Chikungunya virus (CHIKV) is a mosquito-borne alphavirus that induces in humans a disease characterized by fever, rash, and pain in muscles and joints. The recent emergence or reemergence of CHIKV in the Indian Ocean Islands and India has stressed the need to better understand the pathogenesis of this disease. Previous CHIKV disease models have used young or immunodeficient mice, but these do not recapitulate human disease patterns and are unsuitable for testing immune-based therapies. Herein, we describe what we believe to be a new model for CHIKV infection in adult, immunocompetent cynomolgus macaques. CHIKV infection in these animals recapitulated the viral, clinical, and pathological features observed in human disease. In the macaques, long-term CHIKV infection was observed in joints, muscles, lymphoid organs, and liver, which could explain the long-lasting CHIKV disease symptoms observed in humans. In addition, the study identified macrophages as the main cellular reservoirs during the late stages of CHIKV infection in vivo. This model of CHIKV physiopathology should allow the development of new therapeutic and/or prophylactic strategies.

Introduction

Chikungunya virus (CHIKV) is a mosquito-borne alphavirus (family *Togaviridae*) first described in Africa in 1953 (1). CHIKV belongs to a group of widely distributed arthropod alphaviruses, which include the Australian Ross River virus (RRV), the African O’nyong nyong virus, and the Mayaro virus. CHIKV disease is characterized by high fever, arthralgia/arthritis, papular or maculopapular skin rash, myalgia, and headache. Recovery generally occurred within a few weeks, although persistent CHIKV-induced arthralgia has been reported in 12% of patients (2–4). No specific antiviral therapy is currently available, and treatment generally involves analgesics, antipyretics, and/or nonsteroidal antiinflammatory drugs.

Several outbreaks of CHIKV disease have been reported in Africa and Asia over the last 50 years (5–9). During 2004–2007, the largest documented outbreak of CHIKV disease occurred in the Indian Ocean Islands and India. Particularly affected was Reunion Island, an overseas department of France with a Western health care system. During 2005 and 2006, about 300,000 cases of CHIKV disease (38% of the population) were reported on Reunion Island (10, 11). Of these, approximately 2,200 patients (0.8%) required hospitalization, and more than 250 deaths (0.1%) were reported. Mortality was generally restricted to elderly patients and patients with significant comorbidities. The Reunion Island epidemic was characterized not only by the most common CHIKV symptoms (fever, 95.3%; incapacitating polyarthralgia, 95.2%; headache, 75.8%; myalgia, 64.5%; and cutaneous manifestations, 34.9%; ref. 12), but also by a variety of atypical clinical symptoms, such as gastrointestinal disorders (diarrhea, vomiting, or hepatitis, 21%), neurological complications (encephalitis or meningoencephalitis, 12%), and heart disease (myocarditis or pericarditis, 5%) (13). These atypical cases were mostly observed in young children, the elderly, and patients with comorbidities (14). A few cases of maternoneonatal viral transmission were also reported (about 3 per 1,000 births). In addition, the Reunion Island outbreak appeared to involve more severe and persistent rheumatic disease, with several studies showing that 50%–75% of CHIKV-infected adults had joint pain 1 year after infection (15–17). CHIKV has been declared a high-priority pathogen by the NIH.

To date, little is known about the pathophysiological mechanisms of CHIKV infection in humans, and the only available CHIKV disease models involve infection of very young mice or mice defective in type 1 IFN signaling (18, 19). These models do not recapitulate the disease pattern seen in humans and are unsuitable for testing immunological interventions. Nonhuman primates are particularly relevant for studies of pathogenesis and assessment of therapies because their physiology and immune system are similar to those in humans (20–23). Nonhuman primates are susceptible to CHIKV infection and probably act as part of the natural reservoir in Africa and Asia (24–30). However, previous studies of CHIKV infection in nonhuman primates have not focused on analyzing viral pathogenesis (24, 31, 32). To our knowledge, CHIKV cell and tissue tropism in humans has also not been extensively studied to date. CHIKV antigens have been detected by immunohistochemistry in muscle satellite cells of muscle biopsies from 2 patients with a myositic syndrome (33) and in fibroblasts of the joint capsule, skeletal muscle, and dermis from a fatal neonatal case (18). In vitro studies have shown that other cell types, such as...
human epithelial and endothelial cells, primary fibroblasts, and, to a lesser extent, monocyte-derived macrophages, are also able to sustain productive CHIKV infections (34).

Herein, we describe the characteristics of CHIKV infection in cynomolgus macaques (Macaca fascicularis) using a CHIKV isolate from a patient infected during the recent Reunion Island epidemic (35); the infection produced viremia and clinical signs similar to those seen in humans. Using this model, we investigated viral replication sites and tissue reservoirs during the early and later stages of infection. We showed that CHIKV targeted lymphoid tissues, liver, central nervous system, joint, and muscle during the acute phase of infection and mainly infected macrophages, dendritic cells, and some endothelial cells. At later stages of infection, CHIKV persisted in lymphoid organs, liver, joint, and muscle and was found in macrophages up to 3 months after viral inoculation. Our results thus identify macrophages as the main cellular reservoir of persistent CHIKV infection, potentially explaining long-lasting symptoms observed in humans. These insights into CHIKV pathogenesis should facilitate future development of more effective treatments for CHIKV disease.

