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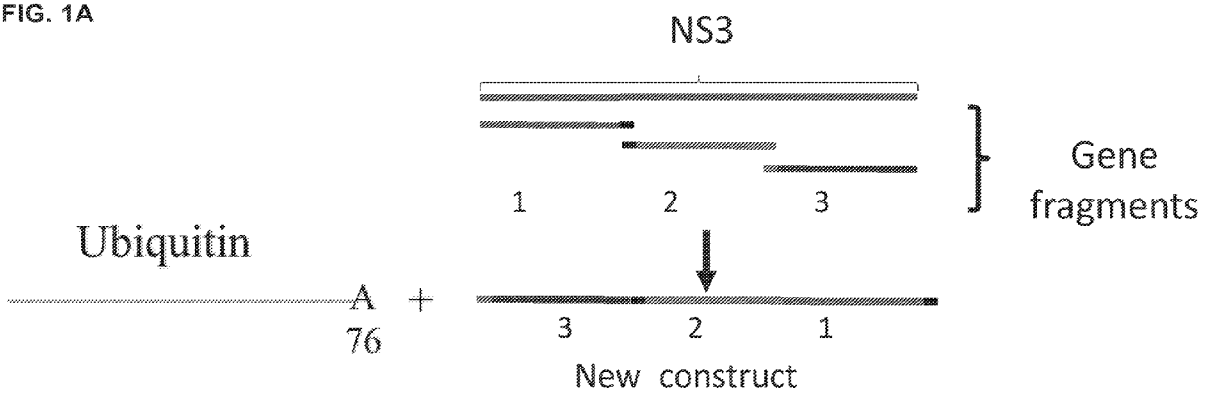
(54) Title: ZIKA VIRUS IMMUNOGENIC COMPOSITIONS

FIG. 1A



(57) Abstract: Provided herein are immunogenic compositions for the prevention of Zika virus infections. Disclosed herein are immunogenic compositions comprising an expression vector and a nucleotide sequence disposed therein, wherein the nucleotide sequence comprises: a nucleotide sequence encoding a Zika virus NS3 protein. Further disclosed herein are methods for preventing a Zika virus infection in a subject in need thereof, the method comprising administering a therapeutically effective amount of an immunogenic composition of the present disclosure to the subject.

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ZIKA VIRUS IMMUNOGENIC COMPOSITIONS

CROSS REFERENCE TO RELATED APPLICATIONS

[0001] This application claims the benefit of U.S. provisional patent application 62/970,592 filed February 5, 2020, the entire contents of which is incorporated by reference herein.

FEDERALLY SPONSORED RESEARCH OR DEVELOPMENT

[0002] This invention was made with government support under Grant No. R21AI145465 and R21AI137790 awarded by the National Institutes of Health. The government has certain rights in the invention.

TECHNICAL FIELD

[0003] The present disclosure relates to immunogenic compositions, and their use, in the prevention and treatment of Zika virus infections.

BACKGROUND

[0004] Zika virus (ZIKV) is a flavivirus in the same genus of human pathogenic arboviruses, including dengue virus (DENV), West Nile virus (WNV), yellow fever virus (YFV), and Japanese encephalitis virus (JEV). Zika virus causes neurological diseases such as Guillain-Barré syndrome and congenital Zika syndrome (symptoms include microcephaly, brain abnormalities, and other congenital malformations). Despite several ZIKV vaccines currently in clinical trials, no vaccines have been approved for preventing ZIKV infections in humans.

[0005] Dengue virus has four serotypes that differ by 30-35%, with their viral envelope (E) protein sequences differing from ZIKV E protein only by 41-46%. Dengue virus infection usually does not cause severe symptoms, but may lead to life-threatening complications such as Dengue Hemorrhage Fever (DHF) and Dengue Shock Syndrome (DSS). Primary infection with DENV leads to life-long immunity to the infecting serotype, but not to the other serotypes. Secondary infection by other serotypes is often responsible for DHF and DSS. In some cases, antibodies generated during primary DENV infection are unable to neutralize, but may opsonize, another serotype virus during secondary infection to target monocytes and macrophages via Fc-receptor-mediated endocytosis, leading to antibody-dependent enhancement (ADE) of infection.

[0006] Similar to DENV infection, ZIKV infection causes mild, if any, symptoms such as fever, myalgia, arthralgia, headache, conjunctivitis, and thrush in the most infected people. However, severe symptoms such as microcephaly and other neurological abnormalities have been associated with ZIKV infection. Human monoclonal antibodies (mAbs) generated from DENV-infected subjects cross-react with ZIKV. Importantly, DENV-specific antibodies may

enhance ZIKV pathogenesis and ZIKV-induced microcephaly-like syndrome in mice. In addition, maternally-acquired ZIKV-specific antibodies enhanced DENV infection and heightened disease states in mice. However, it has been demonstrated that preexisting high antibody titers to DENV are associated with reduced risk of ZIKV infection and symptoms in humans. Vaccination with Dengvaxia®, which expresses the precursor of membrane (prM) and E proteins from four serotypes of DENV, in DENV uninfected children has led to more hospitalization than in the infected children, a possible consequence of ADE.

[0007] These studies strongly suggest that improper pre-existing immunity (non-neutralizing antibodies) may predispose to severe DENV/ZIKV-induced diseases such as DHF/DSS and microcephaly, a vaccine which does not induce antibodies that could enhance either disease should be developed. Thus, innovative approaches are needed in the development of a vaccine against ZIKV without inducing ADE-mediated symptoms.

SUMMARY

[0008] Provided herein are immunogenic compositions useful in the prevention and treatment of Zika virus infections.

[0009] Thus, disclosed herein are immunogenic compositions comprising an expression vector and a nucleotide sequence disposed therein, wherein the nucleotide sequence comprises: a nucleotide sequence encoding a Zika virus NS3 protein, wherein the NS3 nucleotide sequence is reorganized and comprises the nucleotide sequence of SEQ ID NO:3; and a ubiquitin nucleotide sequence upstream of the Zika virus NS3 protein sequence. In some embodiments, the nucleotide sequence is SEQ ID NO:5.

[0010] Disclosed herein are immunogenic compositions comprising an expression vector and a nucleotide sequence disposed therein, wherein the nucleotide sequence comprises a nucleotide sequence encoding a Zika virus NS3 protein, wherein the NS3 nucleotide sequence is reorganized and comprises the nucleotide sequence of SEQ ID NO:3.

[0011] Further disclosed herein are methods for preventing a Zika virus infection in a subject in need thereof, the method comprising administering a therapeutically effective amount of an immunogenic composition of the present disclosure to the subject. In some embodiments, the method further comprises co-administration of an adjuvant.

[0012] In some embodiments, the administration increases production of Zika virus-specific cytotoxic T lymphocytes and does not induce Zika virus-specific antibodies in the subject.

[0013] Also disclosed herein are methods for preventing birth defects associated with a Zika virus infection in a subject at risk of Zika virus infection, comprising immunizing a woman who is pregnant, who may become pregnant, or who plans to become pregnant, with an

immunogenic composition of the present disclosure. In some embodiments, the immunized woman does not produce neutralizing antibodies after infection with Zika virus. In some embodiments, the immunized woman exhibits decreased decreases viral titers after infection with Zika virus compared to a woman not immunized with an immunogenic composition disclosed herein.

[0014] In some embodiments, the administration increases production of Zika virus-specific $CD8^+$ T lymphocytes in the woman. In some embodiments, as a result of the administration, a pregnancy in the woman does not result in Zika virus-associated birth defects.

[0015] In some embodiments, as a result of the administration of an immunogenic composition disclosed herein, a strong cytotoxic T lymphocyte (CTL) response against Zika virus is induced. In some embodiments, the CTL response provides protection against Zika virus infection.

[0016] Disclosed here is the use of an immunogenic composition of the present disclosure in the prevention of a Zika virus infection.

[0017] Disclosed here is the use of an immunogenic composition of the present disclosure in the prevention of birth defects associated with Zika virus infection.

[0018] Disclosed here in a composition of the present disclosure for use in the prevention of a Zika virus infection.

[0019] Disclosed here in a composition of the present disclosure for use in the prevention of birth defects associated with Zika virus infection.

DESCRIPTION OF DRAWINGS

[0020] FIG. 1A-C depict the disclosed ZIKV T-cell-inducing (TCI)-DNA vaccine design and antigen expression. FIG. 1A depicts a schematic diagram of plasmid design. The gene sequence (SEQ ID NO:1) encoding for the NS3 protein (SEQ ID NO:2) was split into three parts (denoted 1, 2, 3). The 30 nucleotide bases before and after any cleaved sequence were placed in front of each region to preserve any epitopes that may have been disrupted (SEQ ID NO:3). The open reading frame (ORF) gene encoding for a mouse monomer of ubiquitin (Ub; SEQ ID NO:4) was placed immediately upstream of the rearranged NS3 sequence. A glycine at the 76^{th} residue was modified to encode an alanine to enhance the stability of the Ub/NS3 complex (SEQ ID NO:5). FIG. 1B: 293T cells were transfected with the rearranged Ub/NS3 plasmid overnight. The cells were allowed to stably express plasmid for 36 h. After this period, the proteasome inhibitor MG132 was added overnight. The cell lysates from triplicate experiments were analyzed via Western blot for the expression of NS3 and beta-

actin. FIG. 1C: Total band density was quantified using ImageJ and analyzed using GraphPad (Prism). * and ** indicate $P < 0.05$ and $P < 0.01$, respectively.

[0021] FIG. 2A-B depict mRNA levels of Ub/NS3 gene sequence in 293T cells. 293T cells were transfected with rearranged Ub/NS3 in polyethylenimine (PEI) transfection reagent overnight. RNA was further isolated, cDNA was synthesized, and analysis of gene expression was conducted by quantitative reverse transcription PCR (qRT-PCR). FIG. 2A depicts the relative gene expression of rearranged Ub/NS3 and GAPDH normalized control. FIG. 2B: PCR products were run on a 1% agarose gel. Each treatment condition was replicated twice. Data was analyzed by student's *T* test. Error bars depict standard error of the mean (s.e.m). ** indicates $P < 0.01$.

[0022] FIG. 3A-C depict that the ZIKV TCI-DNA vaccine-protected female pregnant BALB/c mice and their fetuses against ZIKV challenge. Female BALB/c mice were immunized with ZIKV TCI-DNA vaccine, control vaccines (ZIKV full-length E protein and EDI/II mixed peptides), or PBS control for two doses, sera was collected, and then mated with male BALB/c mice at 10 days post-2nd immunization. After receiving antibodies to IFNAR1 (for depleting type I IFN), the pregnant mice (embryonic day (E5-E7)) were intraperitoneally (I.P.) challenged with ZIKV (stain R103451 (2015/Honduras), GenBank: KX262887) (2×10^5 plaque-forming unit (PFU)/mouse). Six days post-challenge, the mice were euthanized, examined for morphological changes in uteri, and ZIKV titers were measured using a plaque-forming assay. FIG. 3A depicts the morphology of representative images of uteri (E11-E13) of ZIKV-challenged pregnant BALB/c mice immunized with one of the four compositions above. Arrows indicate fetal death. Viral titers in placenta (FIG. 3B) and amniotic fluid (FIG. 3C) of ZIKV-challenge pregnant mice were also determined. The detection limit was 12.5 PFU/g for placenta and 25 PFU/ml for amniotic fluid. The data in FIG. 3B and FIG. 3C are represented as mean ± s.e.m (n=6). ** and *** indicate $P < 0.01$ and $P < 0.001$, respectively.

[0023] FIG. 4A-C depict that the ZIKV TCI-DNA vaccine protected adult male and female *Ifnar1*$^{-/-}$ mice against ZIKV challenge with complete survival and reduced viral titers, including in reproductive organs. Equal numbers of male and female *Ifnar1*$^{-/-}$ mice were immunized with ZIKV TCI-DNA vaccine, control vaccines (ZIKV full-length E protein and EDI/II mixed peptides), or PBS control, and sera was collected at 10 days post-2nd immunization. At 13 days post-2nd immunization, the mice were challenged (I.P.) with ZIKV (strain R103451, 10^3 PFU/mouse), and weight (FIG. 4A) and survival (FIG. 4B) were recorded daily for 14 days (n=6). FIG. 4C: The immunized *Ifnar1*$^{-/-}$ mice were challenged with ZIKV (strain PAN2016 (2016/Panama), GenBank: KX198135) (10^3 PFU/mouse), and 6 days later sera and tissues (brain, kidney, lung, heart, liver, spleen, muscle, and testis) were collected for detection of viral

titers using a plaque-forming assay. The detection limit was 25 PFU/ml (for sera), 12.5 PFU/g (for brain), 20 PFU/g (for kidney, spleen, and muscle), and 25 PFU/g (for lung, heart, liver, and testis). The data are represented as mean ± s.e.m (n=3 for testis, and n=6 for other groups). *, **, and *** represent $P < 0.05$, $P < 0.01$, and $P < 0.001$, respectively.

