SHIV Antigen Immunization Alters Patterns of Immune Responses to SHIV/Malaria Coinfection and Protects against Life-Threatening SHIV-Related Malaria

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Whether vaccination against a virus can protect against more virulent coinfection with the virus and additional pathogen(s) remains poorly characterized. Overlapping endemicity of human immunodeficiency virus (HIV) and malaria suggests that HIV/malaria coinfection frequently complicates acute and chronic HIV infection. Here we showed that vaccination of macaques with recombinant Listeria ΔactA prfA* expressing simian/human immunodeficiency virus (SHIV) gag and env elicited Gag- and Env-specific T-cell responses, and protected against life-threatening SHIV-related malaria after SHIV/Plasmodium fragile coinfection. SHIV antigen immunization reduced peak viremia, resisted SHIV/malaria-induced lymphoid destruction, and blunted coinfection-accelerated decline of CD4+ T-cell counts after SHIV/malaria coinfection. SHIV antigen immunization also weakened coinfection-driven overreactive proinflammatory interferon-γ (IFNγ) responses and led to developing T helper cell 17/22 (Th17/Th22) responses after SHIV/malaria coinfection. The findings suggest that vaccination against AIDS virus can alter patterns of immune responses to the SHIV/malaria coinfection and protect against life-threatening SHIV-related malaria.

Keywords. co-infection; HIV/AIDS; immunology; malaria; T cell; vaccination.

It is well known that a vaccine can elicit a pathogen-specific immune response, and protect against the pathogen-induced infection or disease. However, whether vaccination against a virus can protect against more virulent coinfection with this virus and additional pathogens remains understudied [1]. Some single infections are frequently complicated by concurrent or secondary infections, resulting in increased clinical deterioration and death [2–7]. Influenza-infected patients are commonly afflicted with a secondary pneumococcal pneumonia infection that causes severe lung pathology and death in chronic obstructive pulmonary disease patients [8]. Likewise, infection with human or simian immunodeficiency virus (HIV or SIV) predisposes the host to some highly pathogenic coinfections with additional pathogens even before CD4+ T-cell counts drop to the level below 200 cells/µL [9]. In nonhuman primate models of SIV/Mycobacterium coinfection, antiretroviral treatment alone can attenuate the coinfection-induced pathogenic events and protect against fatal SIV-related tuberculosis-like disease [10]. Although vaccine-induced protection against HIV-1 or SIV have been demonstrated in a recent human clinical trial and there have been some experimental vaccine studies in macaques [11–13], studies have not been done to determine whether vaccination against an AIDS virus can protect against life-threatening coinfection with the virus and additional pathogen(s).
In addition to the over 30 million people worldwide infected with HIV (http://www.who.int/hiv/data/en), approximately 300–500 million malaria infections occur annually, causing 1–3 million deaths (http://apps.who.int/malaria), primarily due to Plasmodium falciparum infections. Because both HIV and malaria are highly prevalent in overlapping geographic areas, co-infection is common [14, 15]. Studies of individuals that present with febrile illness presumably caused by malaria infection in sub-Saharan indicate that many patients present with acute or chronic HIV-malaria coinfection [16]. While mutual effects of HIV and malaria on co-infection morbidity and mortality may be complex [17–23], a number of recent studies indicate that immune suppression due to progressive HIV infection results in an increase in clinical malaria cases in HIV-infected adults whose CD4 counts are below 350 cells/μL [18, 19, 22, 23]. HIV-infected pregnant women and children appear to be particularly susceptible to malaria and show decreased ability to clear malaria perhaps due to immune suppression by concurrent HIV infection [23, 24]. Malaria patients may have acute HIV co-infection [16], and concurrent acute HIV/malaria co-infection has been reported in clinical studies of outcomes of transfusion-associated HIV infection in patients receiving blood transfusions for severe malaria [25–27]. A majority of patients succumb to co-infection or subsequently die of AIDS within a year of transfusion [25–27], although it is not known whether community-acquired acute HIV infection impacts the morbidity and mortality associated with malaria co-infection. Further in-depth studies are needed to elucidate the pathogenic events of HIV/malaria co-infection and determine if immune intervention can attenuate the progression of co-infection or HIV-related malaria.