Results

**CHIKV infection in cynomolgus macaques mimics CHIKV infection in humans.** Herein we describe a nonhuman primate model of infection with the CHIKV isolate LR2006-OPY1, obtained from a patient infected during the recent Reunion Island epidemic (35). This model allowed for analysis of CHIKV tropism and examination of the pathophysiological basis of CHIKV disease. We inoculated 13 adult cynomolgus macaques (Macaca fascicularis, 3–5 years old) i.v. with 10^5 PFU CHIKV, corresponding to 10^5 viral RNA (vRNA) copies. This amount of vRNA is similar to the amount of virus secreted from salivary glands of mosquitoes collected from Reunion Island and artificially infected with CHIKV strains isolated from the Reunion outbreak (36). In parallel, 2 cynomolgus macaques, animals 20337 and 20348, were inoculated intradermally (i.d.) with 10^3 PFU to compare the effects of this inoculation route on clinical and biological parameters. Virus was detected by real-time RT-PCR in the plasma of infected animals from day 1 after i.v. or i.d. CHIKV inoculation. Viremia in both i.v.- and i.d.-inoculated animals reached a peak by 2 days postinoculation (dpi), with viral loads ranging from 7 × 10^7 to 5 × 10^9 vRNA copies/ml and viremia persisting until 6 or 7 dpi (Figure 1A). Although CHIK viremia has not been extensively studied in humans, studies to date suggest a short duration (not exceeding 1 week in most patients), with viral loads ranging from 1 × 10^3 to 1.2 × 10^10 vRNA copies/ml (37–39). These prior findings in humans are consistent with the data described herein for macaques.

Clinically, monkeys developed a high fever by day 1 or 2 (up to 39.6°C), regardless of the inoculation route (Figure 1A). A similar level of fever was observed in humans during the Reunion Island outbreak (40). The fever in the monkeys remained significantly above baseline from 2 dpi (P < 0.0015, Mann Whitney U test [MWU]) until 7 dpi (P < 0.02, MWU). In the first week after inoculation, all animals developed morbilliform skin rashes of varying intensities. These cutaneous manifestations were similar to those observed in infected patients (17, 41). Gingival bleeding was also observed in half the infected animals. Gingivorrhagia has been previously reported in humans, mainly in CHIKV-infected children (2, 41). Other substantial manifestations observed during the CHIKV Reunion Island epidemic, such as arthralgia, headache, or myalgia, were difficult to evaluate in an animal model.

Serum of 5 animals was tested for aspartate transaminase (AST) and alanine transaminase (ALT) levels. All tested animals exhibited elevated levels of AST (2.5 times higher at 4 dpi; P < 0.05, Wilcoxon rank test) and ALT (1.8 times higher at 10 dpi; P < 0.05, Wilcoxon
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rank test; Supplemental Figure 1; supplemental material available online with this article; doi:10.1172/JCI40104DS1). AST and ALT levels remained significantly elevated even at 15 dpi (P < 0.05, Wilcoxon rank test). This pattern of biochemical changes is consistent with data from CHIKV patients recently described by Ng and colleagues (42) and is indicative of liver or muscle injury.

All i.v.- or i.d.-infected animals showed substantial and significant monocytopenia, lymphopenia, granulocytosis, and thrombocytopenia compared with uninfected animals (P = 0.012, 0.012, 0.028, and 0.03, respectively, MWU; Figure 1B and Supplemental Table 1). These changes were associated with peak viremia, with the nadir occurring between 2 and 4 dpi, and returned to normal by 10–15 dpi. Little information about hematopoietic cell numbers is available for human cases, although leukopenia is often observed during CHIKV infection (4, 17, 42).

To study the effect of the inoculation dose, 13 additional monkeys were inoculated with various doses of CHIKV, ranging from 10^1 to 10^8 PFU (Table 1). A clear relationship emerged between the inoculation dose and the period and magnitude of the viremia. The AUC of viremia over 0–10 dpi significantly correlated with the inoculation dose (r^2 = 0.71, P < 0.024; data not shown). Monkeys could be classified into 3 groups according to the inoculation dose and clinical signs: (a) in animals inoculated with a low dose of CHIKV (10^1 PFU), viral replication was detected in plasma of 50% of the animals and no clinical signs were observed; (b) in animals inoculated with an intermediate dose (10^2–10^6 PFU), viremia was associated with fever and rash; (c) in animals inoculated with a high dose (≥10^7 PFU), swelling in wrist and ankle joints, clinical signs of meningoencephalitis (hunching and wobbling, as well as

Table 1

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<td>1</td>
<td>10^7</td>
<td>1 5 × 10^9</td>
<td>Fever, rash, joint effusion</td>
</tr>
<tr>
<td>1</td>
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<td>1</td>
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Figure 2