[0024] FIG. 5A-E depict that the ZIKV TCI-DNA vaccine-protected female pregnant *Ifnar1*$^{-/-}$ mice and their fetuses against ZIKV challenge. Female *Ifnar1*$^{-/-}$ mice were immunized with ZIKV TCI-DNA vaccine, control vaccines (ZIKV full-length E protein and EDI/II mixed peptides), or PBS control, and then mated with male *Ifnar1*$^{-/-}$ mice at day 10 post-2nd immunization. The pregnant mice (E10-E12) were challenged with ZIKV (strain R103451, 10^4 PFU/mouse), and 6 days later, uteri and fetuses were collected to evaluate morphological changes, as well as collection of sera, body fluid, and tissues (including placenta) to measure viral titers using plaque-forming assay. Placentas were also evaluated for apoptosis and vascular damage, and inflammatory cytokines and chemokines were assayed as described. FIG. 5A depicts a representative image of morphology of uteri (E16-E18) and fetuses from pregnant mice challenged with ZIKV at E10-E12. The total numbers and dead fetuses from each group are shown in FIG. 5B. Viral titers in placenta and fetal brain (FIG. 5C), sera and amniotic fluid (FIG. 5D) and tissues (brain, kidney, heart, liver, spleen, and muscle) (FIG. 5E), were measured in a plaque-forming assay 6 days post-challenge. The detection limit was 12.5 PFU/g (for placenta and fetal brain), 20 PFU/g (for heart), 25 PFU/ml (for sera and amniotic fluid), and 25 PFU/g (for brain, kidney, liver, spleen, and muscle). The data are represented as mean ± s.e.m (n = 6). *, **, and *** indicate $P < 0.05$, $P < 0.01$, and $P < 0.001$, respectively.

[0025] FIG. 6A-C depict that the ZIKV TCI-DNA vaccine prevented ZIKV-caused apoptosis in placenta of female pregnant *Ifnar1*$^{-/-}$ mice. Placentas collected from the ZIKV-challenged pregnant (E10-E12) *Ifnar1*$^{-/-}$ mice were stained for the activated form of caspase-3 (an apoptotic marker) by immunofluorescence assay. FIG. 6A depicts representative images of immunofluorescence staining of activated caspase-3 in placenta. ZIKV, activated caspase-3, and nuclei were stained with anti-ZIKV antibody, anti-active caspase-3 antibody, and DAPI, respectively. The images were magnified at 63X, with a scale bar of 10 μm. Quantification of ZIKV$^+$ (FIG. 6B) and activated caspase-3$^+$ (FIG. 6C) staining in the samples of FIG. 6A were conducted with ImageJ software. The data are presented as mean ± s.e.m of fluorescence intensity for ZIKV$^+$ or caspase-3$^+$ staining in each field (n=6: "n" indicates numbers of images from different placentas). *, ** and *** indicate $P < 0.05$, $P < 0.01$, and $P < 0.001$, respectively.

[0026] FIG. 7A-C depict that the ZIKV TCI-DNA vaccine prevented ZIKV-caused vascular damage to placenta of female pregnant *Ifnar1*$^{-/-}$ mice. Placentas collected from the ZIKV-challenged pregnant (E10-E12) *Ifnar1*$^{-/-}$ mice were stained for vimentin (a marker for fetal

capillary endothelium and fetal blood vessels in placenta) by an immunofluorescence assay. FIG. 7A depicts representative images of immunofluorescence staining of vimentin in placenta. ZIKV, vimentin, and nuclei were stained with anti-ZIKV antibody, anti-vimentin antibody, and DAPI, respectively. The images were magnified at 63X, with a scale bar of 20 μm. Quantification of $ZIKV^+$ (FIG. 7B) and $vimentin^+$ (FIG. 7C) staining in the samples of FIG. 7A were conducted with ImageJ software. The data are presented as mean ± s.e.m of fluorescence intensity for $ZIKV^+$ or $vimentin^+$ staining in each field (n = 6: "n" indicates numbers of image from different placentas). *, ** and *** indicate $P < 0.05$, $P < 0.01$, and $P < 0.001$, respectively.

[0027] FIG. 8A-B depict that the ZIKV TCI-DNA vaccine prevented ZIKV-caused inflammation in placenta of female pregnant *Ifnar1*$^{-/-}$ mice. Placentas collected from the challenged pregnant (E10-E12) *Ifnar1*$^{-/-}$ mice were evaluated for inflammatory cytokines (FIG. 8A) and chemokines (FIG. 8B) by Mouse Inflammatory Cytokines Multi-Analyte ELISArray Kit and Mouse Common Chemokines Multi-Analyte ELISArray Kit, respectively. The data are presented as mean ± s.e.m (n = 6). *, ** and *** indicate $P < 0.05$, $P < 0.01$, and $P < 0.001$, respectively.

[0028] FIG. 9A-E depicit that the ZIKV TCI-DNA vaccine induced low to no ZIKV-, E-, and NS3-specific antibodies, eliminating the antibody-dependent enhancement (ADE) effect in BALB/c mice. Mouse sera collected at 10 days post-2nd immunization were assayed for ZIKV E-, NS3-, and ZIKV-specific IgG antibody, neutralizing antibodies, and ADE of ZIKV infection. ZIKV strain R103451 was used for the neutralization and ADE tests. Enzyme-linked immunosorbent assay (ELISA) for detection of IgG antibody specific to ZIKV full-length E protein (FIG. 9A), NS3 peptides (FIG. 9B), and ZIKV (R103451 strain) (FIG. 9C) in sera of BALB/c mice immunized with ZIKV full-length E protein, EDI/II mixed peptides, TCI-DNA, or PBS control. IgG antibody titers are presented as positively detectable endpoint serum dilutions. Measurement of neutralizing antibodies (FIG. 9D) by plaque reduction neutralization test (PRNT) and ADE (FIG. 9E) by a flow cytometry-based assay was performed with sera of immunized BALB/c mice. Neutralizing antibody titers are presented as 50% plaque reduction neutralizing antibody titer ($PRNT_{50}$) of 2-fold serially diluted sera. The ADE is presented as percent of infected cells, which was calculated based on fluorescence signals in the presence or absence of serially diluted sera. The data are expressed as mean ± s.e.m (n = 6). * indicates $P < 0.01$.

[0029] FIG. 10A-E depicit that the ZIKV TCI-DNA vaccine induced low to no ZIKV-, E-, and NS3-specific antibodies, eliminating the ADE effect in *Ifnar1*$^{-/-}$ mice. Mouse sera collected at 10 days post-2nd immunization were assayed for ZIKV E-, NS3-, and ZIKV-specific IgG

antibody, neutralizing antibodies, and ADE of ZIKV infection. ZIKV strain R103451 was used for the neutralization and ADE tests. ELISA for detection of IgG antibody specific to ZIKV full-length E protein (FIG. 10A), NS3 peptides (FIG. 10B), and ZIKV (R103451 strain) (FIG. 10C) in sera of *Ifnar1*$^{-/-}$ mice immunized with ZIKV full-length E protein, EDI/II mixed peptides, TCI-DNA, or PBS control. IgG antibody titers are presented as positively detectable endpoint serum dilutions. Measurement of neutralizing antibodies (FIG. 10D) by plaque reduction neutralization test (PRNT) and ADE (FIG. 10E) by flow cytometry-based assay was performed in sera of immunized *Ifnar1*$^{-/-}$ mice. Neutralizing antibody titers are presented as 50% plaque reduction neutralizing antibody titer ($PRNT_{50}$) of 2-fold serially diluted sera. The ADE is presented as percent of infected cells, which was calculated based on fluorescence signals in the presence or absence of serially diluted sera. The data are expressed as mean ± s.e.m (n = 6). * indicates $P < 0.01$.

[0030] FIG. 11A-C depicts that $CD8^+$ T-cells induced by ZIKV TCI-DNA vaccine were essential in protecting adult mice against ZIKV infection. Male and female BALB/c mice were immunized with ZIKV TCI-DNA or PBS control for two doses; 10 days post-2nd dose they were injected (I.P.) with anti-CD4 (for depleting $CD4^+$ T cells), anti-CD8a (for depleting $CD8^+$ T cells), or IgG2b isotype control (i.e., Iso con; without depleting either $CD4^+$ or $CD8^+$ T cells) antibody (200 μg/mouse) for three times (-2, -1, and 1 day p.i.). One day before challenge, the mice were injected with anti-IFNAR1 blocking antibody (for depleting type I IFN; 2 mg/mouse), and then infected with ZIKV (strain R103451, 2.5×10^5 PFU/mouse). Three days post-challenge, the mice were sacrificed and the frequencies of $CD4^+$ or $CD8^+$ T cells in blood cells (FIG. 11A) and splenocytes (FIG. 11B) were quantified by flow cytometry analysis, as well as viral titers were determined by plaque-forming assay in sera and tissues (lung, eye, and muscle) (FIG. 11C). The detection limit was 50 PFU/ml (for sera) or 50 PFU/g (for lung, eye, and muscle). The data are represented as mean ± s.e.m (n = 5). *, ** and *** indicate $P < 0.05$, $P < 0.01$, and $P < 0.001$, respectively.

[0031] FIG. 12A-B depicts that $CD8^+$ T-cell-mediated immune responses induced by the ZIKV TCI-DNA vaccine played a key role in protecting pregnant mothers and their fetuses against ZIKV infection. Female BALB/c mice were immunized with the ZIKV TCI-DNA vaccine or PBS control for two doses, and then mated with male BALB/c mice at 10 days post-2nd immunization. The pregnant (E10-E12) mice were then injected (I.P.) with anti-CD8a (for depleting $CD8^+$ T cells) or IgG2a isotype control (i.e., Iso con; without depleting $CD8^+$ T cells) antibody (200 μg/mouse) three times (-2, -1, and 3 days p.i. (post-infection)). One day before challenge, the mice were also injected with anti-IFNAR1 blocking antibody (for depleting type I IFN; 2 mg/mouse), and then infected with ZIKV (strain R103451, 10^6 PFU/mouse). Six days

post-challenge, the mice were euthanized, and morphology of uteri and fetuses (FIG. 12A) and number of total and dead fetuses (FIG. 12B) were recorded.

[0032] FIG. 13A-E depict viral titers in placenta (FIG. 13A), amniotic fluid (FIG. 13B), and fetal brain (FIG. 13C). Viral titers were determined in sera collected at three (FIG. 13D) and six (FIG. 12E) days post-challenge in the mice of FIG. 12. The detection limit was 20 PFU/g (for placenta), 40 PFU/g (for fetal brain), and 50 PFU/ml (for sera and amniotic fluid). The data are represented as mean ± s.e.m (n = 6). *, ** and *** indicate $P < 0.05$, $P < 0.01$, and $P < 0.001$, respectively.

[0033] FIG. 14A-B depicts ZIKV-specific $CD8^+$ T cell responses in the mice of FIG. 12. Six days post-challenge, splenocytes were isolated from the mice injected with isotype control antibody (i.e., Iso con), and analyzed for ZIKV-specific $CD8^+$ T cell responses by flow cytometry analysis. The frequencies of $CD8^+$ T cells (FIG. 14A), as well as $IL2^+$, IFN-γ^+ and TNF-α secretion were quantitated in $CD8^+$ T cells (FIG. 14B). The data are represented as mean ± s.e.m (n = 6). *, ** and *** indicate $P < 0.05$, $P < 0.01$, and $P < 0.001$, respectively.

[0034] FIG. 15 depicts that the ZIKV TCI-DNA vaccine cross-protected adult male and female *Ifnar1*$^{-/-}$ mice against DENV challenge with reduced viral titers. Male and female *Ifnar1*$^{-/-}$ mice were immunized with ZIKV TCI-DNA vaccine, control vaccines (ZIKV full-length E protein and EDI/II mixed peptides), or PBS control, challenged with ZIKV at 13 days post-2^{nd} immunization, and survival was measured for 14 days, as described in FIG. 4B. The mice that survived the ZIKV challenge were infected with DENV-2 (strain V594 (2006/Puerto Rico) (SEQ ID NO:5), 2×10^6 PFU/mouse); and 3 days later, they were euthanized, and sera and tissues were collected to measure DENV titers by plaque-forming assay. The mock control represents mice infected with DENV only. The detection limit was 12.5 PFU/g (for muscle), 25 PFU/ml (for sera), or 25 PFU/g (for brain, kidney, lung, heart, liver, spleen and testis). The data are represented as mean ± s.e.m (n=3 mice/group for testis, and n=3-6 mice/group for sera and other tissues). *, **, and *** indicate $P < 0.05$, $P < 0.01$, and $P < 0.001$, respectively.