We have recently developed animal models of HIV/malaria co-infection using pathogenic SHIV89.6P virus and falciparum-like Plasmodium fragile in Chinese-origin rhesus macaques [28]. P. fragile malaria co-infection of macaques acutely infected with SHIV results in hyperimmune activation with massive production of proinflammatory tumor necrosis factor-α (TNFα)/IFNγ cytokines, accelerated depletion of CD4+ T cells with lymphoid destruction, bursting parasitemia with severe anemia, and moribund condition. In contrast, chronically HIV-infected macaques challenged with P. fragile develop subclinical transient malaria with moderate anemia and parasite burdens, without enhanced HIV disease. Interestingly, this subclinical transient malaria coincides with a major expansion of Th17/Th22 cells and an absence of overreactive TNFα/IFNγ response. These observations led us to hypothesize that the preexisting antiviral immune responses in HIV-infected macaques might be sufficient to prevent rapid progression of co-infection or life-threatening HIV-related malaria.

To determine whether vaccine-elicited SHIV-specific T-cell responses can attenuate pathogenic events of SHIV/malaria co-infection, we made use of our recombiant Listeria ΔactA prfA+ vector expressing SHIV gag and env (τListeria-gag/env) [29–31]. Attenuated forms of Listeria monocytogenes have been used as delivery systems to vaccinate humans against tumor associated antigens for a variety of cancers [32], and our τListeria ΔactA prfA+ vector has been shown to be attenuated but highly immunogenic [29–31]. In the current study, we showed that vaccination of macaques with τListeria ΔactA prfA+ expressing SHIV gag and env elicited Gag- and Env-specific T-cell responses, and can alter patterns of immune responses to SHIV/malaria co-infection, weaken pathogenic events of the co-infection, and protect against life-threatening SHIV-related malaria.

**METHODS**

**Animals**

Twelve weight- and age-matched Chinese-origin rhesus macaques, free of retroviral infections, were used in this study. Six rhesus macaques infected with SHIV and 6 macaques chronically infected with SHIV and challenged with P. fragile from previous studies were used as historic controls for this study [28, 33]. All animals were maintained and used in accordance with guidelines of the Institutional Animal Care and Use Committee. Animals were anesthetized with 10 mg/kg ketamine HCl (Fort Dodge Animal Health) for all blood sampling, infections, and treatments, except routine malaria parasite monitoring. Chloroquine treatment was given to macaques that demonstrated high parasitemia (above 10% packed red blood cells [pRBCs] in 2 consecutive thin blood smears). Chloroquine treatment was given as two 37.5 mg/kg doses through oral intubation and administration of ground-up chloroquine tablets in saline.

**Construction of τListeria Monocytogenes Expressing gag and env**

Insertion of simian immunodeficiency virus of macaques (SIVmac)251 gag sequence into τListeria monocytogenes ΔactA prfA+ (G155S) (provided by Dr Nancy Freitag) was described previously. For insertion of SHIV89.6P env-encoded gp120 into τListeria, reverse-transcription polymerase chain reaction (RT-PCR) was performed on isolated RNA from SHIV89.6P virus stock using the primers 5′-GCAAGGATCCATGAGGAGTGAA GGGATCAGG-3′ and 5′-CCACTCAGTTGCGCTTTGGTG GGTGCATTCC-3′, and cloned into the BamH1 and SpeI sites of shuttle plasmid pPL6-myc. The ligated plasmid was transformed into SM10 mating strain of Escherichia coli and transferred to Listeria monocytogenes actA prfA+ through conjugation.

**Vaccination of Rhesus Macaques**

To 6 Chinese-origin rhesus macaques, 10⁶ colony forming units (CFU) of actA prfA+ Listeria monocytogenes expressing gag and env (10⁶ of each, 2 × 10⁸ CFU total) was administered intravenously. Seven weeks following initial vaccination, 2 × 10⁸ CFU of the same vaccine was intravenously administered to
macaques to boost vaccine responses. Macaques were isolated following vaccination and monitored for signs of vaccine-induced disease, and were released from isolation after *Listeria* was cleared from the bloodstream. Figure 1A shows the schedules for prime and boost vaccinations.