Lesions observed in tissues collected from 12 macaques inoculated with intermediate doses of CHIKV. Histology of tissues from CHIKV-infected macaques. (A) Spleen, 6 dpi. Density of mononuclear cells was diffusely increased in the red pulp. These mononuclear cells corresponded mostly to macrophages with abundant cytoplasm and large nucleolated nucleus (inset). Some mononuclear cells were undergoing mitosis (arrows). (B) Spleen, 32 dpi. Macrophages were still numerous in the red pulp; a few mitotic cells were visible (arrow). (C) Normal spleen. Red pulp contained numerous red blood cells. (D) Lymph node, 6 dpi. The cortex was distended by numerous macrophages (some denoted by arrowheads). (E) Lymph node, 44 dpi. Severe follicular enlargement (asterisks) was associated with macrophage infiltration. Postcapillary venules of the T-dependent area (arrows) and medulla (M) are indicated. (F) Normal lymph node. Lymphoid follicles (asterisks) and medulla are indicated. (H) Liver, 6 dpi. The number of apoptotic hepatocytes with nuclei (arrows), detected by TUNEL assay, increased. (I) Liver, 90 dpi. Multifocal interstitial mononuclear cell infiltration (arrowheads) was observed in the liver parenchyma. (J) Normal liver. (K and L) Skeletal muscle, 55 dpi. Mild multifocal necrosis of muscle fibers (asterisk) was associated with infiltration by mononuclear cells, including macrophages (arrowheads). (M) Normal muscle. (A–G and I–M) Hematoxylin eosin safran stain. (H) In situ detection of cell death using TUNEL staining. Scale bars: 100 μm (A–D, F, and H–M); 10 μm (insets); 1 mm (E and G).
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The neurological complications and fatalities were similar to the severe forms of disease described in humans during the Reunion Island outbreak (13, 43). The present study focused on the animals receiving intermediate- or high-dose CHIKV inoculations.

The clinical and biological parameters seen in this macaque model were remarkably similar to those reported in patients infected during the Reunion Island epidemic. Importantly, the magnitude and virulence of infection was dependent on the inoculation dose, with larger inocula resulting in earlier and higher peak viremias and greater severity of clinical symptoms (Table 1). Finally, the inoculation route did not influence CHIKV infection or disease in macaques inoculated with the intermediate 10^8 PFU dose.

Infected macaque tissues display extensive mononuclear cell infiltration. Various tissues, collected at 6, 19, 32, 44, 55, 90, and 97 dpi from 12 animals inoculated with intermediate doses of CHIKV, were examined by histology and compared with tissues from control uninfected animals (Figure 2 and Table 2). Major abnormalities were observed in spleen and lymph nodes of all animals from 6 dpi. Severe and persistent histiocytosis was observed in the spleen, appearing as an infiltrate in the red pulp consisting of mononuclear cells, with abundant eosinophilic cytoplasm, euchromatic nucleus, and prominent nucleolus, characteristic of macrophages (Figure 2, A and B, and Supplemental Figure 2). Lymph nodes also showed extensive infiltration of mononuclear cells, which were found mainly in the cortex and, to a lesser extent, in the medulla (Figure 2D). Severe follicular enlargement was associated with mononuclear cell infiltration at 32–44 dpi (Figure 2E). This decreased in severity thereafter, but was still present with mild intensity on 97 dpi.

In liver, we observed mild to marked centrolobular hepatocytic hydropic degeneration. TUNEL assays revealed abnormally high levels of hepatocyte death, mainly through apoptosis, peaking at 6 dpi (Figure 2H), and this was associated with the increased serum AST and ALT levels described above (Supplemental Figure 1). This early apoptotic process might result in part from hyperthermia (Figure 1A), as described previously in pigs and dogs (44). Between 44 and 90 dpi, all tested animals exhibited mild multifocal interstitial mononuclear cell infiltration of the hepatic parenchyma (Figure 2I). In the liver, between 6 and 97 dpi, large amounts of intracytoplasmic granular pigment (stained blue using Perls stain for hemosiderin) was observed in Kupffer cells. Similar hemosiderin deposition in Kupffer cells has been previously observed in other viral infections (45, 46), as iron scavenging is associated with the inflammatory response (47).

Mononuclear cell infiltration was associated with sporadic localized areas of muscle necrosis in 1 macaque (Figure 2, K and L). No major abnormalities were observed in synovial samples or central nervous tissue samples of intermediate-dose animals (data not shown).

We also examined 45 tissues (including lymphoid organs, liver, muscle, joint, central nervous system, and skin) collected at 2, 5, 6, 7, and 186 dpi from 5 high-dose animals (Supplemental Table 2). No extensive mononuclear cell infiltrations were detected at 2 dpi,

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Table 2

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<th>44</th>
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<th>90</th>
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<tr>
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</table>

Values denote total number of lesions. n = 2 for all time points, except 6 and 44 dpi (n = 1).

