, Sweden). Fresh PBMCs (4×10^5/well were then mixed with 10 µg/mL of each synthetic peptide and plates were incubated for 40 hrs at 37°C in an atmosphere of 5% CO_2.[25]

Spots were counted with a spot counting system (Scanalytics, Fairfax, VA), and the results were expressed as the mean number of IFN-γ spot-forming cells (sfc) per 10^6 PBMC. Volunteers were considered responders if the number of sfc in their samples had increased from their own baseline level (before immunization on Day 0), any increase ≥ 5 sfc were considered positive.[25]

Statistical methods. The main outcomes we evaluated were AE and SAE related to vaccination during the study period. An AE was considered related if it was determined to be possibly, probably, or most probably related to vaccination. Rates of related and other common AE were compared among experimental groups using Fisher's exact tests. Main comparisons of interest were between adjuvants and between vaccine doses. Antibody titers and IFN-γ production were compared among peptides, vaccine doses, and adjuvants at several points in the studies using Wilcoxon signed-rank and Kruskal-Wallis tests. Two-tailed, non-parametric *P* values ≤ 0.05 were considered significant.

RESULTS

Study population. A total of 100 people were asked to participate; of these 49 consented to screening. Finally, 40 participants willing to continue in the study (18 males and 22 females) were consecutively allocated to one of the five treatment groups, as shown in Table 1. Allocation started in the low-dose groups and once they were completed, and no SAEs were reported in response to the first vaccination dose, the study continued with the high dose. Groups were comparable in baseline demography, and clinical laboratory values did not show statistically significant differences (data not shown). One volunteer received a dose of tetanus vaccine 1 week after the first immunization and another one was immunized against rubella and smallpox at Day 68 of the study. These events were evaluated by the clinical monitor and the IRBs, and they both agreed that these two volunteers could continue in the study. Two other participants abandoned the study voluntarily, both after the first immunization, and a third participant abandoned after the second immunization.

Safety. All three immunization doses were well tolerated by all participants from the low and high vaccine doses. Low grade pain (mild or moderate) at the injection site up to 48 hrs after injection was the most frequent AE related to immunization, followed by local swelling and local erythema (Table 2). We found no statistically significant differences of AEs between doses. When comparing between adjuvants, pain at injection site was the only difference significantly higher at the third dose of the injection with Montanide ISA 720. No significant differences were observed in the occurrence of the remainder AEs. When both adjuvants were taken together and compared with placebo, local pain was more frequent in the malaria immunized group in the first and third injections (*P* = 0.03). Although local swelling seemed to be more frequent in the immunized group compared with placebo, the difference did not reach statistical significance. Headache was the most common systemic AE with both adjuvants, but again its difference with the placebo group did not reach statistical significance.

TABLE 2
Number of volunteers reporting vaccine-related adverse events per dose and adjuvant group

Adverse event	No. doses	Montanide*						Placebo		
		ISA 51			ISA 720					
		1	2	3	1	2	3	1	2	3
	n =	(16)	(15)	(15)	(16)	(15)	(14)	(N = 8)		
Local										
Injection site pain		14	12	9	14	13	12†	4	8	3
Swelling		5	2	2	11	6	8	4	1	2
Erythema		1	0	1	1	0	2	1	0	1
Systemic										
Fever (> 37.5°C)	0	1	0	1	1	0	2	1	1	
Headache	3	2	1	5	4	0	2	2	0	
Dizziness	1	1	0	1	0	0	3	0	0	
Nausea/Emesis	1	2	0	2	0	0	2	1	0	
Abdominal pain	1	0	0	2	0	0	1	0	0	
Adenopathy (Axilar/cervical)	0	1	0	1	0	0	0	0	0	

* Montanide at 150 µg or 300 µg dose.
† Two-tailed *P* values < 0.05 by Fisher exact test, for comparison among adverse events (AE) in adjuvant and placebo groups.

None of the participants experienced SAE related to the vaccine, whereas two volunteers showed SAE that were considered not related to immunization. In the placebo group, 7 days after first immunization one volunteer was diagnosed with chronic cholecystitis and another in the high dose group formulated in Montanide ISA 51 presented an acute episode of urolithiasis on Day 82 of the study. All laboratory tests for the remaining participants yielded normal values during the study period.