**Infections**

Animals were inoculated intravenously with 1000AID50 SHIV89.6P and $10^4$ *P. fragile* pRBCs as previously described [28]. The pRBCs were propagated in a donor rhesus, then frozen and stored in liquid nitrogen until use. The pRBCs were thawed following previously described procedures [34]. SHIV89.6P was stored at $-20^\circ$C, washed, and resuspended in Roswell Park Memorial Institute 1040 medium plus 10% heat-inactivated fetal bovine serum. Chronic SHIV infection and chronic SHIV infection–*P. fragile* coinfection macaque controls were done in previous studies [28, 33]. Concurrent SHIV/malaria coinfection challenge was performed at 12 weeks after the boost vaccination (Figure 1A). Naive and vaccinated macaques were challenged with the same lot of SHIV89.6P and *P. fragile* Nilgiri strain, which were stably stored as aliquots. Two macaques were previously given the *rListeria*-based vaccine expressing *gag/env* and challenged with SHIV89.6P. These macaques show lower-level viremia and preserved CD4 counts compared to unvaccinated controls. These preliminary observations led us to use *rListeria*-based SHIV vaccine as a tool to induce anti-SHIV responses in naive macaques and examine the effect of preexisting anti-SHIV immune responses on the coinfection.

![Figure 1](https://academic.oup.com/jid/article-abstract/208/2/260/802195)
Estimation of Parasitemia
Thin blood smears were made by expressing a drop of blood from a tail prick of malaria-infected monkeys. Smears were air dried, and then stained using DipQuick stain kit (Jorgenson Laboratories, Loveland, CO) according to manufacturer’s instructions. Parasitemia was estimated by comparing parasitized total erythrocytes in blood film.

Isolation of Lymphocytes From Peripheral Blood
Peripheral blood lymphocytes (PBLs) were isolated from freshly collected ethylene diamine tetraacetic acid (EDTA)-treated blood by a Ficoll-Paque Plus (Amersham, Piscataway, NJ) density gradient centrifugation before analysis.

Immunofluorescent Staining and Flow Cytometric Analysis
For cell-surface staining, PBLs were stained with up to 5 Abs (conjugated to fluorescein isothiocyanate, phycoerythrin, allophycocyanin, Pacific Blue, and phycoerythrin-Cy7) for 15 minutes, then washed twice with phosphate-buffered saline, fixed with formalin, and analyzed on a CyAn fluorescence-activated cell sorter, as previously described [28].

Intracellular Cytokine Staining
Modified intracellular cytokine staining (ICS) without in vitro antigen stimulation was adopted as recently described [28].

Serum Enzyme-Linked Immunosorbent Assay of Proinflammatory Cytokines
Serum samples of macaques prior to infection and throughout infection were stored at −20°C until use. IFNγ Monkey ELISA Kit (Life Technologies, Grand Island, NY) was used to determine serum concentrations of IFNγ.

Statistical Analysis
Statistical analysis was done using paired or unpaired 2-tailed Student t test using GraphPad software (Prism, La Jolla, CA). Data compared were based on percentage, unless otherwise stated.