DETAILED DESCRIPTION

[0035] A conventional vaccine is expected to induce neutralizing antibodies. However, it also induces non-neutralizing antibodies, which are responsible for ADE of DENV or ZIKV infection when neutralizing antibodies wane. In contrast, a vaccine which elicits only ZIKV-specific cytotoxic T lymphocytes (CTLs), but not ZIKV-specific antibodies, is expected to prevent ZIKV infection without risk of ADE-mediated consequences. As humans mount significant T cell responses to ZIKV nonstructural protein 1 (NS1), the disclosed vaccine targets ZIKV nonstructural protein 3 (NS3). Thus, disclosed herein is a DNA vaccine which not only targets ZIKV nonstructural protein 3 (NS3) without E and prM proteins but also uses

a ubiquitin and/or gene rearrangement strategy to enhance its degradation in the proteasome with the goal of inducing only NS3-specific CTLs. The efficacy of this T-cell-inducing (TCI) ZIKV DNA (i.e., TCI-DNA) vaccine protects against ZIKV challenge in animal models. In alternative embodiments, the protein encoded in the DNA vaccine is produced using standard biotechnology and used as a vaccine.

[0036] A number of embodiments of the disclosed immunogenic compositions have been described. Nevertheless, it will be understood that various modifications may be made without departing from the spirit and scope of the present disclosure.

[0037] As used herein an "immunogenic composition" refers to composition comprising a nucleic acid or an expressed protein, with or without an adjuvant, and which elicits an immune response in the host. The immunogenic compositions disclosed herein are immunoprotective or therapeutic. When the immunogenic compositions may prevent, ameliorate, palliate, or eliminate disease from the host then the immunogenic composition may also optionally be referred to as a vaccine. In some embodiments, the immunogenic composition includes one or more pharmaceutically acceptable excipients and may optionally include an adjuvant.

[0038] Some embodiments comprise a ZIKV DNA vaccine that expresses an ubiquitinated and rearranged ZIKV NS3 protein to generate CTLs without ADE-mediating antibodies. This unique property is due to rapid degradation of the vaccine antigen NS3 in the proteasome. Western blot analyses showed negligible amounts of the rearranged NS3 protein in the cells transfected with the plasmid expressing the NS3. In contrast, large amounts of NS3 are seen in the presence of a proteasome inhibitor, indicating that the ubiquitinated/rearranged NS3 protein is rapidly degraded in the proteasome. It is not expected that large amounts of NS3-specific antibodies would be induced with this DNA vaccine because of lack of intact NS3. There is not much concern that even small amounts of antibodies to NS3 were induced, because NS3 is not on the ZIKV virion surface and NS3-specific antibodies would not induce ADE. Indeed, sera from mice immunized with the disclosed ZIKV TCI-DNA vaccine did not show any ADE activity. As expected, the vaccine induced a strong NS3-specific CTL response. This is most likely due to the inclusion of an ubiquitin sequence upstream of the rearranged NS3 sequence, which promotes protein degradation in the proteasome, where antigenic peptides are loaded on MHC class I to induce the CTL response.

[0039] The NS3 sequence was rearranged to avoid potential harmful effects of an intact NS3 protein. In an exemplified embodiment, the NS3 gene is divided into three segments and their order inverted. In further alternative embodiments, ubiquitin is placed upstream of NS3, but the NS3 sequence is not rearranged. In still further alternative embodiments, the NS3

sequence is rearranged, but ubiquitin is not included. The misfolding due to the rearrangement of NS3 segments can induce endogenous ubiquitination of the expressed protein.

[0040] A conventional vaccine can enhance both CTL numbers and titers of antibodies including unwanted non-neutralizing antibodies, and the non-neutralizing antibodies may enhance viral infection, causing ADE. However, the vaccine strategy disclosed herein can selectively boost CTL responses rather than nonselectively amplifying all immune responses including the unwanted non-neutralizing antibodies. This is the first report of the development of such a TCI vaccine against a virus. The present disclosure demonstrates that a ZIKV DNA vaccine inducing NS3-specific CTLs, but no antibodies against prM or E proteins, provided full protection against ZIKV challenge, and in particular, against fetal damage in pregnant mice. The data demonstrate that the CTLs controlled the virus infection in the placenta so that virus-induced inflammation was greatly reduced and fetal damage was prevented.

[0041] The most devastating consequence of ZIKV infection is the congenital syndrome, which may develop in DENV-endemic countries. DENV-specific antibodies enhance transmission of ZIKV from mother to fetuses, and these antibodies cross-react with ZIKV but do not neutralize the virus. In contrast, CTLs cross-reactive with DENV and ZIKV can protect the host against ZIKV challenge. There is an 11-13% risk of microcephaly in children born to Brazilian women infected with ZIKV during pregnancy, particularly in the first trimester of pregnancy. However, not all of the DENV-immune individuals are protected against ZIKV infection. This may be dependent on titers of cross-reacting neutralizing and non-neutralizing antibodies and numbers of cross-reacting CTLs at the time of ZIKV infection.

[0042] ZIKV-induced microcephaly occurs in the DENV-immune mothers, suggesting that T cell immunity do not provide sufficient cross protection among ZIKV and DENV serotypes. The protection may be dependent on the numbers of cross-reacting CTLs and amounts of neutralizing antibodies (if any) at the time of ZIKV infection. It is likely that DENV-immune individuals presenting large amounts of CTLs cross-reacting with ZIKV and high titers of cross-neutralizing antibodies reacting with ZIKV will be protected, whereas those with small amounts of CTLs and low titers of cross-neutralizing antibodies reacting with ZIKV will suffer from congenital syndromes such as microcephaly.

[0043] Thus, disclosed herein is a vaccine expressing NS3 from ZIKV and DENV to induce a large amount of memory CTLs to prevent the consequences of ZIKV infections. Vaccination in the DENV-immune population with the disclosed ZIKV DNA vaccine will boost cross-reacting CTLs and prevent the transmission from mother to fetus and its consequences, such as microcephaly.

[0044] Table 1 discloses amino acid sequences of ZIKV and DENV used herein.

Table 1. Sequence Identifiers

SEQ ID NO:1	ZIKV (PRVABC59/2015 strain) NS3 wild-type DNA sequence agtggtgctctatgggatgtgcctgctcccaaggaagtaaaaaaggggagaccaca gatggagtgtacagagtaatgactcgtagactgctaggttcaacacaagttggagtg ggagttatgcaagaggggtctttcacactatgtggcacgtcacaaaaggatccgcg ctgagaagcggtgaagggagacttgatccatactggggagatgtcaagcaggatctg gtgtcatactgtggtccatggaagctagatgccgcctgggatgggcacagcgaggtg cagctcttggccgtgccccccggagagagagcgaggaacatccagactctgcccgga atatttaagacaaaggatggggacattggagcggttgcgctggattacccagcagga acttcaggatctccaatcctagacaagtgtgggagagtgataggactttatggcaat ggggtcgtgatcaaaaacgggagttatgttagtgccatcacccaagggaggagggag gaagagactcctgttgagtgcttcgagccctcgatgctgaagaagaagcagctaact gtcttagacttgcatcctggagctgggaaaaccaggagagttcttcctgaaatagtc cgtgaagccataaaaacaagactccgtactgtgatcttagctccaaccagggttgtc gctgctgaaatggaggaggcccttagagggcttccagtgcgttatatgacaacagca gtcaatgtcacccactctggaacagaaatcgtcgacttaatgtgccatgccaccttc acttcacgtctactacagccaatcagagtccccaactataatctgtatattatggat gaggcccacttcacagatccctcaagtatagcagcaagaggatacatttcaacaagg gttgagatgggcgaggcggctgccatcttcatgaccgccacgccaccaggaacccgt gacgcatttccggactccaactcaccaattatggacaccgaagtggaagtcccagag agagcctggagctcaggctttgattgggtgacggatcattctggaaaaacagtttgg tttgttccaagcgtgaggaacggcaatgagatcgcagcttgtctgacaaaggctgga aaacgggtcatacagctcagcagaaagacttttgagacagagttccagaaaacaaaa catcaagagtgggactttgtcgtgacaactgacatttcagagatgggcgccaacttt aaagctgaccgtgtcatagattccaggagatgcctaaagccggtcatacttgatggc gagagagtcattctggctggacccatgcctgtcacacatgccagcgctgcccagagg aggggcgcataggcaggaatcccaacaaacctggagatgagtatctgtatggaggt gggtgcgcagagactgacgaagaccatgcacactggcttgaagcaagaatgctcctt gacaatatttacctccaagatggcctcatagcctcgctctatcgacctgaggccgac aaagtagcagccattgagggagagttcaagcttaggacggagcaaaggaagaccttt gtggaactcatgaaaagaggagatcttcctgtttggctggcctatcaggttgcatct gccggaataacctacacagatagaagatggtgctttgatggcacgaccaacaacacc ataatggaagacagtgtgccggcagaggtgtggaccagacacggagagaaaagagtg ctcaaaccgaggtggatggacgccagagtttgttcagatcatgcggccctgaagtca ttcaaggagtttgccgctgggaaaaga
SEQ ID NO:2	ZIKV (PRVABC59/2015 strain) NS3 protein wild-type amino acid sequence MTRRLLGSTQVGVGVMQEGVFHTMWHVTKGSALRSGEGRLDPYWGDVKQDLVSYCGP WKLDAAWDGHSEVQLLAVPPGERARNIQTLPGIFKTKDGDIGAVALDYPAGTSGSPI LDKCGRVIGLYGNGVVIKNGSYVSAITQGRREEETPVECFEPSMLKKKQLTVLDLHP GAGKTRRVLPEIVREAIKTRLRTVILAPTRVVAAEMEEALRGLPVRYMTTAVNVTHS GTEIVDLMCHATFTSRLLQPIRVPNYNLYIMDEAHFTDPSSIAARGYISTRVEMGEA AAIFMTATPPGTRDAFPDSNSPIMDTEVEVPERAWSSGFDWVTDHSGKTVWFVPSVR NGNEIAACLTKAGKRVIQLSRKTFETEFQKTKHQEWDFVVTTDISEMGANFKADRVI DSRRCLKPVILDGERVILAGPMPVTHASAAQRRGRIGRNPNKPGDEYLYGGGCAETD EDHAHWLEARMLLDNIYLQDGLIASLYRPEADKVAAIEGEFKLRTEQRKTFVELMKR GDLPVWLAYQVASAGITYTDRRWCFDGTTNNTIMEDSVPAEVWTRHGEKRVLKPRWM DARVCSDHAALKSFKEFAAGKR
SEQ ID NO:3	Rearranged NS3 ZIKV (PRVABC59/2015 strain) DNA sequence caagagtgggactttgtcgtgacaactgacatttcagagatgggcgccaactttaaa gctgaccgtgtcatagattccaggagatgcctaaagccggtcatacttgatggcgag

	agagtcattctggctggacccatgcctgtcacacatgccagcgctgcccagaggagg gggcgcataggcaggaatcccaacaaacctggagatgagtatctgtatggaggtggg tgcgcagagactgacgaagaccatgcacactggcttgaagcaagaatgctccttgac aatatttacctccaagatggcctcatagcctcgctctatcgacctgaggccgacaaa gtagcagccattgagggagagttcaagcttaggacggagcaaaggaagacctttgtg gaactcatgaaaagaggagatcttcctgtttggctggcctatcaggttgcatctgcc ggaataacctacacagatagaagatggtgctttgatggcacgaccaacaacaccata atggaagacagtgtgccggcagaggtgtggaccagacacggagagaaaagagtgctc aaaccgaggtggatggacgccagagtttgttcagatcatgcggccctgaagtcattc aaggagtttgccgctgggaaaagacctggagctgggaaaaccaggagagttcttcct gaaatagtccgtgaagccataaaaacaagactccgtactgtgatcttagctccaacc agggttgtcgctgctgaaatggaggaggcccttagagggcttccagtgcgttatatg acaacagcagtcaatgtcacccactctggaacagaaatcgtcgacttaatgtgccat gccaccttcacttcacgtctactacagccaatcagagtccccaactataatctgtat attatggatgaggcccacttcacagatccctcaagtatagcagcaagaggatacatt tcaacaagggttgagatgggcgaggcggctgccatcttcatgaccgccacgccacca ggaacccgtgacgcatttccggactccaactcaccaattatggacaccgaagtggaa gtcccagagagagcctggagctcaggctttgattgggtgacggatcattctggaaaa acagtttggtttgttccaagcgtgaggaacggcaatgagatcgcagcttgtctgaca aaggctggaaaacgggtcatacagctcagcagaaagacttttgagacagagttccag aaaacaaaacatcaagagtgggactttgtcgtgacaactgacagtggtgctctatgg gatgtgcctgctcccaaggaagtaaaaaaggggggagaccacagatggagtgtacaga gtaatgactcgtagactgctaggttcaacacaagttggagtgggagttatgcaagag ggggtctttcacactatgtggcacgtcacaaaaggatccgcgctgagaagcggtgaa gggagacttgatccatactggggagatgtcaagcaggatctggtgtcatactgtggt ccatggaagctagatgccgcctgggatgggcacagcgaggtgcagctcttggccgtg ccccccggagagagagcgaggaacatccagactctgcccggaatatttaagacaaag gatggggacattggagcggttgcgctggattacccagcaggaacttcaggatctcca atcctagacaagtgtgggagagtgataggactttatggcaatggggtcgtgatcaaa aacgggagttatgttagtgccatcacccaagggaggagggaggaagagactcctgtt gagtgcttcgagccctcgatgctgaagaagaagcagctaactgtcttagacttgcat cctggagctgggaaaaccaggagagttctt
SEQ ID NO:4	Ubiquitin DNA sequence atgcagatcttcgtgaagactctgactggtaagaccatcaccctcgaggttgagccca gtgacaccatcgagaatgtcaaggcaaagatccaagataaggaaggcatccctcctga ccagcagaggctgatctttgctggaaaacagctggaagatgggcgcaccctgtctgac tacaacatccagaaagagtccacccctgcacctggtgctccgtctcagaggtggg
SEQ ID NO:5	Rearranged ubiquitin (Ub)/NS3 ZIKV (PRVABC59/2015 strain) DNA sequence (used for construction of ZIKV TCI-DNA vaccine) ctagaattcgttcttgccaccatgcagatcttcgtgaagactctgactggtaagacca tcaccctcgaggttgagcccagtgacaccatcgagaatgtcaaggcaaagatccaaga taaggaaggcatccctcctgaccagcagaggctgatctttgctggaaaacagctggaa gatgggcgcaccctgtctgactacaacatccagaaagagtccaccctgcacctggtgc tccgtctcagaggtgcccaagagtgggactttgtcgtgacaactgacatttcagagat gggcgccaactttaaagctgaccgtgtcatagattccaggagatgcctaaagccggtc atacttgatggcgagagagtcattctggctggacccatgcctgtcacacatgccagcg ctgcccagaggaggggcgcataggcaggaatcccaacaaacctggagatgagtatct gtatggaggtgggtgcgcagagactgacgaagaccatgcacactggcttgaagcaaga atgctccttgacaatatttacctccaagatggcctcatagcctcgctctatcgacctg aggccgacaaagtagcagccattgagggagagttcaagcttaggacggagcaaaggaa gacctttgtggaactcatgaaaagaggagatcttcctgtttggctggcctatcaggtt gcatctgccggaataacctacacagatagaagatggtgctttgatggcacgaccaaca acaccataatggaagacagtgtgccggcagaggtgtggaccagacacggagagaaaag agtgctcaaaccgaggtggatggacgccagagtttgttcagatcatgcggccctgaag