Humoral response. Figure 1 shows antibody responses to each peptide. After the first immunization with mixtures containing the N and C peptides, 74% of participants seroconverted for peptide N, but none for peptide C. With the second immunization, which was performed with the mixture of the three LSP, 100% of the volunteers became positive to N peptide and 71% of volunteers seroconverted to C peptide. Few of the volunteers seroconverted to R peptide after this second immunization that corresponded to a priming dose for R, but 93% of the volunteers responded to this peptide after first boosting (third immunization). Antibody titers to R peptide reached comparable levels as those obtained with the three doses of C peptide in most study groups, except for the group immunized with the 150 µg/dose in Montanide ISA 51 adjuvant, which showed titers four times higher to C peptide than to R peptide. In general, 96% of volunteers produced specific IgG antibodies to all peptides after the third immunization with the three peptide mixtures. Volunteers responded earlier to N peptide, and all volunteers required only two immunizations to seroconvert. The N peptide also elicited the highest median titer (1:9,600) when administered at 300 µg dose in Montanide ISA 720 adjuvant.

The response in low-dose groups seemed to be more rapid, but chance effect could not be securely discarded (100% versus 77.8%, *P* = 0.1). Antibody profiles in high-dose groups were very similar to those of the low-dose groups, and after the third immunization, all volunteers responded to all peptides. Comparison of antibody responses by dose showed no statistically significant differences (*P* = 0.16) or did comparison by adjuvant (*P* = 0.77), however, total antibody response to the N peptide differed from that of C and R peptides (*P* < 0.01). At 150-µg vaccine-dose, the antibody response was higher in Montanide ISA 51 than in Montanide ISA 720 group. With the 300 µg/dose all volunteers responded regardless of adjuvant.

The specific anti-peptide IgG isotypes response determined at Day 150, after the third immunization is presented in Table 3 related to peptide, adjuvant, and vaccine dose. The N peptide showed a stronger response for all isotypes than the other peptides, although it was more evident for IgG3, in contrast C peptide showed a more specific increase of IgG1. All four IgG isotypes specific for R peptide presented similar low titers in all groups. Although there was a difference among adjuvants, showing higher median IgG1 titers for this peptide in the Montanide ISA 51 group, this did not reach statistical significance, and there was no difference by peptide dose either. Concordant with all this, when the ratio of IgG1 plus IgG3 versus IgG2 plus IgG4 was evaluated, C peptide showed a higher ratio, followed by N peptide, but not a significant difference was observed between these two peptides (Figure 2).