RESULTS
Immunization of Macaques With \( r\)Listeria \( \Delta ActA \) prfA* Expressing SHIV gag and env Elicited Gag- and Env-Specific T-Cell Responses
Strong T-cell immune responses have been demonstrated as elite suppressors coincident with control of HIV-1 infection and long-term nonprogression [35]. HIV-1-specific CD4⁺ and CD8⁺ T cells play a role in immunity against HIV-1 and SIVmac/SHIV infections [36, 37]. In fact, Gag- or Env-specific CD4⁺ and CD8⁺ T cells can mount polyfunctional T helper cell 1 (Th1) responses, producing IFNγ, TNFα, and interleukin-2 (IL-2) [36–38]. Because acute coinfection of macaques with SHIV and malaria induces life-threatening HIV-related malaria [28], we hypothesize that intervention of SHIV/malaria coinfection by prior SHIV antigen immunization can attenuate or disrupt active SHIV-malaria interplays and protect against life-threatening malaria. To test this hypothesis, we developed attenuated highly immunogenic \( r\)Listeria \( \Delta ActA \) prfA* vector expressing SHIV gag and env (\( r\)Listeria \( \Delta ActA \) prfA*) for eliciting SHIV-specific T-cell responses prior to SHIV/malaria coinfection. As a proof-of-concept study, macaques were immunized intravenously with \( r\)Listeria \( \Delta ActA \) prfA* to maximize vaccine-elicited T-cell responses as described previously [29]. This approach was also justified by our recent observation that systemic vaccination with \( r\)Listeria \( \Delta ActA \) prfA* vector is safe in mice and macaques, and is able to elicit high levels of immunogen-specific CD4⁺/CD8⁺ T effector cells [29, 31]. Thus, macaques were primed at week 0 and boosted at week 7 with \( r\)Listeria \( \Delta ActA \) prfA* gag/env (Figure 1A), and assessed over time for the development of immunogen-specific CD4⁺ and CD8⁺ T cells. Following vaccination, macaques exhibited increases in numbers of both Gag- and Env-specific CD4⁺ (Figure 1D) and CD8⁺ T effector cells (Figure 1E). Vaccine-elicited, Gag-/Env-specific CD4⁺ T cells in vaccinated macaques produced TNFα or IL-2 (Figure 1D), whereas Gag-/Env-specific CD8⁺ T cells primarily expressed TNFα or granulysin (Figure 1E). Neither CD4⁺ nor CD8⁺ T cells produced significant IL-4 following restimulation with HIV-specific peptides (Figure 1C). Even at 11 weeks after the boost vaccination, Gag-/Env-specific CD4⁺/CD8⁺ T effector cells were still detected at high levels in all vaccinated macaques (Figure 1D and 1E). Thus, vaccination with \( r\)Listeria \( \Delta ActA \) prfA* expressing SHIV gag and env elicited Gag- and Env-specific Th1 and cytolytic responses.

Recombinant Listeria \( \Delta ActA \) prfA* Vaccination Against SHIV Conferred Protection Against Life-Threatening Malaria After Concurrent SHIV/P. Fragile Coinfection in Macaques
To examine if vaccine-elicited, SHIV-specific T-cell responses can impact acute SHIV/malaria coinfection, vaccinated macaques were challenged with SHIV89.6P and falciparum-like P. fragile concurrently through intravenous administration at 12 weeks after the boost vaccination. Naïve macaques served as controls. Naïve macaques typically succumbed to the coinfection within 21 days and most became moribund despite treatment with chloroquine (Figure 2A and 2B). These acute SHIV/malaria-coinfected controls exhibited a striking increase in parasite burden, with parasitemia levels being above 20% of red blood cells (Figure 2C) and severe anemia (Figure 2D). In contrast, all vaccinated macaques survived concurrent SHIV/malaria coinfection without life-threatening syndromes of SHIV-related malaria (Figure 2A). Only 1 vaccinated macaque received chloroquine treatment due to slightly higher than 10% parasitemia, and 5 other vaccinated macaques survived the coinfection without the need for chloroquine treatment (Figure 2B),...
with parasitemia levels being below 10% (Figure 2C). Furthermore, vaccinated macaques exhibited only a transient decline of red blood cells with less severe anemia despite a lack of clinical syndromes of severe malaria. By contrast, all 6 naive macaques coinfected with SHIV and *P. fragile* developed fatal moribund conditions (Figure 2B) that required antimalaria treatment and, despite treatment, 3 of 6 succumbed to the coinfection (Figure 2A). Treatment was given to all macaques that demonstrated more than 10% parasitemia on thin blood smears. C, Parasite counts after malaria coinfection challenge of naive control macaques (top) and *rListeria*-vaccinated (bottom) macaques. *P. fragile* counts were determined by measuring the number of parasitized RBCs on thin blood smears. At least 1000 RBCs were counted to determine percent parasitemia (*P* = .0004 for day 18, *P* = .01 for day 21, *P* = .02 at day 24, and *P* = .02 for peak parasitemia naive vs vaccinated). D, Hemoglobin levels of naive (top) and vaccinated (bottom) macaques over time after SHIV/malaria coinfection. Data were generated by CBC analysis of EDTA anticoagulated blood (*P* = .05 for day 18, *P* = .007 for day 21, and *P* = .001 for day 28 naive vs vaccinated). Abbreviations: CBC, complete blood count; EDTA, ethylene diamine tetraacetic acid, RBCs, red blood cells; *rListeria*, recombinant *Listeria*; SHIV, simian/human immunodeficiency virus.