	tcattcaaggagtttgccgctgggaaaagacctggagctgggaaaaccaggagagttc ttcctgaaatagtccgtgaagccataaaaacaagactccgtactgtgatcttagctcc aaccagggttgtcgctgctgaaatggaggaggcccttagagggcttccagtgcgttat atgacaacagcagtcaatgtcacccactctggaacagaaatcgtcgacttaatgtgcc atgccaccttcacttcacgtctactacagccaatcagagtccccaactataatctgta tattatggatgaggcccacttcacagatccctcaagtatagcagcaagaggatacatt tcaacaagggttgagatgggcgaggcggctgccatcttcatgaccgccacgccaccag gaacccgtgacgcatttccggactccaactcaccaattatggacaccgaagtggaagt cccagagagagcctggagctcaggctttgattgggtgacggatcattctggaaaaaca gtttggtttgttccaagcgtgaggaacggcaatgagatcgcagcttgtctgacaaagg ctggaaaacgggtcatacagctcagcagaaagacttttgagacagagttccagaaaac aaaacatcaagagtgggactttgtcgtgacaactgacagtggtgctctatgggatgtg cctgctcccaaggaagtaaaaaaggggggagaccacagatggagtgtacagagtaatga ctcgtagactgctaggttcaacacaagttggagtgggagttatgcaagaggggtctt tcacactatgtggcacgtcacaaaaggatccgcgctgagaagcggtgaagggagactt gatccatactggggagatgtcaagcaggatctggtgtcatactgtggtccatggaagc tagatgccgcctgggatgggcacagcgaggtgcagctcttggccgtgccccccggaga gagagcgaggaacatccagactctgcccggaatatttaagacaaaggatggggacatt ggagcggttgcgctggattacccagcaggaacttcaggatctccaatcctagacaagt gtgggagagtgataggactttatggcaatggggtcgtgatcaaaaacgggagttatgt tagtgccatcacccaagggaggagggaggaagagactcctgttgagtgcttcgagccc tcgatgctgaagaagaagcagctaactgtcttagacttgcatcctggagctgggaaaa ccaggagagttctttaggttcttgcggccgccctа
SEQ ID NO:6	Rearranged Ub/NS3 ZIKV (PRVABC59/2015 strain) amino acid sequence (translated from constructed ZIKV TCI-DNA vaccine in SEQ ID: NO:3) MQIFVKTLTGKTITLEVEPSDTIENVKAKIQDKEGIPPDQQRLIFAGKQLEDGRTLS DYNIQKESTLHLVLRLRGAQEWDFVVTTDISEMGANFKADRVIDSRRCLKPVILDGE RVILAGPMPVTHASAAQRRGRIGRNPNKPGDEYLYGGGCAETDEDHAHWLEARMLLD NIYLQDGLIASLYRPEADKVAAIEGEFKLRTEQRKTFVELMKRGDLPVWLAYQVASA GITYTDRRWCFDGTTNNTIMEDSVPAEVWTRHGEKRVLKPRWMDARVCSDHAALKSF KEFAAGKRPGAGKTRRVLPEIVREAIKTRLRTVILAPTRVVAAEMEEALRGLPVRYM TTAVNVTHSGTEIVDLMCHATFTSRLLQPIRVPNYNLYIMDEAHFTDPSSIAARGYI STRVEMGEAAAIFMTATPPGTRDAFPDSNSPIMDTEVEVPERAWSSGFDWVTDHSGK TVWFVPSVRNGNEIAACLTKAGKRVIQLSRKTFETEFQKTKHQEWDFVVTTDSGALW DVPAPKEVKKGETTDGVYRVMTRRLLGSTQVGVGVMQEGVFHTMWHVTKGSALRSGE GRLDPYWGDVKQDLVSYCGPWKLDAAWDGHSEVQLLAVPPGERARNIQTLPGIFKTK DGDIGAVALDYPAGTSGSPILDKCGRVIGLYGNGVVIKNGSYVSAITQGRREEETPV ECFEPSMLKKKQLTVLDLHPGAGKTRRVL
SEQ ID NO:7	Rearranged NS3 ZIKV (PRVABC59/2015 strain) amino acid sequence MGANFKADRVIDSRRCLKPVILDGERVILAGPMPVTHASAAQRRGRIGRNPNKPGDE YLYGGGCAETDEDHAHWLEARMLLDNIYLQDGLIASLYRPEADKVAAIEGEFKLRTE QRKTFVELMKRGDLPVWLAYQVASAGITYTDRRWCFDGTTNNTIMEDSVPAEVWTRH GEKRVLKPRWMDARVCSDHAALKSFKEFAAGKRPGAGKTRRVLPEIVREAIKTRLRT VILAPTRVVAAEMEEALRGLPVRYMTTAVNVTHSGTEIVDLMCHATFTSRLLQPIRV PNYNLYIMDEAHFTDPSSIAARGYISTRVEMGEAAAIFMTATPPGTRDAFPDSNSPI MDTEVEVPERAWSSGFDWVTDHSGKTVWFVPSVRNGNEIAACLTKAGKRVIQLSRKT FETEFQKTKHQEWDFVVTTDSGALWDVPAPKEVKKGETTDGVYRVMTRRLLGSTQVG VGVMQEGVFHTMWHVTKGSALRSGEGRLDPYWGDVKQDLVSYCGPWKLDAAWDGHSE VQLLAVPPGERARNIQTLPGIFKTKDGDIGAVALDYPAGTSGSPILDKCGRVIGLYG NGVVIKNGSYVSAITQGRREEETPVECFEPSMLKKKQLTVLDLHPGAGKTRRVL
SEQ ID NO:8	DENV-2 (V594 strain) NS3 protein wild-type amino acid sequence

	AGVLWDVPSPPPVGKAELEDGAYRIKQRGIFGYSQIGAGVYKEGTFHTMWHVTRG AVLMHRGKRIEPSWADVKKDLISYGGGWKLEGEWKEGEEVQVLALEPGKNPRAVQ TKPGLFKTNTGTIGAVSLDFSPGTSGSPIVDRKGKVVGLYGNGVVTRSGAYVSAI AQTEKSIEDNPEIEDDIFRKKRLTIMDLHPGAGKTKRYLPAIVREAIKRGLRTLI LAPTRVVAAEMEEALRGLPIRYQTPAIRAEHTGREIVDLMCHATFTMRLLSPVRV PNYNLIIMDEAHFTDPASIAARGYISTRVEMGEAAGIFMTATPPGSRDPFPQSNA PIMDEEREIPERSWNSGHEWVTDFKGKTVWFVPSIKAGNDIAACLRKNGKKVIQL SRKTFDSEYVKTRANDWDFVVTTDISEMGANFRAERVIDPRRCMKPVILTDGEER VILAGPMPVTHSSAAQRRGRIGRNPKNENDQYIYMGEPLENDEDCAHWKEAKMLL DNINTPEGIIPSMFEPEREKVDAIDGEYRLRGEARKTFVDLMRRGDLPVWLAYRV AAEGINYADRRWCFDGIKNNQILEENVEVEIWTKEGERKKLKPRWLDARIYSDPL ALKEFKEFAAGRK

EXAMPLES

Example 1. Design and characterization of a T cell-inducing ZIKV DNA (TCI-DNA) vaccine

[0045] Methods

[0046] *Construction of the vaccine plasmid.* ZIKV NS3 sequence (PRVABC59/2015 strain, GenBank: KX087101) (SEQ ID NO:1) was rearranged and an ubiquitin (Ub) sequence was added to the front of the rearranged NS3 (SEQ ID NO:5). Before this combined Ub/NS3 sequence, a Kozak sequence was placed in order to ensure efficient transcription of the plasmid. Upstream of the Kozak sequence, linker DNA as well as an *EcoRI* restriction site was placed to facilitate proper cloning of the gene segment into the vector of interest. Downstream of the rearranged Ub/NS3 gene sequence, a stop codon was placed along with linker DNA and a *NotI* restriction site. This nucleotide sequence was ordered through GeneArt® program (Thermo Fisher Scientific). The NS3 gene was delivered in a proprietary Thermo Fisher Scientific vector in a lyophilized form. Plasmid DNA was resuspended in molecular biology grade water to a concentration of approximately 200 ng/uL. DNA was digested with FastDigest™ (FD) *EcoRI* and *NotI* for 15 min in a 37°C heat block. The digested DNA was then loaded directly onto a 1% agarose gel and allowed to run for 40 min at 80V. The 2.2 kb Ub/NS3 DNA was exposed to 440 nm UV light in the imaging room and excised. The gel slice was placed into a clear, 1.5 mL microcentrifuge tube and the purified DNA was extracted using a QIAquick® Gel Extraction Kit. This gene fragment was stored in a -20°C freezer and the pVAX1 vector was digested with FD *EcoRI* and FD *NotI*, run on a gel, and extracted using the same kit. The Ub/NS3 gene fragment was ligated using a 3:1 ratio of insert DNA (Ub/NS3) to vector DNA (pVAX1) at room temperature in the presence of T4 DNA ligase.

[0047] *Bacterial transformation.* Previously-made, chemically competent DH5α *E. coli* were removed from -80°C freezer and thawed on ice for 25 min. Ligated Ub/NS3/pVAX1 was introduced to the *E. coli* and incubated on ice for 30 min. Heat shock transformation occurred

by placing the tube into a 42°C heat block for 45 sec and back on ice for 2 min. 1 mL of SOC media (super optimal broth with catabolite repression) was added to the *E. coli* and the transformed bacteria was grown in a shaking incubator at 37°C for 45 min. The *E. coli* was then spun down at 9,000 rpm for 2 min, resuspended in 200 µL SOC media, and streaked on an LB kanamycin (Kan^+) plate. Once dry, the plate was inverted and incubated overnight at 37°C. Colonies from the plate were inoculated into 2 mL LB Kan^+ media, and a miniprep was prepared using a QIAprep® Spin Miniprep Kit according to the manufacturer's instructions. Plasmids were subsequently re-digested with FD *EcoRI* and *NotI*. Upon observance of correct band digestion, the plasmid was sequenced for confirmation of correct insertion.

[0048] *Plasmid transfection.* 293T cells were cultured in Dulbecco's Modified Eagle Medium (DMEM) with 10% fetal bovine serum (FBS) and 1% penicillin/streptomycin. Cells were split upon reaching 90% confluence (every 2-3 days). Upon sufficient generation of 293T cells, 10 µg of Ub/NS3/pVAX1 plasmid was transfected into the cells using polyethylenimine (PEI) transfection reagent overnight. Media was removed the next morning and cells were cultured in DMEM. In some experiments, a proteasome inhibitor, MG132, was added to cell culture medium in a 1:1,000 ratio overnight at 12, 36, or 60 h after transfection.