Sporozoite recognition. Forty-three percent of the participants were (13/30) IFAT positive (titers ≥ 1:20) after the second immunization and 73% (21/29) after the third dose, without taking into account the type of adjuvant used. When responses to both adjuvants were compared after the third dose, 93% of participants receiving Montanide ISA 51 were IFAT positive as compared with 56% of those receiving Montanide ISA 720 (Table 4). Similarly, Montanide ISA 51 adjuvant resulted in higher sporozoite recognition antibody titers than Montanide ISA 720, independently of the vaccine dose (*P* = 0.01; two-tailed Kruskal-Wallis non-parametric *P* value, data not shown). In general, the two-dose immunization schedule using 150 µg/dose resulted in a lower level of anti-sporozoite antibodies when compared with titers after the third dose (*P* = 0.02). However, levels of anti-sporozoite antibodies in the groups vaccinated with both peptide doses formulated in Montanide ISA 51 were similar after the third immunization. At the higher dose, anti-sporozoite antibody levels were similar after two and three immunizations. Specificity of the antibody response was confirmed by negative results obtained by ELISA and IFAT, using sera from volunteers in the control group and from all other volunteers before immunization. Half of the individuals naturally exposed to malaria presented anti-*P. vivax* sporozoite antibodies titers ranging from 1:80 to 1:640. Most of them (10 individuals) had low antibody titers (1:80) similar to those observed in immunized volunteers.
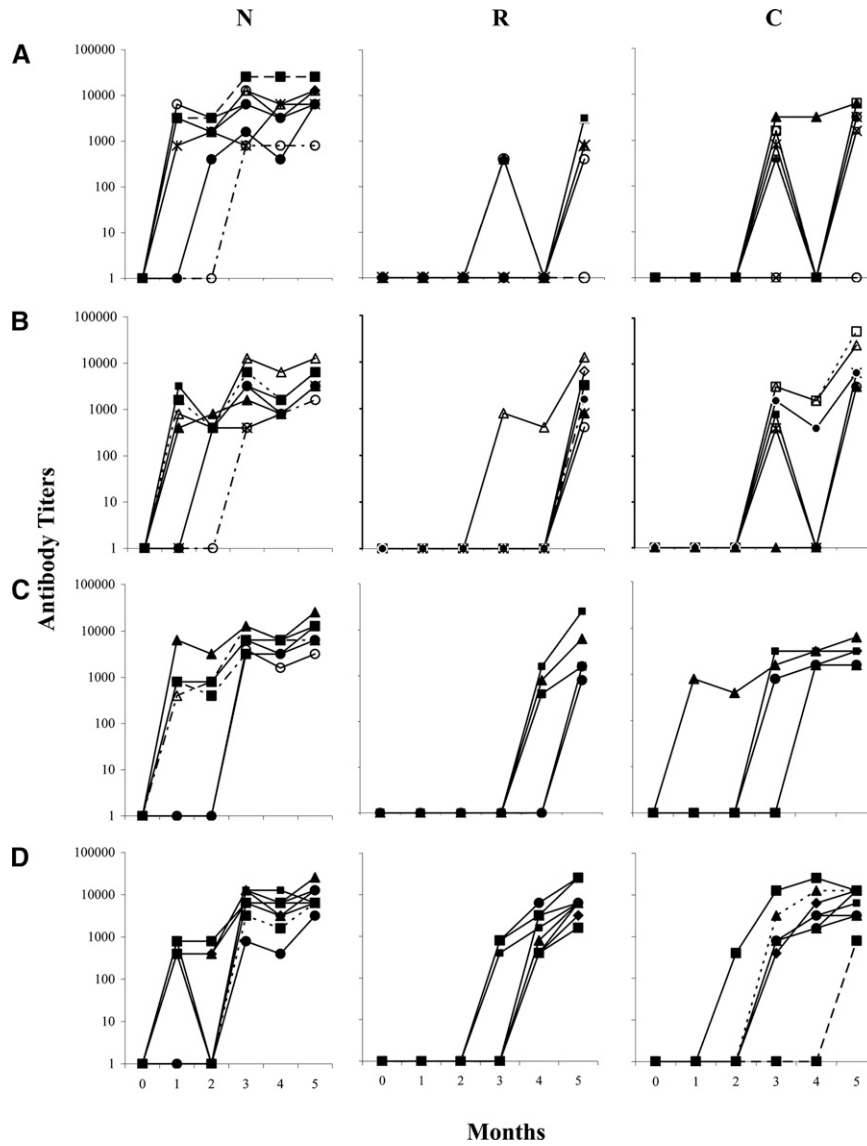
FIGURE 1. Enzyme-linked immunosorbent assay (ELISA) anti-peptide IgG titers upon vaccination with a mixture of N, R, and C peptides. Panels show responses to mixtures using 150 μg total peptide dose in (**Row A**) Montanide ISA 720 or (**Row B**) Montanide ISA 51 and to mixtures using 300 μg total peptide dose in (**Row C**) Montanide ISA 720 or (**Row D**) Montanide ISA 51. Immunizations were made in the 0, 2, and 4 months.