**Figure 2.** *rListeria ΔactA prfA* vaccination against SHIV conferred protection against life-threatening SHIV-related malaria after SHIV/P. fragile coinfection. A and B, Survival curves of rhesus macaques after the coinfection challenge (n = 6 per group). While all vaccinated macaques survived coinfection challenge (Figure 2A), 1 received treatment due to increased parasitemia (Figure 2B) despite a lack of clinical syndromes of severe malaria. By contrast, all 6 naive macaques coinfected with SHIV and *P. fragile* developed fatal moribund conditions (Figure 2B) that required antimalaria treatment and, despite treatment, 3 of 6 succumbed to the coinfection (Figure 2A). Treatment was given to all macaques that demonstrated more than 10% parasitemia on thin blood smears. C, Parasite counts after malaria coinfection challenge of naive control macaques (top) and *rListeria*-vaccinated (bottom) macaques. *P. fragile* counts were determined by measuring the number of parasitized RBCs on thin blood smears. At least 1000 RBCs were counted to determine percent parasitemia (*P* = .0004 for day 18, *P* = .01 for day 21, *P* = .02 at day 24, and *P* = .02 for peak parasitemia naive vs vaccinated). D, Hemoglobin levels of naive (top) and vaccinated (bottom) macaques over time after SHIV/malaria coinfection. Data were generated by CBC analysis of EDTA anticoagulated blood (*P* = .05 for day 18, *P* = .007 for day 21, and *P* = .001 for day 28 naive vs vaccinated). Abbreviations: CBC, complete blood count; EDTA, ethylene diamine tetraacetic acid, RBCs, red blood cells; *rListeria*, recombinant *Listeria*; SHIV, simian/human immunodeficiency virus.

**Recombinant Listeria ΔactA prfA* Vaccination Against SHIV Led to Lower Levels of Peak Viremia and Preserved CD4+ T-cell Counts After SHIV/Malaria Coinfection Challenge**

We then sought to examine potential mechanisms whereby SHIV antigen immunization protected against life-threatening SHIV/malaria coinfection. We first investigated whether SHIV antigen immunization could attenuate malaria-enhanced SHIV pathogenicity as concurrent SHIV/malaria coinfection accelerated CD4+ T cell depletion with increased peak viremia, when compared to SHIV-only infection [28]. We examined the
kinetics of SHIV viremia and CD4 T-cell depletion following the coinfection challenge. Interestingly, rListeria ΔactA prfA*–vaccinated macaques exhibited lower levels of the peak viremia controls after concurrent SHIV/malaria coinfection (Figure 3A). The naive controls had peak 9.5 × 10⁷ copies/mL of plasma viral RNA; the vaccinated macaques showed an average of 2.15 × 10⁵ copies/mL viral plasma RNA (Figure 3A). Moreover, while naive controls concurrently coinfected with SHIV/malaria showed a rapid, massive drop of CD4⁺ T-cell counts to the level below 200 cells/µL during the coinfection (Figure 3), rListeria ΔactA prfA*–vaccinated macaques exhibited less dramatic decline of CD4⁺ T-cell counts, with an average level of 637 cells/µL, following the coinfection (Figure 3B). Interestingly, CD4⁺ T-cell counts in vaccinated macaques rebounded to levels higher than naive controls following clearance of the malaria pathogens (Figure 3B). The subsequent rebound of CD4⁺ T-cell counts might be explained in part by the presumption that massive immune activation by the coinfecting malaria pathogen could collaborate with vaccine-elicited SHIV-specific immune responses to further attenuate SHIV infection. It was reported that bacille Calmette-Guérin coinfection or superantigen administration in SIVmac-infected macaques could hyper-activate the immune system and transiently control SIVmac infection [39].