[0049] *Quantitative reverse transcription PCR (qRT-PCR).* After 293T cells were transfected as described above, purification of total RNA was conducted using an RNeasy® mini Kit. First-strand cDNA was then synthesized using a GoScript™ Reverse Transcription System. In a PCR tube, the RNA harvested from transfected 293T cells was incubated with NS3-specific primers along with GAPDH primers (negative control) in a heat block at 70°C for 5 min. The tubes were immediately placed on ice for 10 min. The RNA/primer mix was mixed with GoScript™ Reverse Transcription mix in a 3:1 ratio for each reaction. The tubes were placed on a heat block at 25°C for 5 min, then placed on a heat block at 42°C for 1 h. Reverse transcriptase was inactivated by placing the tubes in a heat block at 70°C for 15 min. The qRT-PCR was conducted using iTaq™ Universal SYBR Green Supermix using NS3-specific primers as well as GAPDH specific primers (negative control). Fold induction was measured as $2^{-\Delta\Delta C}{}_T$.

[0050] *Western blot.* 293T cells were cultured, transfected, and treated with proteasome inhibitor as described above. After overnight treatment with 50 µM MG132, 293T cells were treated with 0.25% trypsin for 5 min at 37°C in 5% CO_2. 293T cells were resuspended in DMEM, centrifuged at 1,200 rpm for 5 min, and cell pellets were resuspended in RIPA (radioimmunoprecipitation assay) buffer with freshly added proteinase inhibitor. Total protein concentration was calculated via Bradford Assay and 6x SDS loading buffer was added to 20 µg of total protein. Protein was denatured at 100°C for 10 min and then placed on ice for 2-3

min. Proteins were run on a 12% polyacrylamide gel for 20 min at 80V and for 40 minutes at 120V, or until the dye line reached the bottom of the gel. Bands from the polyacrylamide gel were transferred to a nitrocellulose membrane using an iBlot™ Gel Transfer Device. The membrane was blocked in 5% blocking buffer (5% non-fat milk in PBS) for 1 h and the membrane was washed in PBS-Tween 20 (PBS-T) and blocked in 5% blocking buffer containing a 1:1,000 dilution of anti-ZIKV NS3 antibody overnight. The next day, the membrane was washed with PBS-T for 20 min and blocked in 5% blocking buffer with secondary horseradish peroxidase (HRP)-conjugated goat anti-rabbit antibody for 1 h. The membrane was then washed in PBS-T for 20 min, and then exposed to 10 mL chemiluminescent substrate for 3 min devoid of light. Proteins were visualized using a FluorChem™ E system.

[0051] Results

[0052] T cell-inducing ZIKV vaccine (TCI-DNA) design and characterization.

[0053] A predictive epitope analysis found that all $CD8^+$ T-cell epitopes on the NS3 amino acid sequence were conserved across 54 different ZIKV genomes. Normally, the NS3 protein is covalently bonded to NS2B, an anchor protein which functions as a cofactor to promote the productive folding and activity of NS3. The N-terminal region of the NS3 protein encodes for a serine protease, while the latter region encodes for a helicase. This NS2B-NS3pro complex is responsible for the cleavage of the ZIKV polyprotein precursor and generation of the other proteins in the ZIKV viral genome. As the NS3 protein is essential for the function of every other ZIKV viral protein, and its $CD8^+$ T-cell epitopes are conserved across 54 different ZIKV genomes, this protein serves as an attractive target. Thus, a unique TCI-DNA ZIKV vaccine was constructed using ZIKV NS3 as the target protein.

[0054] First, the NS3 gene (PRVABC59/2015 strain of ZIKV in *Homo sapiens*) was split into three parts which were rearranged (FIG. 1A) in order to disrupt NS3's viral functions. Furthermore, this rearrangement may produce an unstable protein which will be likely targeted to the proteasome for degradation. In constructing this sequence, the 30 nucleotide bases before and after all nominal break points were included to preserve any CTL epitopes that might otherwise have been disrupted. The open reading frame (ORF) encoding for a mouse/human monomer of ubiquitin (Ub) was placed immediately upstream the rearranged NS3 DNA sequence. A glycine codon at the 76^{th} residue was modified to encode an alanine in order to enhance the stability of the Ub/NS3 complex (FIG. 1A), which may promote protein degradation in the proteasome. In order to ensure efficient transcription, a Kozak sequence was placed upstream of this combined Ub/NS3 sequence. The rearranged Ub/NS3 sequence

was inserted into pVAX1, an FDA approved vector for the use in DNA vaccines in humans. This construct is the ZIKV TCI-DNA vaccine used in the subsequent experiments.

[0055] To determine expression of the rearranged NS3, the plasmid DNA was used to transfect 293T cells. RNA was isolated and RNA reverse transcription was conducted. qRT-PCR was conducted using primers specific to the Ub/NS3 sequence. NS3 gene transcription was confirmed (FIG. 2A). The expression of NS3 protein was further determined (FIG. 2B). Visualizing a protein that is innately ubiquitinated can be problematic. Many proteins are targeted for degradation by covalent ligation to Ub. Therefore, any protein that is ubiquitinated is targeted for immediate destruction. To address this issue, a proteasome inhibitor MG132 was used in cultures to preserve the ubiquitinated protein.

[0056] 293T cells were transfected overnight with the plasmid DNA delivered in PEI transfection reagents. The 293T cells were allowed to stably express the transfected protein for 36 or 60 hours. After this period, cells were treated with 50 μM MG132 overnight. A Western blot was then run to determine the production of the rearranged Ub/NS3 (FIG. 1B and C). In both un-transfected protein lanes, no Ub/NS3 protein was shown. Of the triplicate experiments shown in FIG. 1B, however, only one of the three shows faint protein bands in the transfected cell lanes without MG132 treatment. In the cells with MG132 treatment, the Ub/NS3 protein was clearly evident (FIG. 1B).

Example 2. The ZIKV TCI-DNA vaccine protected female pregnant BALB/c mice and their fetuses against ZIKV challenge

[0057] Methods

[0058] *Immunization of BALB/c mice with ZIKV vaccines.* BALB/c mice were immunized with ZIKV TCI-DNA vaccine or control vaccines (ZIKV full-length E protein or EDI/EDII mixed peptides (equal concentrations of the five peptides in Table 2)). Briefly, female BALB/c mice (4-weeks old) were intramuscularly (i.m.) immunized with ZIKV full-length E protein (10 μg/mouse) or EDI/EDII mixed peptides (50 μg/mouse) in the presence of aluminum hydroxide (hereinafter Alum; 500 μg/mouse) and monophosphoryl lipid A (MPL; 10 μg/mouse) adjuvants, or with TCI-DNA (10 μg/mouse) in the presence of imiquimod adjuvant (20 μg//mouse). Mice injected with PBS were included as a control. The immunized mice were boosted once at three weeks, and sera were collected 10 days post-boost to detect IgG antibodies by ELISA, neutralizing antibodies by plaque reduction neutralization assay (PRNT), and antibody-dependent enhancement (ADE) (see Example 4). The immunized BALB/c mice were processed for subsequent ZIKV challenge experiments (as described below).

Table 2. ZIKV EDI/II mixed peptides control

Peptide name	Sequence	SEQ ID NO.
1	IGVSNRDFVEGMSGG	9
2	TWVDVVLEHGGCVTV	10
3	MAQDKPTVDIELVTT	11
4	VDRGWGNGCGLFGKG	12
5	VVLGSQEGAVHTALA	13

[0059] *Challenge of pregnant BALB/c mice with ZIKV.* Ten days post-last dose of ZIKV TCI-DNA vaccine, control vaccines (full-length E protein and EDI/EDII mixed peptides) and PBS control, the immunized female BALB/c mice were mated with naïve male BALB/c mice. The pregnant mice (embryonic day E5-E7) were injected with anti-IFNAR1 blocking mAb (MAR1-5A3, 2 mg/mouse), and 24 h later, they were challenged intraperitoneally (I.P.) with ZIKV (strain R103451), 2×10^5 PFU/mouse). Six days post-infection (p.i.), placenta and amniotic fluid were collected for analysis of viral titers (as described below), and uteri were collected for analysis of morphological changes.

[0060] *ZIKV plaque-forming assay.* Viral titers in the ZIKV-challenged mice were measured by plaque-forming assay. Briefly, sera, amniotic fluid, and tissue lysates of ZIKV-challenged mice were serially diluted and transferred to Vero E6 cells, which were cultured at 37°C for 1 h. The cells were further overlaid with DMEM containing 1% carboxymethyl cellulose and 2% FBS, and cultured at 37°C for 4-5 days, followed by staining of plaques with crystal violet (0.5%). ZIKV titers were calculated using the CalcuSyn computer program, and expressed as PFU/g or PFU/ml of test samples.

[0061] Results

[0062] ZIKV TCI-DNA vaccine protected female pregnant BALB/c mice and their fetuses against ZIKV challenge.

[0063] To investigate the efficacy of the ZIKV TCI-DNA vaccine in protecting pregnant mothers and their fetuses against ZIKV infection, this vaccine was evaluated in immunocompetent mice. Immunocompromised mice, such as IFN-α/β receptor (IFNAR)-knockout mice, may have a reduced ability to generate CTLs. Immunocompetent female BALB/c mice (non-lethal to ZIKV infection) were immunized with the TCI-DNA vaccine in the presence of imiquimod adjuvant (an agonist for toll-like receptor 7 (TLR7)), or with ZIKV full-length E protein or EDI/II mixed peptides in the presence of Alum and MPL adjuvants, or PBS as controls. The full-length E protein is expected to induce E protein-specific antibodies which

may result in ADE. The full-length E protein used as a control (Aviva Systems Biology) should be recognized by B cells and be processed in antigen-presenting cells for presentation to $CD4^+$ and $CD8^+$ T cells. The EDI/II mixed peptides control is made up of long peptides containing MHC class I-restricted epitopes including H-2, D^b, K^b, and K^d-restricted epitopes (no MHC class II-restricted epitopes) are expected to induce only CTLs but are less immunogenic than the ZIKV TCI-DNA vaccine. Ten days after the second immunization, the female mice were mated with males. The pregnant female mice (E5-E7) were injected with anti-IFNAR1 antibody (to make the mice susceptible to ZIKV by blocking IFN-α/β receptors). One day later, the mice were challenged with a high-dose of ZIKV (R103451, 2×10^5 PFU), and examined for morphological changes in uteri 6 days after. Mouse placenta and amniotic fluid were also evaluated for ZIKV titers via plaque-forming assay.

[0064] The uteri (E11-E13) from TCI-DNA and full-length E protein-immunized pregnant BALB/C mice exhibited normal morphology without obvious fetal death, indicating complete protection against uterine damage and fetal death. In contrast, EDI/II peptide or PBS-injected pregnant mice had either slightly or severely damaged uteri with reduced size, indicating fetal death and incomplete protection against ZIKV infection (FIG. 3A). Investigation of viral titers in ZIKV-infected placenta and amniotic fluid revealed undetectable, or significantly lower titers of ZIKV in placenta (FIG. 3B) and amniotic fluid (FIG. 3C) of mice receiving the TCI-DNA vaccine, than in those of mice receiving full-length E protein, EDI/II mixed peptides, or PBS. In addition, there were significant, but slightly lower, viral titers in the placenta of mice immunized with full-length E protein than in those of mice injected with PBS (FIG. 3B). Collectively, these results suggest that the TCI-DNA vaccine completely protected immunocompetent pregnant mice and their fetuses against high-dose challenge of ZIKV R103451, a strain responsible for recent ZIKV outbreaks in humans.

Example 3. The ZIKV TCI-DNA vaccine protected ZIKV-susceptible adult or pregnant *Ifnar1*$^{-/-}$ mice and their fetuses against two divergent strains of ZIKV challenge

[0065] Materials and Methods

[0066] *Immunization of Ifnar1*$^{-/-}$ *mice with ZIKV vaccine. Ifnar1*$^{-/-}$ mice were immunized with the ZIKV TCI-DNA vaccine or control vaccines (ZIKV full-length E protein and EDI/EDII mixed peptides) using a similar protocol as described for BALB/c mice (see in Example 2). Briefly, female *Ifnar1*$^{-/-}$ (4-week old), or mixed-sex *Ifnar1*$^{-/-}$ (3 female and 3 male, 5-6-week old) mice were i.m. immunized with ZIKV full-length E protein (10 μg/mouse) or EDI/EDII mixed peptides (50 μg/mouse) in the presence of alum (500 μg/mouse) and MPL (10 μg/mouse) adjuvants, or with the ZIKV TCI-DNA (10 μg/mouse) in the presence of imiquimod adjuvant (20 μg/mouse). Mice injected with PBS were included as a control. The immunized mice were

boosted once at three weeks, and sera was collected 10 days post-boost for detection of IgG antibodies, neutralizing antibodies, and ADE (see Example 4). The immunized mice were further challenged with ZIKV as described below.