Single-cell IFN-γ production. Production of IFN-γ by PBMC varied among volunteers and immunization doses (Figure 3). The response to peptide N (median 140 sfc/10^6 PBMC) was significantly higher than to peptide R (median 80 sfc/10^6 PBMC) and peptide C (median 100 sfc/10^6 PBMC) ($P = 0.001$). Response induced by the 300 μg dose was higher than 150 μg dose ($P = 0.001$). When comparing groups by adjuvant, we found that the response to Montanide ISA 51

TABLE 3
Isotype response to *Plasmodium vivax* CS protein

	Isotype	IgG1			IgG2			IgG3			IgG4		
		Median	IQR*	P†	Median	IQR	P	Median	IQR	P	Median	IQR	P
Peptide	N	10.6	10.4	10.9	6.0	2.0	7.5	25.1	24.2	25.6	12.0	6.7	15.1
	R	0.9	0.6	1.4	< 0.001	0.7	0.5	0.9	< 0.001	0.9	0.8	1.5	< 0.001	0.9	0.7	1.0	< 0.001
	C	10.1	6.7	17.7	0.8	0.7	1.1	2.0	1.4	3.3	1.2	1.1	1.5
Adjuvant													
Motanide	ISA 51	10.3	1.8	10.9	0.06	1.0	0.8	2.6	0.53	2.6	1.4	24.6	0.18	1.4	1	7.8	0.13
	ISA 720	6.2	0.9	10.7	0.9	0.7	5.2	2.0	0.9	22.8	1.1	0.9	2.3
Doses μg	150	8.7	0.9	10.9	0.70	0.9	0.7	3.4	0.79	2.5	0.9	22.8	0.75	1.2	1.0	3.8	0.76
	300	10.1	2.4	10.9	0.9	0.7	2.6	1.9	1.1	24.6	1.3	0.9	11.0

*IQR = interquartile range.
†Two-tailed, Kruskal-Wallis non-parametric *P* value.

* Ratio: (IgG1+IgG3/IgG2+IgG4) after (3rd dose)

** Kruskal-Wallis P value <0.01 for comparison between median of peptide N--R and R--C peptide
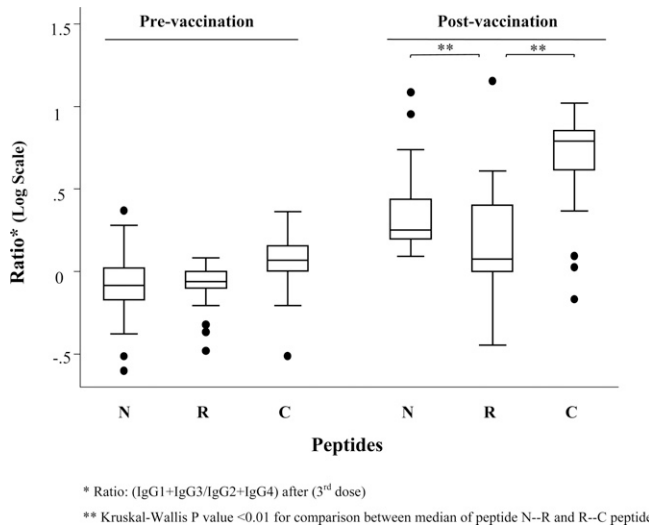
FIGURE 2. Ratio of immunoglobulin isotypes by time and peptide.

FIGURE 3. IFN-γ production in response vaccination with a mixture of N, R, and C peptides. Median of sfc to each peptide independent of doses and adjuvant.

(median 20 sfc/10^6 PBMC) was higher than to Montanide ISA 720 (median 7 sfc/10^6 PBMC) ($P = 0.05$).

DISCUSSION

Our results provide evidence that vaccination of malaria-naive volunteers with mixtures of LSP derived from the *P. vivax* CS protein formulated in Montanide ISA 720 and in Montanide ISA 51 is safe, well tolerated, and immunogenic. This study also confirms data previously reported by our group on the vaccination with similar *P. vivax* CS derived LSP individually formulated in Montanide ISA 720.[25] In this regard AEs related to vaccination occurred with similar frequency in all groups and transient pain at the site of injection, which was described as similar to that caused by commercially available vaccines, was the most frequent complaint. Moreover, the trial indicated that although the peptide mixture as formulated did not appear to produce any synergism on immune responses, we expect an additive effect of cell-mediated immunity and antibodies, especially on their blocking activity on sporozoite invasion, which may be more effective than vaccination with individual peptides.[43–45]

