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Human Ebola virus infection results in substantial immune activation

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Four Ebola patients received care at Emory University Hospital, presenting a unique opportunity to examine the cellular immune responses during acute Ebola virus infection. We found striking activation of both B and T cells in all four patients. Plasmablast frequencies were 10–50% of B cells, compared with less than 1% in healthy individuals. Many of these proliferating plasmablasts were IgG-positive, and this finding coincided with the presence of Ebola virus-specific IgG in the serum. Activated CD4 T cells ranged from 5 to 30%, compared with 1–2% in healthy controls. The most pronounced responses were seen in CD8 T cells, with over 50% of the CD8 T cells expressing markers of activation and proliferation. Taken together, these results suggest that all four patients developed robust immune responses during the acute phase of Ebola virus infection, a finding that would not have been predicted based on our current assumptions about the highly immunosuppressive nature of Ebola virus. Also, quite surprisingly, we found sustained immune activation after the virus was cleared from the plasma, observed most strikingly in the persistence of activated CD8 T cells, even 1 mo after the patients’ discharge from the hospital. These results suggest continued antigen stimulation after resolution of the disease. From these convalescent time points, we identified CD4 and CD8 T-cell responses to several Ebola virus proteins, most notably the viral nucleoprotein. Knowledge of the viral proteins targeted by T cells during natural infection should be useful in designing vaccines against Ebola virus.

Ebola infection | human immune response | immune activation | plasmablasts | T cells

Ebola virus is a member of the Filoviridae family, which are filamentous, negative-stranded RNA viruses that are known to cause severe human disease (1). An ongoing outbreak of Ebola virus in West Africa has brought this virus and the disease it causes (Ebola virus disease; EVD) to the forefront. The World Health Organization has reported over 20,000 cases and 8,000 deaths in West Africa, with Sierra Leone, Guinea, and Liberia the most affected.

Our knowledge of the human immune response to Ebola virus has been severely limited due to the lack of infrastructure to perform such analyses in high containment levels (biosafety level 4; BSL-4). Minimal data exist regarding the human cellular immune response during acute Ebola virus infection, which indicate that aberrant cytokine responses (2–6), decreased CD4 and CD8 T cells, and increased CD95 expression on T cells are all associated with fatal outcomes (4). In vivo studies have revealed an association between apoptosis of lymphocytes and fatal outcome (3), and lymphocyte apoptosis has been seen both in vitro in infected human cells and in vivo in mouse and nonhuman primate models (7–9).

The natural serologic response to Ebola virus infection has been well-characterized, with specific IgM responses detected as early as 2 d after symptom onset but generally occurring 10–29 d after symptom onset in most patients. Ebola virus-specific IgG responses have been detected as early as 6 d post symptom onset, occurring ~19 d after symptom onset in most individuals (10, 11). Serological responses to Ebola virus have been reported as absent or diminished in fatal cases; however, sample sizes have been very limited (3).

Data from in vitro studies have demonstrated that Ebola virus-infected dendritic cells are impaired in their ability to produce cytokines and activate autologous T cells (12), whereas infected macrophages exhibit impaired maturation (13). Ebola virus also encodes several proteins that can interfere with the innate immune response in infected cells (14). These in vitro studies, combined with the limited human data showing T-cell apoptosis, lymphopenia, and absent antibody responses in fatal cases, have led to the assumption that Ebola virus infection is immunosuppressive.

Here we examine the immune responses of four survivors of EVD who received care at Emory University Hospital. This first look, to our knowledge, at the human adaptive immune response during the acute phase of Ebola virus infection shows striking levels of T- and B-cell activation in all four patients.

Results

Analysis of Human Plasmablasts and Activated T Cells During Acute Ebola Virus Infection. Between August and October of 2014, four patients with EVD received care at Emory University Hospital in the Serious Communicable Diseases Unit. We had the unique opportunity to evaluate the cellular and humoral immune responses during acute and convalescent disease phases in these patients. The clinical course of two of these cases has been

Significance

In 2014, Ebola virus became a household term. The ongoing outbreak in West Africa is the largest Ebola virus outbreak ever recorded, with over 20,000 cases and over 8,000 deaths to date. Very little is known about the human cellular immune response to Ebola virus infection, and this lack of knowledge has hindered development of effective therapies and vaccines. In this study, we characterize the human immune response to Ebola virus infection in four patients. We define the kinetics of T- and B-cell activation, and determine which viral proteins are targets of the Ebola virus-specific T-cell response in humans.


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The authors declare no conflict of interest.