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Figure 3

Mononuclear cell infiltration in tissues of macaques inoculated with high-dose CHIKV. (A and B) Tissues lesions in ankle joint collected from a 7-dpi macaque inoculated with 10^8 PFU CHIKV. Mild fibrinous exudate (arrows) was associated with mononuclear cell infiltration of the synovial tissue (arrowheads). Hematoxylin eosin safran staining. Scale bars: 300 μm (A); 100 μm (B). (C) Staining of cerebrospinal fluid cells collected from a macaque inoculated with 10^8 PFU showing clinical signs of meningoencephalitis. Infiltrating cells were mainly CD8+ T cells and activated monocyte/macrophages (CD14+CD16+HLA-DR+). Numbers denote percent of population in the respective gate or quadrant.
We quantified viral genomic RNA relative to a reference gene. Mononuclear cell infiltration appeared to be a major feature of CHIKV infection and disease. The cytokine and chemokine profiles of infected macaques were thus examined. Plasma collected from monkeys inoculated with 10^3 PFU CHIKV was analyzed using an IFN-α/β bioassay or a multiplex-microbead immunoassay. The IFN-α/β concentration increased substantially as early as 2 dpi and then fell sharply by 4 dpi, with peak IFN-α/β correlating with peak viremia (Figure 4). A rapid and large increase in CCL2 (MCP-1) levels was also observed at 1–6 dpi (Figure 4). The levels of proinflammatory cytokine IL-6 significantly increased by 2 dpi, and these high levels persisted up to 6 dpi. Finally, the level of IFN-γ increased sharply between 1 and 2 dpi and then decreased slowly over the subsequent 15 days. Comparison of cytokine levels in infected monkeys (Table 3) between baseline (before infection) and the peak of cytokine production indicated significant increases in IFN-α/β, IFN-γ, CCL2 (MCP-1), CCL3 and CCL4 (MIP-1α and MIP-1β), IL-6, and TNF-α, although the last of these showed considerable variation (Table 3).

Thus, the profile of proinflammatory mediators, which correlated with peak viremia and the decrease in CD14+ cells in blood (Supplemental Table 3), was consistent with early monocyte/macrophage recruitment by MCP-1; continuous activation of macrophages by MCP-1, IFN-γ, and secretion of IL-6 and, to a lesser extent, TNF-α by these and perhaps other cells.

CHIKV persistently infects lymphoid organs and liver and, to a lesser extent, muscle and joints. We quantified viral genomic RNA relative to endogenous control GAPDH using semiquantitative RT-PCR assays in various homogenized tissue lysates (spleen, lymph node, liver, joint, muscle, skin, brain, and spinal cord). Given that the expression of housekeeping genes may be affected by the experimental conditions (50), we first checked that GAPDH mRNA levels remained essentially unaffected in CHIKV-infected lymphoid, splenic, hepatic, and muscular tissues (Supplemental Figure 3). Relative quantification results are presented in Figure 5A. Real-time RT-PCR assays revealed high levels of CHIKV RNA in all tested tissues, particularly in lymph nodes, spleen, and liver, during the acute phase of the infection, which suggests that CHIKV efficiently disseminates into various organs. Whereas viremia peaked at 2 dpi, the viral load in most tissues reached a peak by 6 dpi and then progressively decreased in all tissues, but was still detectable in lymphoid organs until 3 months, and in liver until nearly 2 months, after inoculation. In synovial and muscular tissues, CHIKV RNA was still detectable beyond 1 month after inoculation, although some vRNA was present in the cerebrospinal fluid at 55 dpi. This finding demonstrated the persistence of CHIKV RNA in organs affected during human or young mice infected with CHIKV (18, 19). Similar infiltration were also reported in muscle of mice (48) or knee joints of patients after RRV infection (49), which suggests a causal relationship between monocyte/macrophage infiltration and myalgia and arthralgia/arthritis.

The cytokine pattern is consistent with monocyte recruitment and macrophage activation. Mononuclear cell infiltration appeared to be a major feature of CHIKV infection and disease. The cytokine and chemokine profiles of infected macaques were thus examined. Plasma collected from monkeys inoculated with 10^3 PFU CHIKV was analyzed using an IFN-α/β bioassay or a multiplex-microbead immunoassay. The IFN-α/β concentration increased substantially as early as 2 dpi and then fell sharply by 4 dpi, with peak IFN-α/β correlating with peak viremia (Figure 4). A rapid and large increase in CCL2 (MCP-1) levels was also observed at 1–6 dpi (Figure 4). The levels of proinflammatory cytokine IL-6 significantly increased by 2 dpi, and these high levels persisted up to 6 dpi. Finally, the level of IFN-γ increased sharply between 1 and 2 dpi and then decreased slowly over the subsequent 15 days. Comparison of cytokine levels in infected monkeys (Table 3) between baseline (before infection) and the peak of cytokine production indicated significant increases in IFN-α/β, IFN-γ, CCL2 (MCP-1), CCL3 and CCL4 (MIP-1α and MIP-1β), IL-6, and TNF-α, although the last of these showed considerable variation (Table 3).

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infected lymphoid tissues as what we believe to be a new site of viral persistence.

To further characterize the viral replication pattern in tissues showing positive quantitative RT-PCR results (i.e., spleen, muscle, and joint), 2 independent RNA in situ hybridization assays were performed using probes specific for CHIKV 26S subgenomic RNA, with a RRV 26S RNA probe used as a negative control. No signal was detected using the RRV 26S RNA probe or with the CHIKV RNA probe assayed using uninfected tissues (Figure 5, C, D, F, G, and H). The presence of viral antigen could not be unequivocally demonstrated by immunohistochemistry in skeletal muscles, synovial tissues, and in the nodal T cell areas (data not shown). Viral antigen was also detected in the sinusoidal endothelium of the liver (see below). There were few or no antigen-positive cells within the connective tissue surrounding muscle at 5–7 dpi (18, 19), which suggests that age may affect viral titers in these tissues. Virus isolation from tissues (Figure 6) was consistent with the results of our quantitative RT-PCR experiments showing higher levels of vRNA copies in spleen and liver than in muscle tissue (Figure 5A), with infectious CHIKV being detected in homogenates from these tissues up to 44 dpi.