The peptide mixtures induced antibody titers to each peptide that were similar to those from our previous trial, in which volunteers were immunized with single peptides. This suggests that there is no detectable interference in the peptide mixture. The strategy of initially giving a priming vaccine containing N and C peptides only was used to avoid the potential imbalance that might produce the immunodominant R fragment. It has
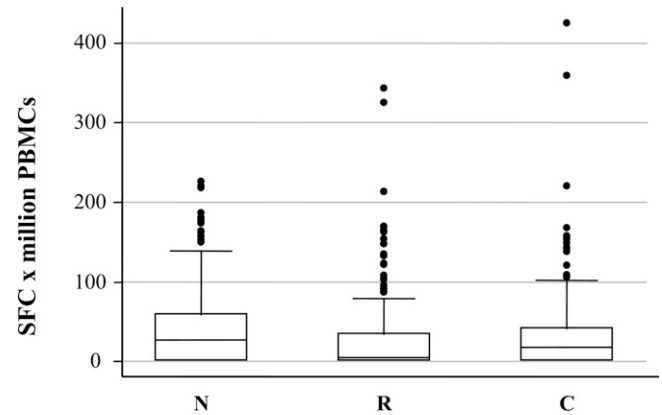
been shown that after continued exposure to malaria, sera of individuals from endemic areas recognize the R region better than the N- and C-terminal regions,[46] which may be caused by its repetitive structure, where the same B- and T-cell epitopes are repeated numerous times, whereas any individual epitope present in the N and C flanking regions is present only once in each CS molecule. This immuno-dominance may represent a "smoke screen" that diverts the response toward it, preventing the development of stronger responses to the flanking regions that contain functional cell-binding domains (regions I and II) required for parasite invasion.[16,17]

Although the use of the full-length protein may be considered desirable, besides its immunodominance, the *P. vivax* central repeat domain is highly polymorphic. Use of the LSP approach allows an easy, inexpensive, and accurate methodology to down-select protein fragments containing epitopes relevant in protection. *Plasmodium falciparum* RTS-S, the most advanced malaria vaccine candidate is based on a recombinant construct containing protein fragments similar to the *P. vivax* R and C fragments studied here. Although that construct might be the best selection for *P. falciparum*, results here indicate that other combinations, i.e., including the N fragment with other CS fragments or other antigens may be more effective in *P. vivax*. In this and in our previous vaccine trial, the C fragment was less immunogenic than N and R.[24]

Although the choice of protective protein fragment is critical, adjuvants are also fundamental. Montanide ISA 720 and Montanide ISA 51 represent a new generation of promising adjuvants, with an overall acceptable safety profile and strong B cell and Th stimulation capacity.[47] Montanide ISA 51 is a mineral

TABLE 4
Recognition of *Plasmodium vivax* sporozoites by immunofluorescence assay

| Montanide adjuvant | Dose ug | Immunization | | | | | | | Natural infection* | |
| | | Second | | | Third | | | | | |
		n	Median†	IQR‡	n	Median†	IQR‡	P	No. of responders	Antibody titers
ISA 51	150	7	0	0–10	7	40	40–320	0.02	10	80
	300	7	20	20–80	7	20	20–80	0.25	5	160
									6	320
ISA 720	150	8	10	10–20	8	10	0–60	0.22	4	640
	300	8	20	10–20	7	20	10–20	0.91	25	Negatives

*Anti-*P. vivax* sporozoite antibodies titers of 50 adults from malaria endemic regions.
†Values are reciprocal dilution titers.
‡IRQ = interquartile ratio. Two-tailed, Wilcoxon signed-rank test non-parametric P value, H_0: 2nd = 3rd.

oil-based adjuvant, which has been used in more than 25 clinical trials, representing more than 4,000 patients, and 40,000 injections, showing that it is well tolerated.[29] Local reactions such as pain, tenderness, and erythema have been the most commonly reported AEs with this adjuvant, whereas the most frequently reported AEs have been nausea, vomiting, and flu-like symptoms, although other studies have reported injection pain nodules and sterile abscesses. Their intensity usually have been classified as mild to moderate, and SAEs reported such as erythema nodosum-like syndrome and transient leukemoid cases, seems to be more related to the antigen used than attributable directly to the adjuvant.[28,36,48] Montanide ISA 720 a squalene-based adjuvant, has also been tested in multiple malaria antigens clinical trials, which have reported from minor,[25] to mild and moderate local reactogenicity[37,49,50]; however, a trial conducted with a malaria vaccine candidate formulated in this adjuvant had to be suspended because of the presence of SAEs.[43]