[0067] *ZIKV challenge studies and evaluation of vaccine efficacy in Ifnar1$^{-/-}$ mice.* The following experiments were designed to evaluate the efficacy of the ZIKV TCI-DNA vaccine and control vaccines (ZIKV full-length E protein and EDI/EDII mixed peptides) in the immunized *Ifnar1*$^{-/-}$ mice.

[0068] (1) At 13 days post-last dose of the afore-mentioned vaccines or PBS control, *Ifnar1*$^{-/-}$ mice (male and female) were challenged (I.P.) with ZIKV (human strain R103451; 10^3 PFU; 200 µl/mouse), and investigated for survival and weight daily for 14 days.

[0069] (2) Immunized *Ifnar1*$^{-/-}$ mice were challenged (I.P.) with ZIKV (human strain PAN2016, 10^3 PFU/mouse; 200 µl/mouse) as in (1), and 6 days later, sera and tissues were collected for measurement of viral titers by plaque-forming assay (see Example 2).

[0070] (3) Ten days post-last dose of the ZIKV TCI-DNA vaccine, control vaccines, or PBS control, female *Ifnar1*$^{-/-}$ mice were mated with naïve male *Ifnar1*$^{-/-}$ mice. The pregnant *Ifnar1*$^{-/-}$ mice (E10-E12) were challenged (I.P.) with ZIKV (strain R103451, 10^4 PFU/mouse). Six days p.i., sera and tissues of adult mice, as well as placenta, amniotic fluid, and fetal brain, were collected for measurement of viral titers by plaque-forming assay, and uteri and fetuses were collected for analysis of morphological changes. Since *Ifnar1*$^{-/-}$ mice are susceptible to ZIKV infection, all ZIKV-challenged *Ifnar1*$^{-/-}$ mice with greater than 25% weight loss and significant clinical symptoms were humanely euthanized.

[0071] Results

[0072] ZIKV TCI-DNA vaccine protected ZIKV-susceptible adult or pregnant *Ifnar1*$^{-/-}$ mice and their fetuses against two divergent strains of ZIKV challenge

[0073] Because there is no disease pathology in wild-type (BALB/c) adult mice challenged with the ZIKV, a lethal mouse model was used to test the efficacy of the ZIKV TCI-DNA vaccine. Thus, *Ifnar1*$^{-/-}$ mice, an IFNAR-deficient mouse model in which ZIKV infection is lethal, were immunized with the ZIKV TCI-DNA vaccine, control vaccines (ZIKV full-length E protein or EDI/II mixed peptides), or PBS control, as described above, and the following three challenge experiments were performed.

[0074] First, immunized adult (male and female) *Ifnar1*$^{-/-}$ mice were challenged with ZIKV (strain R103451, 10^3 PFU) 10 days post-last vaccine dose, and monitored for their weight and survival changes for 14 days. The result showed that mice immunized with TCI-DNA vaccine exhibited only slight weight loss during days 7-9 post-challenge, followed by constantly

increased weight until 14 days (FIG. 4A), and that all mice from this group survived the ZIKV challenge (FIG. 4B). However, the mice immunized with full-length E protein or EDI/II peptides showed reduced survival rates (to about 83% and 50%, respectively) and their weight either slightly or moderately decreased (FIG. 4A-B). In contrast, mice injected with PBS had continuously decreased weight and all mice died within 8 days post-challenge (FIG. 4A-B). These data confirm complete protection by the TCI-DNA vaccine against ZIKV-caused death and weight loss.

[0075] Second, a cohort of immunized adult (male and female) *Ifnar1*$^{-/-}$ mice were challenged with ZIKV PAN2016 (10^3 PFU/mouse), another strain causing human ZIKV disease, and ZIKV titers were measured in sera and tissues via plaque-forming assay 6 days later. There were undetectable viral titers in the lung, muscle, and testis of mice immunized with the TCI-DNA vaccine, and viral titers in the sera and other tissues of these mice were also significantly lower than in those of mice immunized with full-length E, EDI/II mixed peptides, or PBS (for heart, liver, and spleen), or with EDI/II mixed peptides or PBS (for sera, brain, and kidney) (FIG. 4C). In addition, ZIKV titers in sera, brain, kidney, lung, spleen, muscle, or testis of mice receiving full-length E protein and/or EDI/II peptides were also significantly lower than in those of mice injected with PBS (FIG. 4C). These data indicate that although full-length ZIKV E protein or EDI/II mixed peptides may protect *Ifnar1*$^{-/-}$ mice against ZIKV challenge achieving reduced viral titers, the TCI-DNA vaccine significantly enhanced this protection, resulting in undetectable or significantly decreased viremia and viral titers in key organs, including reproductive organs, such as testis.

[0076] Third, a cohort of TCI-DNA vaccine-immunized female *Ifnar1*$^{-/-}$ mice were mated with male *Ifnar1*$^{-/-}$ mice (unimmunized) and the pregnant mice (E5-E7) were challenged with ZIKV (strain R103451; 10^4 PFU/mouse). The mice were then examined for morphological changes in uteri and fetuses, as well as viral titers in sera, amniotic fluid, fetal brain, and tissues at 6 days post-challenge. The uteri from TCI-DNA-immunized pregnant *Ifnar1*$^{-/-}$ mice had intact morphology and normal fetuses without demise, whereas the uteri from mice immunized with full-length E protein or EDI/II mixed peptides, or injected with PBS, exhibited slight or severe damage, with moderate and severe fetal resorption or fetal death in utero, respectively (FIG. 5A-B). Importantly, viral titers in the placenta and fetal brain (FIG. 5C), sera and amniotic fluid (FIG. 5D) of mice receiving TCI-DNA vaccine were either undetectable, or significantly lower than in those of mice receiving full-length E, EDI/II mixed peptides, or PBS. Also, there were significantly lower titers of ZIKV in the placenta, amniotic fluid, and fetal brain of mice immunized with full-length E protein and EDI/II mixed peptides than in those of mice injected with PBS (FIG. 5C-D). Notably, ZIKV titers in the muscle, brain, heart, liver, and

spleen of mice immunized with TCI-DNA were undetectable, or significantly lower than in those of mice immunized with full-length E, EDI/II mixed peptides, or PBS, and viral titers in the sera and kidney of TCI-DNA-immunized mice were also significantly lower than in those of mice receiving EDI/II mixed peptides or PBS (FIG. 5E). Moreover, the results also denoted significantly lower viral titers in the sera and tissues (kidney, heart, liver, spleen, and muscle) of mice vaccinated with full-length E and/or EDI/II mixed peptides than in those of mice injected with PBS (FIG. 5E).

[0077] Collectively, the above data indicate partial protection by immunization with full-length E protein or EDI/II mixed peptides against ZIKV challenge, and that the TCI-DNA vaccine completely protected adult or pregnant *Ifnar1*$^{-/-}$ mice and their fetuses against two divergent strains of ZIKV infection.

Example 4. The ZIKV TCI-DNA vaccine prevented ZIKV-caused apoptosis, vascular damage and inflammation, and ZIKV-associated ADE

[0078] Methods

[0079] *ELISA.* ZIKV-, E-, or NS3-specific IgG antibodies were assayed by ELISA in the sera of above immunized BALB/c and *Ifnar1*$^{-/-}$ mice (see Examples 2 and 3). Briefly, ELISA plates were pre-coated with ZIKV full-length E protein (1 μg/ml), NS3 peptides (Table 3), or ZIKV (strain R103451)-infected Vero E6 cell lysates at 4°C overnight and blocked with PBS-T containing 2% non-fat milk at 37°C for 2 h. After three washes with PBS-T, the plates were then sequentially incubated at 37°C for 1 h with serially-diluted mouse sera and HRP-conjugated anti-mouse IgG-Fab antibody (1:5,000). The substrate 3,3',5,5'-tetramethylbenzidine was added to the plates, and the reaction was stopped after addition of 1N H_2SO_4. Absorbance at 450 nm (A_{450}) was measured using ELISA plate reader.

Table 3. ZIKV NS3 overlapping peptides used for stimulation of $CD8^+$ T cell responses and IgG antibody detection

Peptide name	Sequence	SEQ ID NO.
1	AETDEDHAHWLEARM	14
2	HAHWLEARMLLDNIY	15
3	ARMLLDNIYLQDGLI	16
4	NIYLQDGLIASLYRP	17
5	GLIASLYRPEADKVA	18
6	YRPEADKVAAIEGEF	19
7	KVAAIEGEFKLRTEQ	20
8	GEFKLRTEQRKTFVE	21

9	TEQRKTFVELMKRGD	22
10	FVELMKRGDLPV	23

[0080] *PRNT assay.* This assay was performed to detect neutralizing antibodies in the immunized mouse sera (see Examples 2 and 3). Briefly, ZIKV (strain R103451, 100 PFU/mouse) was incubated with 2-fold serially-diluted immunized mouse sera at 37°C for 1.5 h, which was added to Vero E6 cells and the cells cultured at 37°C for 1 h. The cells were then overlaid with DMEM containing 1% carboxymethyl cellulose and 2% FBS, and cultured at 37°C for 4-5 days, followed by staining with crystal violet (0.5%). PRNT titers ($PRNT_{50}$) were calculated based on 2-fold serial dilutions of individual mouse serum at 50% plaque reduction using the CalcuSyn computer program.

[0081] *In vitro ADE assay*. ADE potentially induced by the immunized mouse serum antibodies (see Examples 2 and 3) was measured in K562 cells using a flow cytometry-based assay. Briefly, 100 PFU of ZIKV (strain R103451) was mixed with sera at 4-fold serial dilutions, and incubated at 37°C for 1 h. The virus-serum mixture was then added to K562 cells (5×10^4/well), and incubated at 37°C for 2 h in DMEM containing 10% FBS and 1% penicillin/streptomycin, followed by washing the cells with fresh DMEM, and culturing them for 3 days. The cells were then fixed, permeabilized, and sequentially stained with mouse anti-flavivirus 4G2 mAb (2 μg/ml) and FITC-conjugated anti-mouse antibody (1:100). The percent of infected cells was calculated based on the fluorescence signals in the presence or absence of serially diluted mouse sera.

[0082] *Immunofluorescence staining.* Maternal placental tissues harvested from the ZIKV-challenged pregnant *Ifnar1*$^{-/-}$ mice (see Example 3) were fixed in 4% paraformaldehyde, which were further embedded in paraffin and sectioned. For vimentin staining, deparaffinized tissue slides were blocked with 2% BSA for 30 min at room temperature, and then sequentially incubated with ZIKV envelope domain III (EDIII)-specific human mAb (ZV-64, 1:200) and rabbit anti-vimentin antibody (1:300). For caspase-3 staining, the tissue slides were fixed and permeabilized with FIX and PERM™ Cell Permeabilization Kit, before being blocked as described above and incubated sequentially with ZV-64 and rabbit anti-active caspase-3 antibodies (1:200). The slides were washed with PBS, and incubated for 1 h at room temperature with anti-human FITC (for ZIKV)- or anti-rabbit Alexa Fluor® 647 (1:300; for vimentin and caspase-3)-conjugated antibodies, which were counter-stained for nuclei for 5 min with DAPI (4′,6-diamidino-2-phenylindole, 300 nM), and mounted in a mounting medium (VectaMount Permanent). The stained slides were imaged on a confocal microscope, and

prepared for images using ZEN software. The fluorescence signals were quantified by ImageJ software for relative intensity (particle analysis).

[0083] *Detection of inflammatory cytokines and chemokines.* Maternal placental tissues collected from the ZIKV-challenged pregnant *Ifnar1*$^{-/-}$ mice (see Example 3) were measured for inflammatory cytokines and chemokines using Mouse Inflammatory Cytokines Multi-Analyte ELISArray Kit and Mouse Common Chemokines Multi-Analyte ELISArray Kit. Briefly, ELISA plates were pre-coated with cytokine or chemokine capture antibodies, followed by incubation with tissue lysates for 2 h at room temperature. After three washes, the plates were sequentially incubated with detection antibody for 1 h, and avidin-HRP conjugates for 30 min at room temperature, followed by incubation with development and stop solutions, respectively. A_{450} value was measured using ELISA plate reader.

[0084] Results

[0085] ZIKV TCI-DNA vaccine prevented ZIKV-caused apoptosis, vascular damage and inflammation, and ZIKV-associated ADE

[0086] ZIKV infection may cause apoptosis and fetal blood vessel damage in placenta, leading to severe inflammation with increased cytokines and chemokines. ZIKV E protein, including the fusion loop (FP) region, may induce cross-reactive antibodies that enhance ZIKV or DENV infection, resulting in ADE.