Taken together, these data suggest that in immunocompetent adult nonhuman primates, CHIKV persists in lymphoid tissues, liver, joints, and muscles for up to 3 months and is able to replicate in spleen, liver, and muscle for extended periods. Furthermore, results of in situ hybridization assays suggested that the virus persists mainly in mononuclear cells and, to a lesser extent, in endothelial cells.

**Macrophages, dendritic cells, and endothelial cells are infected by CHIKV, and macrophages seem to play a prominent role in persistence of the virus in macaques.** Immunohistochemistry was used to detect cells positive for CHIKV antigen in tissue samples taken from macaques inoculated with intermediate or high doses of virus. There was no difference in the signal distribution or intensity between these 2 groups of macaques. CHIKV antigen was detected in the cytoplasm of numerous mononuclear cells in spleen and lymph nodes as early as 2 dpi (Table 4). Antigen-positive cells were mostly distributed around macrophage-sheathed capillaries in the splenic red pulp (Figure 7A) and in the nodal T cell areas (data not shown). There were few or no antigen-positive cells in T cell areas at 32–44 dpi, but viral antigen was found in mononuclear cells infiltrating B cell areas at 2–90 dpi (Figure 7B). Staining was clearly visible in the cytoplasm rather than the nucleus, suggesting that this staining was not the result of Fc receptor binding (data not shown). Viral antigen was also detected in the sinusoidal endothelium of the liver (see below). The presence of viral antigen could not be unequivocally demonstrated by immunohistochemistry in skeletal muscles, mononuclear...
membranes, or skin connective tissues because of high background signals associated with the presence of collagen fibers.

CHIKV tissues were further analyzed by immunofluorescence and were costained with cell type–specific markers. Viral antigen was present in CD68+ macrophages from all macaques until 3 months after infection (Figure 7, D and E), with a majority of these cells in spleen being CHIKV+ at 2 dpi. Other macrophage lineage cells, including hepatic Kupffer cells and neural microglia, were negative for CHIKV antigen (data not shown). CHIKV antigen was also detected early in infection in some lymphoid dendritic cells (S100+; Figure 7, G and H) and in some endothelial cells (factor VIII–positive [FVIII+]) of the liver sinusoids (Figure 7, J and K) and spinal cord meninges (Supplemental Figure 4, B and C). Direct examination of spleen indicated a relative amount of 1 CHIKV+ dendritic cell per 10 CHIKV+ macrophages. After 19 dpi, we were not able to identify CHIKV+S100+ cells. As described above, in situ hybridization results also suggested that positive cells in muscle connective tissue and in the splenic trabecula had the morphology of an endothelial cell type.

In order to further characterize CHIKV persistence in macrophages, combined in situ hybridization for CHIKV and immunohistochemistry for CD68 was performed in spleen of infected macaques at 6, 19, and 44 dpi. CHIKV genome was detected in macrophages at 6 dpi (Figure 8, A–C) and 19 dpi (data not shown), indicative of viral persistence rather than simply long-term retention of viral antigen in these cells. Furthermore, we confirmed that human monocyte-derived macrophages were susceptible to CHIKV LR2006-OPY1 infection in vitro (Figure 8D), as previously described for other CHIKV strains (34).

The results of the present study show, for the first time to our knowledge, that macrophages act as a cellular reservoir for the persistence of CHIKV during the late stages of infection in macaques. CHIKV persistence in macrophages may be responsible for the long-lasting symptoms observed in humans.

Discussion
Although the clinical manifestations of CHIKV infection have been well described, the pathogenesis of CHIKV disease in humans is poorly understood. Herein we provided a detailed analysis of CHIKV infection in nonhuman primates and demonstrated that experimental infection of macaques with CHIKV represents a relevant model of human CHIKV infection. We also identified macrophages as central players in CHIKV infection and persistence.

Using a virus from the recent Reunion Island outbreak, we demonstrated that CHIKV infection in macaques recapitulated the clinical and biological features observed in humans during the Reunion Island epidemic. The acute phase of infection, coinciding with peak viremia, was characterized in macaques — as it is in humans — by (a) fever and cutaneous manifestations; (b) increased levels of serum AST and ALT; (c) sharp rise, then fall, of IFN-α/β and IL-6 concentrations; (d) rapid increase, then gradual decline, of MCP-1 and IFN-γ
secretion; and (e) lymphopenia, monocytopenia, and granulocytosis, probably due in part to the presence of IFN-α and MCP-1 (51, 52). During this phase, high levels of CHIKV RNA were detected in the spleen, lymph nodes, and liver, and to a lesser extent in joints, muscle, skin, and the central nervous system. Many of these tissues are affected during human disease (12, 13). The subacute phase, beginning at the end of viremia, was characterized by (a) normalization of leukocyte counts by 10–20 dpi; (b) pronounced macrophage infiltrates in secondary lymphoid organs from 6 dpi onward; and (c) presence of vRNA and/or antigens in lymphoid organs, liver, meninges, joint, and muscle. Finally, the chronic phase was characterized by the persistence of (a) activated macrophages, (b) vRNA, and (c) antigen for up to 2 months in lymphoid organs and liver, potentially explaining the long-lasting symptoms observed in humans.