These results suggested that rListeria ΔactA prfA* vaccination against SHIV led to lower levels of peak viremia and preserved CD4⁺ T-cell counts following concurrent SHIV/malaria coinfection challenge.

**Vaccinated Macaques Showed Preserved Lymphoid Structures and Exhibited Less Lymphocyte Depletion of Secondary Lymphoid Organs**

Our previous studies in acute SHIV/malaria coinfection demonstrated a significant destruction of secondary lymphoid tissues during the peak of SHIV/malaria infection [28] (Figure 4C and 4D). To examine whether rListeria ΔactA prfA* vaccination against SHIV, while protecting against life-threatening SHIV/malaria coinfection, could potentially attenuate lymphoid destruction or damage, superficial inguinal lymph nodes were collected from macaques at week 4 after the coinfection. Hematoxylin and eosin staining of lymph nodes demonstrated that naive controls concurrently coinfected with...
SHIV/malaria exhibited apparent lymphoid depletion and destruction of secondary lymphoid structures in the lymph nodes of acute SHIV/malaria-coinfected macaques (Figure 4C and 4D).

Although vaccinated macaques showed some degree of lymphoid depletion relative to uninfected controls (Figure 4A, 4E, and 4F), secondary lymphoid structures were preserved, and germinal center formation was seen in the vaccinated macaques. These results suggested that vaccination against SHIV helped to resist the coinfection-induced lymphoid destruction and damage.

Vaccination Against SHIV Weakened the Coinfection-Induced Hyperimmune Activation During the Concurrent SHIV/Malaria Coinfection

Our previous studies of SHIV/malaria coinfection allowed us to hypothesize that hyperimmune activation and excess production of IFNγ and TNFα contribute to the life-threatening SHIV-related malaria as acute SHIV/malaria coinfection led to overreactive Th1 responses and marked increases in levels of proinflammatory cytokines IFNγ/TNFα. To determine whether rListeria ΔactA prfA* vaccination against SHIV could attenuate overreactive T-cell activation and reduce production of proinflammatory cytokines, we performed direct ICS without in vitro antigen stimulation [28] and enzyme-linked immunosorbent assays (ELISAs) to measure Th1 responses and Th1 cytokines in plasma. Following concurrent SHIV/malaria coinfection, rListeria ΔactA prfA*-vaccinated macaques exhibited much smaller numbers of CD4+/CD8+ T cells de novo producing IFNγ than naive controls (Figure 5A and 5B). Consistently, plasma IFNγ levels were significantly lower in vaccinated macaques than those in naive controls after concurrent SHIV and P. fragile coinfection (Figure 5C). Collectively, these data demonstrated that vaccination against SHIV attenuated the coinfection-induced hyperimmune activation during the concurrent SHIV/malaria coinfection.

Recombinant Listeria ΔactA prfA* Vaccination Against SHIV Allowed Vaccinated Macaques to Develop Th17/Th22 Responses After Concurrent SHIV/Malaria Coinfection Challenge