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www.pnas.org/cgi/doi/10.1073/pnas.1502619112
EVD9 McElroy et al. | Kinetics of plasmablasts, activated CD4 and CD8 T-cell responses, and viral load in EVD patients. Percentages of plasmablasts (CD27+CD38+CD19+), activated CD4 T cells (HLA-DR+CD38+CD3+CD4+), activated CD8 T cells (HLA-DR+CD38+CD3+CD8+), and viral load are graphed as a function of time. Responses from a healthy control are shown in red. The dotted lines represent the limit of detection for the viral load assay. TCID_{50}, 50% tissue culture infective dose.
Phenotyping activated CD8 T cells in EVD patients. The expression of CD8 T cells from EVD9 on day 31 after symptom onset, consistent with their plasmablast responses (Fig. S4). EVDS's case at Emory began during the second week of illness; upon arrival, the patient had already developed both IgM and IgG responses. EVDS demonstrated the classic kinetics of an IgM response before the IgG response. However, EVDS had detectable IgM and IgG responses at about the same time. The frequencies of plasmablasts expressing IgA, IgM, and IgG were measured in select samples by intracellular staining of CD19+/CD27+/CD38+ cells. These samples demonstrated predominantly IgG-positive plasmablasts (data not shown).

Plasmablast frequencies were very high in all patients during the acute phase of illness but had returned to baseline levels at the follow-up visits (Fig. S2). ELISPOT assays were performed to quantitate Ebola virus-specific antibody-secreting cells at the first follow-up visits (approximately 2 mo post symptom onset). The data for EVD2 are shown in Fig. 5B, which shows plasmablasts clearly producing IgG that recognize the Ebola virus lysate but not a control lysate; total IgG-secreting cells are also depicted in this figure. Strikingly, both EVD2 and 5 still had 5–15% Ebola virus-specific plasmablasts at the time of their first follow-up visit (Fig. 5C). EVD2 and 5 both had plasmablasts that specifically secreted antibodies that bound to whole-cell lysate from Ebola virus-infected cells (Fig. 5C) and purified viral nucleoprotein (NP) (Fig. S3). The magnitude of the antigen-specific IgG responses was significantly higher when whole-cell lysate was used rather than NP alone, suggesting multiple viral antigen targets. Of note, whereas up to 15% of the plasmablasts were Ebola virus-specific, there was still a significant proportion of the IgG-producing plasmablasts that was not antigen-specific, suggesting that there may be polyclonal B-cell activation that is mediated by the inflammatory response. However, the time point at which these assays were performed was in convalescence (approximately 2 mo post symptom onset) and, at this time, only 3% of the CD19-positive cells are plasmablasts (Fig. S1). We suspect that during the acute phase, when up to 50% of the CD19+ cells were plasmablasts, the frequency of Ebola-specific plasmablasts would have been much higher.

Development of Humoral Immunity in EVD Patients. Serologic responses to the viral nucleoprotein were measured by ELISA. All patients developed peak IgG responses around 2–3 wk after symptom onset, consistent with their plasmablast responses (Fig. S4). EVDS's case at Emory began during the second week of illness; upon arrival, the patient had already developed both IgM and IgG responses. EVDS demonstrated the classic kinetics of an IgM response before the IgG response. However, EVDS had detectable IgM and IgG responses at about the same time. The frequencies of plasmablasts expressing IgA, IgM, and IgG were measured in select samples by intracellular staining of CD19+/CD27+/CD38+ cells. These samples demonstrated predominantly IgG-positive plasmablasts (data not shown).

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Sustained Activation of T-Cell Responses in EVD Patients. All four patients were seen in follow-up appointments after discharge from the hospital, and the same analyses were performed on blood samples obtained during the convalescent phase. Representative flow plots for EVD2, who was seen twice in follow-up, are depicted in Fig. 4. Significant numbers of activated CD4 and CD8 T cells were still present in EVD2’s peripheral blood at the first follow-up visit but not at the second follow-up. Similar levels were seen in EVD5 at the first follow-up appointment (Fig. S1). In both cases, the high levels of activated CD8 and CD4 T cells suggest ongoing antigen stimulation via the T-cell receptor. In contrast, activated T-cell levels of EVD9 and 15 were almost at baseline at their first follow-up visits (Fig. S1). However, for EVD9, the first follow-up appointment was 71 d after symptom onset, which is later in the disease course than the follow-up visits for the other patients. In contrast, EVD15, who had mild disease with rapid resolution of viremia, had low numbers of activated CD4 and CD8 T-cell populations even at discharge, and these levels remained low at the first follow-up visit.

Fig. 3. Phenotyping activated CD8 T cells in EVD patients. The expression of various effector cell markers on CD3+CD8+ T cells from EVD9 on day 31 after symptom onset (A) and in EVD15 3-9 d after onset of symptoms (B). The Ki-67 histogram is derived from the population depicted in red in the first plot.

Fig. 4. CD4 and CD8 T-cell responses in convalescent EVD patients. Representative flow plots from EVD2 at two time points after discharge (first follow-up was 1 mo post discharge and the second follow-up was 3 mo post discharge) from the hospital demonstrating activated CD4 and CD8 T-cell populations. Days noted in all panels are days post symptom onset.