Our study also demonstrated a relationship among the amount of inoculated virus, viremia, and disease. Interestingly, we did not observe any differences between i.d. and i.v. inoculation in our model. At high doses of virus, we observed arthritis, meningoencephalitis, and death; at intermediate doses, only fever and rash were observed; and at the lowest dose, no clinical signs were observed. This spectrum of symptoms is also observed in humans. Thus, whether an infected individual develops the disease or remains asymptomatic may be determined, at least in part, by the amount of virus delivered by the mosquito. The observation that CHIKV infection in macaques mimicked CHIKV infection in humans suggests that our macaque model is a relevant model to study CHIKV disease. Mouse models of CHIKV disease have been reported, but thus far have used neonatal or young mice (18, 19) or adult mice with a totally or partially abrogated type I IFN signaling pathway (18). This contrasts with CHIKV disease in humans, which is usually milder in children (12, 40) and not restricted to immunosuppressed individuals. Furthermore, we observed that animals inoculated with the highest doses of virus produced larger amounts of IFN-α/β (about 25,000 IU/ml plasma), which did not prevent the development of viremia or disease.

A limitation of our study is the limited pathology observed in muscles or joints of macaques inoculated with the intermediate 10^3 PFU dose of viral inocula, considering these are major sites of pain in human CHIKV disease. However, the coincidence of localized pain or clinical symptoms with tissue lesions has only been demonstrated in very severe human cases (18, 33, 37, 53, 54). Similarly, in our model, only macaques infected with high doses of virus showed such a marked pathology: joint effusion, meningoencephalitis (Figure 3), and severe rash. However, we found significant macrophage infiltration and detected virus in these tissues by immunochemistry and PCR.

In order to further characterize CHIKV pathogenesis, we investigated the viral distribution and persistence in our macaque model. At early stages of infection, CHIKV was found in skeletal muscles, joints, meninges, and skin, as described in mouse models using larger viral inocula (18, 19). Interestingly, in our macaque model, CHIKV also exhibited a marked tropism for spleen, lymph nodes, and liver during the viremia peak. We believe the high level of infection of lymphoid organs is a novel finding for arthrogenic alphavirus infections, although moderate levels of spleen infection were previously reported in young and IFN-α/β receptor–deficient mice (18, 55) and in Venezuelan equine encephalitis virus infections (56). The present study also provided evidence that CHIKV can persist and replicate in vivo in primates for extended periods, with vRNA and antigen detected in several organs and tissues for 3 months. Alphaviral persistence has been described in vitro, in human synovial fibroblasts and murine macrophages (57, 58), and in vivo, in mouse muscle cells (59), up to 25 dpi with another arthrogenic alphavirus, RRV. The only study addressing in vivo persistence of alphavirus in humans found viral RNA 5 weeks after the onset of symptoms in 2 RRV disease patients (49). These findings suggest that arthrogenic alphaviruses can persist in primates for extended periods, despite the presence of antiviral antibodies and T cell responses. Such persistence may provide a possible explanation for the long-lasting symptoms observed in humans.

Our results provide compelling evidence for an important role for macrophages in the pathology of CHIKV disease. The high levels of macrophage/mononuclear cell infiltration in lymphoid organs and the large amounts of CHIKV antigen and vRNA detected in macrophages in spleen for prolonged periods (up to 3 months)
demonstrated that macrophages act as the cellular reservoirs for CHIKV persistence. Moreover, long-term detection of both viral genome and infectious virus in lymphoid organs, liver, and muscle was consistent with macrophages being a major site of viral replication. Although previous immunohistochemistry studies on muscles, joints, and skin in mouse models suggested that fibroblasts are the predominant target cell of CHIKV infection, CHIKV antigens were also found in a few mature macrophages in liver, spleen, and muscle of infected adult IFN-α/β receptor–deficient mice at 3 dpi (18). Our in vitro studies showed that human monocyte-derived macrophages were susceptible to CHIKV infection (Figure 8D), in agreement with previous studies in human monocyte-derived macrophages (34) and primary liver macrophages isolated from mice (18). Jaffar-Bandjee et al. also described CHIKV-infected macrophages in synovial tissue 18 months after CHIKV infection in a single patient from Reunion Island (54). Previous in vitro studies and mouse models of RRV disease have also suggested a central role for macrophages in alphaviral arthropathies (49, 60). Taken together, these results point to macrophages as having an important role in CHIKV infection and disease.

Cells other than monocytes/macrophages may also be involved in CHIKV pathology. Despite their relatively low number, we showed that dendritic cells were infected by CHIKV. Although we could not demonstrate CHIKV replication in dendritic cells in vivo, the high levels and diffuse distribution of CHIKV antigens in the cytoplasm of these cells were highly suggestive of productive infection. However, we and others have not been able to infect human monocyte-derived dendritic cells in vitro (Figure 8D), regardless of whether the CHIKV was derived from mammalian or mosquito cells (34). Given that dendritic cells are phenotypically heterogeneous, the exact type of dendritic cells infected in vivo remains to be determined. That alphaviruses can infect dendritic cells has been reported for RRV, Sindbis, and Venezuelan equine encephalitis viruses (61–63).