[0087] To evaluate whether the ZIKV TCI-DNA vaccine can prevent apoptosis and vascular damage associated with ZIKV, placental tissues of vaccine-immunized and ZIKV-challenged pregnant *Ifnar1*$^{-/-}$ mice (as described above) were immunofluoresent stained for active caspase-3, an apoptotic marker, and vimentin, a marker for fetal blood vessels and fetal capillary endothelium. There were significantly lower numbers of caspase-3^{+} and ZIKV^{+} signals in the placenta of mice immunized with TCI-DNA vaccine than in those of mice immunized with full-length E, EDI/II, or PBS (FIG. 6A-C), suggesting nearly no ZIKV-associated cell death in the TCI-DNA-immunized mouse placenta. However, there was moderate to strong staining of caspase-3 and ZIKV in the placenta from other vaccine groups (full-length E and EDI/II) or PBS control (FIG. 6A-C), illustrating that full-length E or EDI/II may not fully prevent ZIKV- related cell death. In contrast, there was strong staining for vimentin in the placenta of mice immunized with TCI-DNA (FIG. 7A), with significantly higher numbers of vimentin^{+} signals than those of mice receiving other vaccines or PBS (FIG. 7B-C), suggesting intact vasculature in the TCI-DNA-vaccinated mouse placenta, but partially or completely damaged vasculature in the placenta of other groups.

[0088] To determine whether the ZIKV TCI-DNA vaccine can prevent ZIKV-caused inflammation, inflammatory cytokines and chemokines were measured in the placenta of immunized and ZIKV-infected pregnant *Ifnar1*$^{-/-}$ mice using Multi-Analyte ELISArray kits. Significantly lower level of cytokines (IL-1α, IL-1β, IL-6, IL-10, G-CSF, and GM-CSF) (FIG. 8A) and chemokines (MCP-1, SDF-1, IP-10, MIG, Eotaxin, KC, and 6Ckine) (FIG. 8B) were identified in the TCI-DNA-immunized mouse placenta than in the placenta of mice immunized with EDI/II mixed peptides, and/or full-length E or PBS. In addition, the level of these cytokines and chemokines in the full-length E-immunized mouse placenta was also significantly lower than in the placenta of mice injected with PBS and/or EDI/II mixed peptides. These results indicate improved capacity of full-length E protein in preventing the inflammation than EDI/DII peptides, but TCI-DNA was the most effective in preventing ZIKV-associated inflammation.

[0089] To investigate whether the ZIKV TCI-DNA vaccine induces ZIKV-specific antibodies and if so, whether these antibodies can cause ZIKV-associated ADE, ZIKV antibodies were measured by ELISA and plaque-forming neutralization assay, and tested for ADE *in vitro* using immunized sera of BALB/c (FIG. 9A-E) and *Ifnar1*$^{-/-}$ (FIG. 10A-E) mice. No, or very low levels, of IgG antibodies were detected against ZIKV E protein, NS3 peptides, and/or ZIKV lysates in the sera of mice immunized with TCI-DNA (FIG. 9A-C, 10A-C) and there were no neutralizing antibodies detected against ZIKV in these sera (FIG. 9D, 10D). Moreover, similar to the sera collected from PBS-injected mice, TCI-DNA-immunized mouse sera did not exhibit any ADE (FIG. 9E, 10E). In contrast, ZIKV full-length E protein elicited high-level E- and ZIKV-specific IgG antibodies with neutralizing activity against ZIKV infection, exhibiting strong ADE of ZIKV infection (FIG. 9 and 10). However, the ADE only showed up when the sera was diluted so that the neutralizing activity was gone. These data demonstrate that unlike ZIKV full-length E protein, TCI-DNA did not induce ZIKV E-specific antibodies, but only elicited very weak NS3-specific antibody responses, eliminating the possibility to cause ZIKV-associated ADE.

[0090] Collectively, the above results confirm that the ZIKV TCI-DNA vaccine demonstrated the ability to prevent ZIKV-associated apoptosis, vascular damage, and inflammation, without leading to ADE.

Example 5. The ZIKV TCI-DNA vaccine-induced CD8$^+$ T cells play a key role in protecting pregnant mice and their fetuses against ZIKV infection

[0091] Methods

[0092] *Immunization of BALB/c mice with vaccines, depletion of CD8$^+$ T cells, and challenge of pregnant BALB/c mice with ZIKV.* Female BALB/c mice (8-10-week old) were immunized with TCI-DNA vaccine (10 μg/mouse) and imiquimod adjuvant, or PBS (control), and boosted

once at 3 weeks. Ten days post-last dose, female BALB/c mice were mated with naïve male BALB/c mice for pregnancy. The pregnant mice (E10-E12) were injected (I.P.) with or without anti-CD8a IgG2a mAb (200 µg/mouse, for TCI-DNA) or IgG2a isotype control mAb (for PBS) at -2, -1, and 3 days post-ZIKV challenge (described below), and peripheral blood cells (collected at 6 h before infection and 3 days p.i.) and splenocytes (collected at 6 days p.i.) were evaluated for $CD8^+$ T cell depletion by flow cytometry analysis (described below). The pregnant mice (with or without $CD8^+$ depletion) were also injected with anti-IFNAR1 blocking mAb (MAR1-5A3, 2 mg/mouse), and 24 h later, they were (I.P.) challenged with ZIKV (strain R103451, 2×10^5 PFU/mouse). Sera (collected 3 and 6 days p.i.) and tissues (placenta, amniotic fluid, and fetal brain collected 6 days p.i.) were assayed for viral titers by plaque-forming assay, fetuses and uteri (collected 6 days p.i.) were observed for morphological analysis, and splenocytes (collected 6 days p.i.) were assayed for ZIKV-specific $CD8^+$ T cell responses by flow cytometry analysis, as described below.

[0093] *Flow cytometry.* Flow cytometry analysis was performed to evaluate $CD8^+$ cell depletion and ZIKV-specific $CD8^+$ T cell responses in the challenged mice. For analysis of $CD8^+$ depletion in whole blood and splenocytes, peripheral blood cells (collected at 6 h before infection and 3 days p.i.) and splenocytes (collected at 6 days p.i.) were treated with 1× Red Blood Cell Lysis Buffer, and stained with PerCP-Cy5.5 anti-mouse CD8a mAb, followed by flow cytometry analysis using BD LSRFortessa 4 system. For analysis of ZIKV-specific $CD8^+$ T cell responses, the above-treated splenocytes (2×10^6 cells/well) were incubated with ZIKV NS3 overlapping peptides (0.25 nM/peptide, final concentration 5 µg/ml; equal concentrations of each of the peptides in Table 3) in the presence of 5 µg/ml brefeldin A, and cultured at 37°C for 5 h. After stimulation, the cells were washed with PBS and stained for surface marker using PerCP/Cy5.5 anti-mouse CD8a. After fixation and permeabilization, the cells were stained for intracellular markers using FITC anti-mouse IL-2, PE anti-mouse IFN-γ, and Brilliant Violet 421™ anti-mouse TNF-α mAbs, followed by analysis using flow cytometry as described above.

[0094] Results

[0095] ZIKV TCI-DNA vaccine-induced $CD8^+$ T cells play a key role in protecting pregnant mice and their fetuses against ZIKV infection

[0096] Since ZIKV TCI-DNA induced very low to no antibody responses, we determined whether the T cell responses elicited by this vaccine were essential in protecting against ZIKV infection. Therefore, two experiments were conducted.

[0097] First, immunocompetent male and female BALB/c mice were immunized with TCI-DNA or PBS control, and then their $CD4^+$ and $CD8^+$ T cells were depleted, respectively (using anti-CD4 or anti-CD8a antibody), followed by ZIKV challenge. There were minimal numbers of $CD4^+$ or $CD8^+$ T cells in the peripheral blood cells (FIG. 11A) and splenoctyes (FIG. 11B) of anti-CD4- or anti-CD8a-treated, TCI-DNA or PBS-immunized mice as compared to those of mice treated with isotype antibody control (FIG. 11A-B), confirming complete depletion of $CD4^+$ or $CD8^+$ T cells in these mice. Compared to PBS control, the mice immunized with TCI-DNA vaccine have significantly more $CD8^+$ T cells as seen in the mice receiving anti-CD4 or isotype control antibody (no $CD8^+$ T cell depletion) (FIG. 11A-B). In contrast, the mice immunized with TCI-DNA have similar numbers of $CD4^+$ T cells as control mice as seen in the mice receiving anti-CD8a or isotype control antibody (no $CD4^+$ T cell depletion) (FIG. 11A-B). In addition, high viral titers were detected in the sera and tissues (lung, eye, and muscle) of mice immunized with TCI-DNA vaccine and $CD8^+$ T cells depleted, which were significantly higher than those of TCI-DNA-immunized mice injected with anti-CD4 or isotype control antibody (no $CD8^+$ T cell depletion) (FIG. 11C). In contrast, there were no significant differences of viral titers in the mice immunized with TCI-DNA and received either anti-CD4 ($CD4^+$ T cell depletion) or isotype control antibody (FIG. 11A-C). These data suggest that $CD8^+$ T cells in TCI-DNA-immunized adult mice are essential in prevention of ZIKV infection.

[0098] Second, $CD8^+$ T cells were evaluated by flow cytometry analysis in the whole blood of mice 6 h before and 3 days after ZIKV challenge. There were minimal numbers of $CD8^+$ T cells in the peripheral blood cells of anti-CD8a-treated TCI-DNA or PBS-immunized mice as compared to those of mice treated with isotype antibody control (not shown), confirming complete depletion of $CD8^+$ T cells in these mice when they were challenged with ZIKV. In the mice immunized with TCI DNA vaccine, significantly damaged uteri and severe fetal demise were found in the mice with $CD8^+$ T cells depleted, whereas intact uteri and fetuses without any damage were found in the mice injected with isotype control antibody (no $CD8^+$ T cell depletion) (FIG. 12A). The mice receiving PBS and injected with anti-CD8a or isotype control antibody exhibited different degrees of uterine damage and/or fetal death (FIG. 12A-B). In addition, $CD8^+$ T cell depletion leads to significantly increased ZIKV titers in the placenta, amniotic fluid, and fetal brain (FIG. 13A-C), as well as in day-3 or day-6 post-infection (p.i.) sera (FIG. 13D-E) in the TCI-DNA-immunized pregnant mice and their fetuses. These data showed enhanced infection of TCI-DNA-vaccinated pregnant mice to ZIKV after their $CD8^+$ T cells were depleted.

[0099] ZIKV-specific $CD8^+$ T cell responses were also evaluated using flow cytometry analysis in the TCI-DNA-immunized and ZIKV-challenged mice without $CD8^+$ T cell depletion

(i.e., mice receiving isotype antibody). Splenocytes were isolated from these mice 6 days post-challenge, and stimulated with ZIKV NS3 overlapping peptides (Table 3). Remarkably, the TCI-DNA vaccine elicited ZIKV-specific $CD8^+$ T cell responses in the mice (FIG. 14A), exhibiting high-level secretion of IL-2, IFN-γ and TNF-α cytokines. However, splenocytes from mice immunized with the PBS control only induced background levels of these cytokines (FIG. 14B).

[0100] Collectively, the above data demonstrate that the ZIKV TCI-DNA vaccine-induced $CD8^+$ T cell responses play an essential role in protecting pregnant mice and their fetuses against ZIKV-associated fetal death and viral infection.

Example 6. The ZIKV TCI-DNA vaccine cross-protected against dengue virus (DENV) infection

[0101] Methods

[0102] *Challenge of vaccine-immunized Ifnar1$^{-/-}$ mice with DENV.* *Ifnar1$^{-/-}$* mice (male and female) were immunized with the ZIKV TCI-DNA vaccine, control vaccines (ZIKV full-length E protein and EDI/EDII mixed peptides), or PBS control, and boosted once at 3 weeks (as described in Example 3). At 13 days post-last dose of immunization, *Ifnar1$^{-/-}$* mice were challenged (I.P.) with ZIKV (human strain R103451; 10^3 PFU; 200 µl/mouse), and investigated for survival and weight daily for 14 days. The surviving mice in each group were further challenged (I.P.) with DENV-2 (human strain V594, 2×10^6 PFU; 200 µl/mouse). Three days p.i., sera and tissues were collected for detection of viral titers by plaque-forming assay (as described below). Naïve *Ifnar1$^{-/-}$* mice were included as a mock control in the DENV-2 challenge studies.

[0103] *DENV plaque-forming assay.* Viral titers in the above DENV-2 (strain V594)-challenged *Ifnar1$^{-/-}$* mice were measured by DENV plaque-forming assay. This assay was similar to ZIKV plaque-forming assay (see Example 2), except that LLC-MK2 cells were used for DENV-2 infection. DENV titers were calculated using the CalcuSyn computer program, and expressed as PFU/g or PFU/ml of test samples.