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The largest fraction of producing double-producers (CD8). Re-
mild disease, rapidly cleared viremia accompanied by an equally rapid contraction of activated T-cell populations. Also of note is the fact that the mildly affected patient, EVD15, did not have two peaks of activated CD4 and CD8 T cells. This phenomenon was noted in the other three patients, and likely represents the return of the tissue-based T cells to the peripheral blood after control of the infection in the most affected tissues was achieved. Prolonged antigen expression in the affected tissues, most likely the liver, could have also contributed to the prolonged responses that were noted in the three more clinically affected patients.

As a first step toward defining the viral antigen targets of the human T-cell response to Ebola virus, we measured T-cell cytokine production in response to various pools of peptides derived from Ebola virus antigens. The strongest responses were CD8 T cell-mediated and directed against the Ebola virus NP, which is not surprising given that this is the most highly expressed protein in infected cells. All patients had low-level detectable CD8 T-cell responses against VP40, the viral matrix protein. Only two of the three EVD patients tested had detectable CD8 T-cell responses against the viral GP. Two Ebola virus vaccine candidates are being evaluated in phase I trials for human use (25), and both express only viral GP. One of these vaccine candidates, the cAd3-EBO vaccine, is aimed at generating T-cell responses, which correlate with protection induced by this vaccine in the nonhuman primate model (26). Our data could inform future vaccine design, and suggest that NP should be targeted in addition to GP to generate the most robust Ebola virus-specific human CD8 T-cell responses.

It is worth noting that these Ebola patients received experimental therapeutic interventions (Table S1). ZMapp (27) was given to EVD2 and 5, EVD9 received an siRNA product against Ebola virus (28), EVD15 received a DNA polymerase inhibitor, and convalescent serum was given to EVD9 and 15. It is unknown whether any of these experimental interventions impacted the course of disease in these patients. It is also not clear whether any of these treatments modified the immune response to Ebola virus. It remains plausible that infusion of ZMapp, a monoclonal antibody preparation directed against the Ebola GP, could have impacted the specificity of the responding B cells to the GP. Also, immune complexes generated by ZMapp antibodies could have influenced the T-cell response. However, it is important to note that all treatments were done after onset of symptoms and, in the case of ZMapp, was given 9 or 10 d after symptom onset. Thus, the initiation and activation of the adaptive immune response occurred under natural conditions without any interventions.

In summary, this study provides to our knowledge the first longitudinal kinetic data on the activation status of human B- and

![Fig. 6. Antigen specificity of CD4 and CD8 T cells in EVD patients. Flow cytometry plots showing IFN-γ and TNF-α expression in response to stimulation with the indicated peptide pools from Ebola viral proteins. Assays were performed on PBMCs obtained from EVD2, EVD5, and EVD9 at 28, 144, and 71 d post onset of symptoms, respectively.](image-url)
T-cell populations during acute Ebola virus infection. We have described the presence of robust B- and T-cell responses in four humans infected with Ebola virus. Not only was the magnitude of this response notable but the duration of these responses persisted into convalescence in some patients. Several viral proteins were targets of the Ebola virus-specific T-cell response, with the NP being the major viral target of CD8 T cells, suggesting the inclusion of this protein in future T cell-based vaccine designs.

Materials and Methods

Human Subjects and Biosafety. Institutional review board approval (IRB) was obtained from Emory University (IRB00067700) and CDC (6643.0) prior to patient enrollment. Written consent was obtained from all patients. All work with infectious acute phase specimens was performed in the CDC BSL-4 laboratory space. Plasma samples were γ-irradiated with 5 × 10^7 rads prior to removal from BSL-4 for qRT-PCR and ELISA analyses. Throughout the paper, data are presented in days after onset of patient-reported symptoms.

Virus-Specific qRT-PCR. RNA was isolated from plasma using the MagMax Total RNA Isolation Kit (Life Technologies), and qRT-PCR was performed using established primer/probe sets that target the nucleoprotein gene (29). A standard curve of known virus concentration, expressed as TCID50 per mL, was generated from a passage 3 stock of the virus isolated from EVD2 and used to convert raw C values to relative TCID50 per mL.

Antibodies, Flow Cytometry, ELISPOT, and ELISA. All staining reagents, including antibodies, lysis buffer, and cytokine/cytokine kits, were obtained from BD, except for CX3CR1 (BioLegend) and Aqua live/dead stain (Life Technologies). All phenotype stains and intracellular cytokine stimulations were done as described previously (16). All samples were read using a BD Accuri C6 or LSRII and analyzed using Flowjo software (Treestar). Ebola virus NP (His-tagged; GenScript) was used to assay Ebola-specific IgG and IgM by ELISA and ASC by ELISPOT. Additionally, lystate from Ebola-infected or infected Vero E6 cells was used for the ASC ELISPOT. Further experimental details for the flow cytometry, PBMC peptide stimulations, ELISA, and ELISPOT are presented in SI Materials and Methods.

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