In addition to macrophages and dendritic cells, CHIKV antigen was found in endothelial cells of spinal meninges at 6 dpi, of muscle up to 55 dpi, and of liver up to 3 months after inoculation. CHIKV antigen detection in sinusoidal capillary endothelial cells has been described during the early stages of infection in IFN-α/β receptor–deficient mice (18). Infection of endothelial cells in muscle contrasts with earlier studies reporting CHIKV infection of muscular satellite cells. However, satellite cell infection was described in cases of severe and extended muscle necrosis observed in some rare patients with myositic syndrome (33) or in infected neonatal mice (18). In our model, and probably in most human cases, muscular lesions comprise only small areas of muscular infiltration by mononuclear cells and infection appears to be limited to endothelial cells.

Our present study demonstrated the importance of macrophages in primates, both as sites of infection and viral persistence and as key players in pathogenesis. One might speculate that early infection in several organs leads to recruitment of monocytes/macrophages. Viral induction of MCP-1 and IFN-α/β may be responsible for monocyte/macrophage recruitment and activation, with further activation by NK and/or T cell–derived IFN-γ also probable (60). Clinical manifestations may result from excessively activated macrophages releasing proinflammatory mediators such as IL-6 and, to a lesser extent, TNF-α (64). These observations also suggest that the chronic course of CHIKV disease in humans is caused by continuing inflammatory responses associated with persistent virus, rather than by virally induced autoimmunity (65).

In conclusion, our results provide insights into the pathogenesis of CHIKV. We have developed a relevant macaque model of CHIKV infection, in which we demonstrated long-term CHIKV persistence.
The concentrations of cytokines/chemokines in monkey plasma was determined by Luminex technology using antibodies crossreactive with cynomolgus macaque cytokines as described previously (67) and according to the manufacturer’s instructions. MCP-1 and IFN-γ were assayed using Biosource (Cliniscience SA), and IL-6 was measured using Upstate (Millipore) beads and antibody pairs. IFN-γ/β was measured by biosassay as described previously (68).

Histology and immunohistochemistry. We sampled 45 different tissues in duplicate during complete necropsy examination of each of 18 macaques. Either tissues were frozen and 8-μm-thick sections were cut, or tissues were fixed in 10% neutral buffered formalin, embedded in paraffin wax, and 6-μm-thick sections were cut and stained with hematoxylin eosin safranin. During morphological analysis, macrophages were identified by their abundant eosinophilic cytoplasm, euchromatic nucleus, and prominent Nissl. During morphological analysis, macrophages were identified by their abundant eosinophilic cytoplasm, euchromatic nucleus, and prominent Nissl.
nent nucleolus. Liver sections were also stained with Fouchet for bilirubin and Perls for hemosiderin.

Immunohistochemical analysis involved the use of immunoperoxidase techniques for paraffin-embedded sections and indirect immunofluorescence for frozen sections. Hyperimmune mouse ascitic fluid (69) and monoclonal antibody 3E4 (70), provided by P. Desprès (Pasteur Institute), were used as primary antibodies (at dilutions of 1:1,600 and 1:200, respectively). Other antibodies used were anti-CD68 (clone KPI) for macrophages (Abcam), anti-S100 for dendritic cells, and anti-FVIII-related antigen for endothelial cells (Dako).

Paraffin-embedded sections were pretreated at 98°C for 40 minutes in citrate buffer (Dako) then incubated in 3% hydrogen peroxide for 10 minutes and in 20% normal goat serum (Dako) and 0.2% Tween (Sigma-Aldrich) for 30 minutes. They were then incubated with primary antibody in 2% goat serum, 2% BSA (Sigma-Aldrich), and 0.2% Tween overnight at 4°C and with biotinylated secondary antibodies (EA33, Dako) in 20% normal goat serum and 0.2% Tween for 30 minutes; bound antibodies were detected either with streptavidin (P397; Dako) and DAB Liquid Substrate (Dako) for immunoperoxidase or with Alexa Fluor 555–conjugated streptavidin (Invitrogen) for immunofluorescence, following the manufacturer’s instructions. Nuclei were stained with Topro-3 diluted 1:1,000 (Invitrogen), and sections were mounted using Mowiol medium (Calbiochem). Sections of tissues from an uninfected macaque were used as negative controls. Immunofluorescent labeling was assessed by serial scanning with He-Ne and argon ion lasers and C1 Nikon laser scanning confocal microscope. The autofluorescence associated with hemosiderin pigment in Kupffer cells of the liver was distinguished from the specific signal by multispectral analysis using a C1-SHS Nikon multispectral confocal microscope. The extent of apoptosis in liver sections was evaluated with an in situ cell death detection kit (Roche) according to the manufacturer’s instructions. The numbers of total and apoptotic hepatocytes were calculated (variation coefficient, 3.4%) after random selection of 2 microscopic fields, such that more than 400 hepatocytic nuclei were scored for each sample (483 ± 49 per sample).

**Flow cytometry.** Flow cytometry was performed on either FACScan or LSR1 apparatus (BD Biosciences) using CellQuest software. Percentages of CD4+ and CD8+ T lymphocytes and monocytes were determined with direct immunofluorescence labeling. Cerebrospinal fluid (2 ml) collected from a monkey inoculated with 10⁶ PFU was centrifuged, and cells were resuspended in 100 μl phosphate-buffered saline. Resuspended cells (50 μl) were then incubated at room temperature for 15 minutes with anti-rhesus CD3–FITC (clone sp34-2, BD Biosciences – Pharmingen), anti-human CD4–PE (L200, BD Biosciences) and CD8–PC5 (SK1, BD Biosciences) monoclonal antibodies to estimate lymphocyte infiltrate proportion. Populations of monocytes were evaluated using anti-human HLA-DR–FITC (clone G46.6, BD Biosciences – Pharmingen; or clone B8.12.2; Beckman Coulter), CD14–PE (clone M5E2; BD Biosciences – Pharmingen), and CD16–PC5 (clone 3G8; BD) by the same procedure.