In this study, all formulations were immunogenic inducing both, specific anti-peptide antibodies and IFN-γ production. Importantly, even low LSP vaccine doses were enough to induce sero-conversion in 95% of the volunteers and sera from 86% of the participants recognized the native protein in sporozoites. Although IFAT titers may appear low, the high seroconversion is encouraging because in field conditions only a limited number of the individuals continuously exposed to *P. vivax* recognize sporozoites,[51,52] even if they are continuously exposed to the complete mass of parasite proteins. Interestingly, similar antibody titers were indicated in a previous trial[53] to induce significant *in vitro* sporozoites invasion inhibition.

Throughout our study, antibody responses to the N peptide developed a more homogeneous profile and were consistently stronger than those to the other peptides. As expected most volunteers produced anti-R-peptide antibodies only after a boosting dose on Month 4, thereafter they followed a trend comparable to that produced by peptide N. Similarly to our previous study, volunteers required one or two boosting doses to respond to the C-terminal peptide. Therefore, it seems that higher doses are necessary for responses to peptides R and C to reach a similar degree of maturity than induces peptide N. This may indicate the importance of attempting an even better balance among the different specificities that may be important for the protective capacity of the vaccine.

In general, antibody responses were similar in their pattern and titers to those obtained in volunteers immunized previously with individual peptides,[25] and in preclinical trials in *Aotus* monkeys vaccinated with the same vaccine formulations.[53] Moreover, titers were higher than those observed in sera of most people from *P. vivax* endemic areas of Colombia.[42]

As we expected, IgG isotype profile response was different for each peptide. The N peptide showed increased titers for all IgG isotypes, compared with C peptide that showed more defined IgG1 and IgG3 responses. This is certainly of interest, because of reports indicating that these are the main isotypes involved in protection against malaria infection, that IgG4 is non-protective and that IgG2 is not only non-protective but could even compete and interfere with the protective isotypes.[54]

Recognition of sporozoites by anti-peptide antibodies is encouraging because of the potential boosting effect of sporozoites on the humoral response upon natural exposure in endemic areas and the greater possibilities of a functional role of antibodies in blocking parasite invasion to hepatocytes.

Although anti-sporozoite antibody titers were low, it has not yet been defined what antibody levels are needed for protection. Indeed, similar antibody titers were able to block *in vitro* parasite invasion.[53] Furthermore, the fact that Montanide ISA 51 elicited a more vigorous anti-sporozoite response than Montanide ISA 720 formulations should be considered when moving forward in designing further clinical trials with these peptides.

Specific induction of IFN-γ production by T cells by all peptides but mainly by peptide N, particularly when formulated in Montanide ISA 51, is consistent with the higher antibody response; peptide N may contain stronger T-cell epitopes than in R and C peptides.[55] Recently, the N-terminal region of the *P. falciparum* CS in combination with the C-terminal region had a better ability to inhibit sporozoite invasion to hepatocytes and recognition of short N-terminal peptide (PfCS65-110) by sera from children living in a malaria-endemic region was associated with protection from disease.[56,57]

In conclusion, vaccination of human volunteers with a combination of LSP derived from the *P. vivax* CS protein formulated Montanide ISA 720 or Montanide ISA 51 is safe, well tolerated, and immunogenic. Peptides formulated in Montanide ISA 51 produced better anti-sporozoite recognition antibody response, suggesting that the choice of adjuvant for the formulation of these vaccines is an important variable to be considered in future research.[48] This study confirms LSP as a safe and immunogenic antigen. The recent development of a *P. vivax* challenge model for humans creates ideal conditions to assess these antigens in phase II studies (Herrera and others, 2011, in press).

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