We previously showed that malaria coinfection challenge of chronically SHIV-infected macaques resulted in a dramatic increase in Th17- and IL-22-producing T cells at the peak of malaria infection [28], and the Th17/Th22 responses correlated with the protection of macaques from severe anemia and death. To determine whether vaccinated macaques would exhibit similar Th17/Th22 responses to SHIV/malaria coinfection as chronically SHIV/malaria-coinfected macaques, we performed direct ICS [28] over time to measure Th17/Th22 effector cells after the coinfection of vaccinated macaques. Recombinant Listeria ΔactA prfA*–vaccinated macaques developed much greater numbers of T effector cells de novo producing IL-17 and IL-22 at 3–7 weeks after the coinfection than naive controls (Figure 6A–C). The increases in trends were similar to what was observed after malaria coinfection challenge of chronically
SHIV-infected macaques (Figure 6A–C). These results demonstrated that rListeria ΔactA prfA* vaccination against SHIV allowed vaccinated macaques to develop Th17/Th22 responses after concurrent SHIV/malaria coinfection challenge, suggesting that potent Th17/Th22 responses might be one of the immune correlates for vaccine-induced protection against life-threatening SHIV/malaria coinfection.

DISCUSSION

Concurrent or secondary infection with multiple pathogens in an ill individual is a common cause of increased morbidity and mortality compared to disease caused by a single pathogen [8, 40]. HIV-1–infected humans exhibit high rates of coinfection with other pathogens or opportunistic pathogens. Overlapping endemicity of HIV and malaria suggests that malaria coinfection frequently complicates acute and chronic HIV infection [16]. We have used nonhuman primate models of acute HIV-malaria coinfection to demonstrate that vaccination against one pathogen, SHIV, can blunt pathogenic events of SHIV/malaria coinfection, and prevent the life-threatening outcome after SHIV/malaria coinfection. Our finding supports an interesting concept that immunization targeting the AIDS virus alone can impact the virus/malaria coinfection and prevent progression to life-threatening virus-related malaria. Mechanistically, rListeria ΔactA prfA*–elicited T-cell immune responses appear to attenuate pathogenic events that occur as a result of SHIV-malaria interplay, and therefore protect against life-threatening SHIV-related malaria. Specifically, the vaccinated macaques show the following 3 major immune interventions: (1) reduced malaria-enhanced SHIV pathogenicity as indicated by high peak viremia and rapid peak parasitemia, (2) reduced IFN-γ responses after SHIV/malaria coinfection, and (3) reduced malaria-enhanced T-cell responses.
decline of CD4+ T-cell counts with lymphoid destruction/depletion, (2) downregulated coinfection-induced hyperimmune activation as indicated by large increases in circulating T cells producing proinflammatory IFNγ and plasma levels of this cytokine, and (3) attenuated bursting parasitemia, leading to marked anemia.

The data from the current study suggest that T-cell immune responses to the AIDS virus may be important for attenuating coinfection-induced pathogenic events and converting life-threatening virus/malaria coinfection to a subclinical setting. HIV and malaria are prevalent pathogens within sub-Saharan Africa, and acute HIV/malaria coinfection has been demonstrated to occur in countries endemic to both of these pathogens [16]. Our nonhuman primate model predicts that humans concurrently infected with these 2 pathogens will suffer significantly increased morbidity compared to chronically HIV-infected individuals coinfected with malaria or HIV-negative individuals infected with malaria alone. The limited screening for HIV infection in individuals with suspected malaria [16] likely contributes to the infrequent reports of acute HIV/malaria coinfected patients. Increased screening of individuals with suspected malaria for HIV infection could allow for more aggressive treatment to be initiated in these patients to prevent HIV-related severe malarial disease.

Our study makes use of the rListeria ΔactA prfA* vaccine vector expressing SHIV antigens to elicit Gag-/Env-specific T-cell responses in macaques. The Listeria-based vaccination appears to serve as a useful delivery system for immunization against prostate, breast, and cervical cancers [32]. The rListeria vaccine vectors for infections reported to date by other investigators are either generated from wild-type Listeria [41, 42] or from Listeria deleted of the essential D-alanine synthesis pathway [43, 44], thus raising safety concerns (wild-type) or requiring special D-alanine supplemental treatments during vaccination of animals. Our rListeria ΔactA prfA* vaccine vector has been shown to secrete >100-fold more immunogens than wild-type rListeria or rListeria ΔactA, and elicited much greater T-cell and antibody responses than rListeria ΔactA after intravenous vaccination of mice [29]. Notably, Listeria-based vectors can readily translocate to cytosol and present HIV