**In situ hybridization.** Hybridizations were performed with a DIG-UTP–labeled CHIKV-specific riboprobe derived from pCRII-TOPO-CHIKV plasmid. A 450-bp conservative region of the virus genome, mainly specific to the 26S subgenomic RNA (region 7,371–7,820 on CHIKV LR2006-OPY1 strain, accession no. DQ443344), was amplified by RT-PCR, purified, and cloned into the pCRII-TOPO vector using a TOPO-TA cloning kit (Invitrogen) according to the manufacturer’s instructions (71). A riboprobe specific for the RRV (complementary for RRV nucleotides 7,393–7,871), synthesized as described above, was used as a control for nonspecific binding (71–73). Presence and orientation of the CHIKV and RRV inserts into pCRII-TOPO plasmids were sequenced by screening. Antisense riboprobes were obtained as follows. Plasmids were linearized with either BamHI and NotI for the CHIKV plasmid, or KpnI and NotI for the RRV plasmid, and labeled according to the manufacturer’s instructions by in vitro transcription with either T7 or SP6 polymerase, using a digoxigenin labeling kit (DIG RNA Labeling; Roche).

All steps before and during hybridization were carried out under RNase-free conditions. After drying, sections were postfixed in 4% PFA and pre-treated with 0.2% DEPC in 2x sodium chloride sodium citrate buffer (SSC; 0.6 M, pH 7, Dako) at room temperature for 30 minutes. Sections were prehybridized for 60 minutes at 42°C in hybridization buffer containing 50% deioned formamide, 10% (v/v) dextran sulfate, 4x SSC, 1x Denhardt’s solution, 10x blocking solution (Roche), and 425 μg/ml salmon fish DNA, then hybridized overnight at 42°C with 1 μg/ml CHIKV antisense probes diluted in hybridization buffer. Negative controls were RRV probes. Slides were then washed with 2x SSC and treated for 20 minutes at 37°C with 5 μg/ml RNaseA in NTE buffer (0.5 M NaCl, 10 mM Tris-HCl, and 1 mM EDTA, pH 8.0). After stringent washing for 30 minutes with 60% (v/v) formamide plus 0.2x SSC at 37°C, sequential washes were performed with 2x SSC (2x, each 10 minutes), buffer 1 (0.1 M Tris and 0.15 NaCl, pH 7.5) containing 5% blocking reagent (Roche) for 30 minutes, and buffer 1 containing 1% BSA and 0.3% Triton X-100 for 30 minutes. Slides were incubated for 2 hours at room temperature with alkaline phosphatase-conjugated sheep anti-DIG antibody (Roche), diluted 1:1,000 in buffer 1, and sequentially washed with buffer 1 (3x, each 5 minutes) and buffer 2 (0.1 M Tris-HCl, 0.1 M NaCl, and 50 mM MgCl₂, pH 9.5) for 10 minutes. Slides were then incubated with alkaline phosphatase substrate (NBT/BCIP; Roche) for 2 hours. Finally, after washing, slides were counterstained with fast green for 5 seconds, dehydrated, and mounted.

**Viral titrations in tissue samples.** Splenic, hepatic, muscular, and joint tissues collected from macaques inoculated with 10⁶ (6 dpi) or 10⁷ (44 dpi) PFU were washed, and tissues (approximately 100 mg) were titrated and homogenized in DMEM supplemented with 10% FCS (1 ml) using tubes with ceramic beads and a Precellys system (Bertin technologies). Viral titers of each tissue sample were determined on mammalian BHK-21 cell lines based on their TCID₅₀ using 4–5 replicates. After 3 days of incubation, the plates were stained with crystal violet to visualize cytopathic effects. 2 independent virus titrations were carried out, and viral titers were expressed as TCID₅₀/g.

**In vitro infection of macrophages and dendritic cells.** Monocytes were isolated from buffy-coat PBMCs using elutriation or CD14+ magnetic beads (Miltenyi Biotec) and were cultured for 6 days in DMEM with 10% FCS supplemented with either M-CSF (10 ng/ml) or GM-CSF (1 ng/ml) or GM-CSF (20 ng/ml) and IL-4 (20 ng/ml) for differentiation of macrophages or dendritic cells, respectively. By day 7, macrophages or dendritic cells were infected with the CHIKV viral stock for 3 hours and extensively washed. Supernatants were collected at the indicated time points, and viral titers were evaluated on BHK-21 cell lines using TCID₅₀/ml as above.

**Statistics.** We used nonparametric Spearman rank correlation tests as well as Wilcoxon and MWU rank tests adapted to small sample sizes and non-Gaussian distribution using StatView software (SAS Institute). A P value less than 0.05 was considered significant. Viral production during a selected period of time was measured by computation of the AUC using the Trapezoid calculation.

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