Figure 6. rListeria ΔactA prfA* vaccination against SHIV allowed vaccinated macaques to develop Th17/Th22 responses after concurrent SHIV/malaria coinfection challenge. A, Representative flow histograms of Th17 (top) and IL-22-producing T cells (bottom) measured after SHIV/malaria coinfection of naive and rListeria-vaccinated macaques. Panels represent PBMCs stained as described above and gated on CD3+ lymphocytes. B, Curves for fold changes in IL-17+ CD3+ T cells following coinfection. Shown are fold changes in IL-17+ CD3+ T cells after SHIV/malaria coinfection of naïve control macaques (top), rListeria-vaccinated macaques (middle), and after malaria coinfection of chronic-SHIV macaques from a previous study [28] (bottom) (P = .04 for day 15, P = .0003 for day 22, naive vs vaccinated macaques). C, Fold change of IL-22-producing T cells following coinfection. Shown are fold change in IL-22+ CD3+ T cells after SHIV/malaria coinfection of naïve controls (top) and rListeria-vaccinated macaques (middle), and after malaria coinfection of chronic-SHIV macaques (bottom) (P = .0009 for day 15, P = .0001 for day 22, naive vs vaccinated). Abbreviations: IL-17, interleukin-17; IL-22, interleukin-22; PBMCs, peripheral blood mononuclear cells; rListeria, recombinant Listeria; SHIV, simian/human immunodeficiency virus; Th17, T helper cell 17; Th22, T helper cell 22.

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immunogens via the major histocompatibility complex class I pathway for recognition by CD8+ T cells. It is therefore attractive to explore the capacity of *Listeria* ΔactA prfA* to elicit CD8+ T-cell responses for vaccine-induced immunity against infection or coinfection.

Significant Th17/Th22 responses appear to be one of the immune correlates for vaccine-induced protection against life-threatening SHIV/malaria coinfection. Antibody responses might not be actively involved in the early stage, as there are no significant differences in titers of malaria-specific antibodies between SHIV/malaria-coinfected macaques and macaques infected only with malaria [28]. Potent Th17/Th22 responses were detected not only during concurrent SHIV/malaria coinfection of *Listeria*-vaccinated macaques, but were also seen during malaria coinfection of chronically SHIV-infected macaques. The Th17/Th22 responses correlated in both cases with survival and improved hematologic recovery from malaria infection. Few studies have examined immune responses of Th17/Th22 cells in malaria infection [45], and the role of these effector cells remains to be defined in malaria-infected patients or malaria. It has recently been shown that Th17 cells are able to induce class switching of B cells to immunoglobulin G (IgG)1, IgG2a, IgG2b, and IgG3 subtypes [46]. It is possible that the Th17 cells generated during coinfection help to produce antimalaria IgG antibodies, as immune protection against malaria infection is strongly associated with production of antimalarial IgG2a, IgG2b, and IgG3 [47, 48]. Further studies are needed to examine the impact of Th17 cells on malaria infection and whether malaria vaccine–elicited Th17 responses would confer protection.

**Notes**

**Acknowledgments.** We thank Dr Lisa Halliday and the BRL staff for animal care and assistance with obtaining samples, and Dr Balaji Ganesh and the RRC Flow Cytometry Core for technical assistance with fluorescence-activated cell sorter analysis.

**Author contributions.** J. F. designed and performed experiments, analyzed data, and wrote the paper. D. H., R. W., and C. Y. C performed experiments; Z. W. C. designed experiments and wrote the paper; all others provided reagents or provided scientific expertise.

**Financial support.** This work was supported by the National Institutes of Health (NIH grants R01 HL64560, U01AI070426, R01 RR13601; all to Z. W. C.).

**Potential conflicts of interest.** All authors: No reported conflicts. All authors have submitted the ICMJE Form for Disclosure of Potential Conflicts of Interest. Conflicts that the editors consider relevant to the content of the manuscript have been disclosed.

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