[0104] Results

[0105] ZIKV TCI-DNA vaccine cross-protected against DENV infection, leading to significantly reduced viral titers

[0106] ZIKV and DENV belong to the same genus, and their NS3 regions contain high levels of homology. To explore the potential of the ZIKV TCI-DNA vaccine to induce cross-protection against DENV infection, male and female *Ifnar1$^{-/-}$* mice, which were immunized with TCI-DNA or control vaccines (i.e., full-length E or EDI/EDII mixed peptides) and survived ZIKV challenge

(as described above), were further challenged with DENV-2 (strain V594, 2×10^6 PFU), and DENV titers were measured in the sera and tissues of mice 3 days post-challenge. There were lower, or significantly lower, titers of DENV in the TCI-DNA-immunized mouse sera and other tissues tested, including testis, than in those of the mice receiving full-length E, EDI/II peptides, or mock controls. DENV titers in the full-length E protein or EDI/II peptide-immunized mouse sera and several (but not all) tissues tested, such as brain, kidney, lung, spleen, and/or muscle, were only slightly reduced as compared with those of the mock control (FIG. 15).

[0107] These data confirm the efficacy of the ZIKV TCI-DNA vaccine in cross-protecting mice against DENV infection, with significantly reduced DENV titers, particularly in the reproductive organ, testis.

[0108] Unless otherwise indicated, all numbers expressing quantities of ingredients, properties such as molecular weight, reaction conditions, and so forth used in the specification and claims are to be understood as being modified in all instances by the term “about.” As used herein the terms "about" and “approximately” means within 10 to 15%, preferably within 5 to 10%. Accordingly, unless indicated to the contrary, the numerical parameters set forth in the specification and attached claims are approximations that may vary depending upon the desired properties sought to be obtained by the present invention. At the very least, and not as an attempt to limit the application of the doctrine of equivalents to the scope of the claims, each numerical parameter should at least be construed in light of the number of reported significant digits and by applying ordinary rounding techniques. Notwithstanding that the numerical ranges and parameters setting forth the broad scope of the invention are approximations, the numerical values set forth in the specific examples are reported as precisely as possible. Any numerical value, however, inherently contains certain errors necessarily resulting from the standard deviation found in their respective testing measurements.

[0109] The terms “a,” “an,” “the” and similar referents used in the context of describing the invention (especially in the context of the following claims) are to be construed to cover both the singular and the plural, unless otherwise indicated herein or clearly contradicted by context. Recitation of ranges of values herein is merely intended to serve as a shorthand method of referring individually to each separate value falling within the range. Unless otherwise indicated herein, each individual value is incorporated into the specification as if it were individually recited herein. All methods described herein can be performed in any suitable order unless otherwise indicated herein or otherwise clearly contradicted by context. The use of any and all examples, or exemplary language (e.g., “such as”) provided herein is intended merely to better illuminate the invention and does not pose a limitation on the scope of the

invention otherwise claimed. No language in the specification should be construed as indicating any non-claimed element essential to the practice of the invention.

[0110] Groupings of alternative elements or embodiments of the invention disclosed herein are not to be construed as limitations. Each group member may be referred to and claimed individually or in any combination with other members of the group or other elements found herein. It is anticipated that one or more members of a group may be included in, or deleted from, a group for reasons of convenience and/or patentability. When any such inclusion or deletion occurs, the specification is deemed to contain the group as modified thus fulfilling the written description of all Markush groups used in the appended claims.

[0111] Certain embodiments of this invention are described herein, including the best mode known to the inventors for carrying out the invention. Of course, variations on these described embodiments will become apparent to those of ordinary skill in the art upon reading the foregoing description. The inventor expects skilled artisans to employ such variations as appropriate, and the inventors intend for the invention to be practiced otherwise than specifically described herein. Accordingly, this invention includes all modifications and equivalents of the subject matter recited in the claims appended hereto as permitted by applicable law. Moreover, any combination of the above-described elements in all possible variations thereof is encompassed by the invention unless otherwise indicated herein or otherwise clearly contradicted by context.

[0112] Specific embodiments disclosed herein may be further limited in the claims using consisting of or consisting essentially of language. When used in the claims, whether as filed or added per amendment, the transition term “consisting of” excludes any element, step, or ingredient not specified in the claims. The transition term “consisting essentially of” limits the scope of a claim to the specified materials or steps and those that do not materially affect the basic and novel characteristic(s). Embodiments of the invention so claimed are inherently or expressly described and enabled herein.

[0113] Furthermore, numerous references have been made to patents and printed publications throughout this specification. Each of the above-cited references and printed publications are individually incorporated herein by reference in their entirety.

[0114] In closing, it is to be understood that the embodiments of the invention disclosed herein are illustrative of the principles of the present invention. Other modifications that may be employed are within the scope of the invention. Thus, by way of example, but not of limitation, alternative configurations of the present invention may be utilized in accordance

with the teachings herein. Accordingly, the present invention is not limited to that precisely as shown and described.

WHAT IS CLAIMED IS:

1. An immunogenic composition comprising an expression vector and a nucleotide sequence disposed therein, wherein the nucleotide sequence comprises:

a nucleotide sequence encoding a Zika virus NS3 protein, wherein the NS3 nucleotide sequence is reorganized and comprises the nucleotide sequence of SEQ ID NO:3; and

a ubiquitin nucleotide sequence upstream of the Zika virus NS3 protein sequence.

2. The immunogenic composition of claim 2, wherein the nucleotide sequence is SEQ ID NO:5.

3. An immunogenic composition comprising an expression vector and a nucleotide sequence disposed therein, wherein the nucleotide sequence comprises a nucleotide sequence encoding a Zika virus NS3 protein, wherein the NS3 nucleotide sequence is reorganized and comprises the nucleotide sequence of SEQ ID NO:3.

4. A method for preventing a Zika virus infection in a subject in need thereof, the method comprising administering a therapeutically effective amount of an immunogenic composition of any one of claims 1-3 to the subject.

5. The method of claim 4 further comprising co-administration of an adjuvant.

6. The method of claims 4 or 5, wherein the administration increases production of Zika virus-specific cytotoxic T lymphocytes and does not induce Zika virus-specific antibodies in the subject.

7. A method for preventing birth defects associated with a Zika virus infection in a subject at risk of Zika virus infection, comprising immunizing a woman who is pregnant, who may become pregnant, or who plans to become pregnant, with an immunogenic composition according to any one of claims 1-3.

8. The method of claim 7, wherein the immunized woman does not produce neutralizing antibodies after infection with Zika virus.

9. The method of claim 7, wherein the immunized woman exhibits decreased decreases viral titers after infection with Zika virus compared to a woman not immunized with the immunogenic composition according to any one of claims 1-3.

10. The method of claim 7, wherein the administration increases production of Zika virus-specific $CD8^+$ T lymphocytes in the woman.

11. The method of claim 7, wherein as a result of the administration, a pregnancy in the woman does not result in Zika virus-associated birth defects.

12. The method of claim 7, wherein as a result of the administration of the immunogenic composition of either of claims 1 or 2, a strong cytotoxic T lymphocyte (CTL) response against Zika virus is induced.

13. The method of claim 12, wherein the CTL response provides protection against Zika virus infection.

14. Use of an immunogenic composition of any one of claims 1-3 in the prevention of a Zika virus infection.

15. Use of an immunogenic composition of any one of claims 1-3 in the prevention of birth defects associated with Zika virus infection.

16. A composition of any one of claims 1-3 for use in the prevention of a Zika virus infection.

17. A composition of any one of claims 1-3 for use in the prevention of birth defects associated with Zika virus infection.

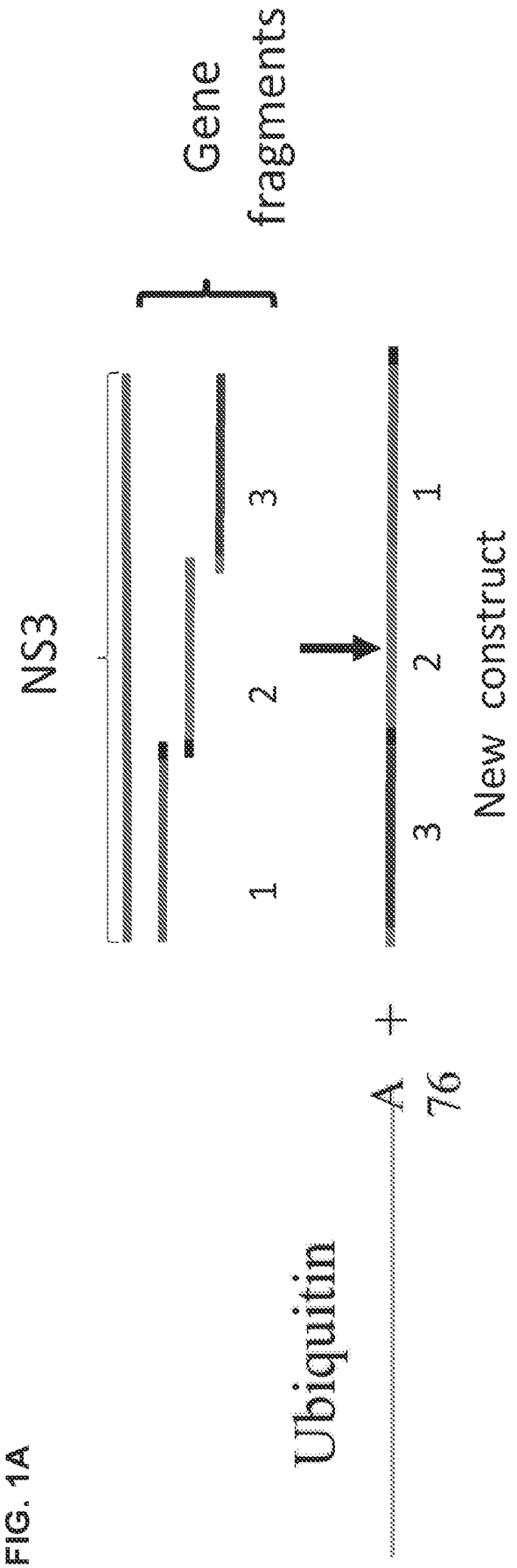
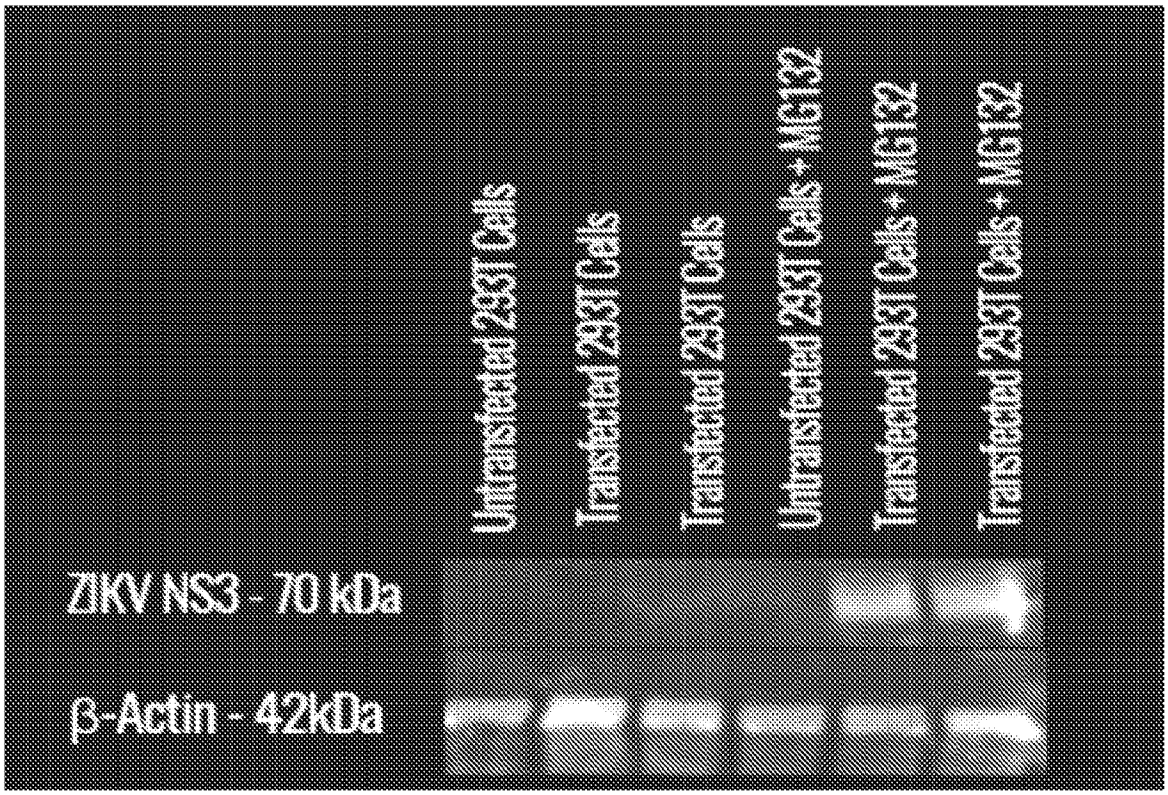


FIG. 1A

FIG. 1B


Untransfected 293T Cells
Transfected 293T Cells
Transfected 293T Cells
Untransfected 293T Cells + MG132
Transfected 293T Cells + MG132
Transfected 293T Cells + MG132
ZIKV NS3 - 70 kDa
β-Actin - 42kDa

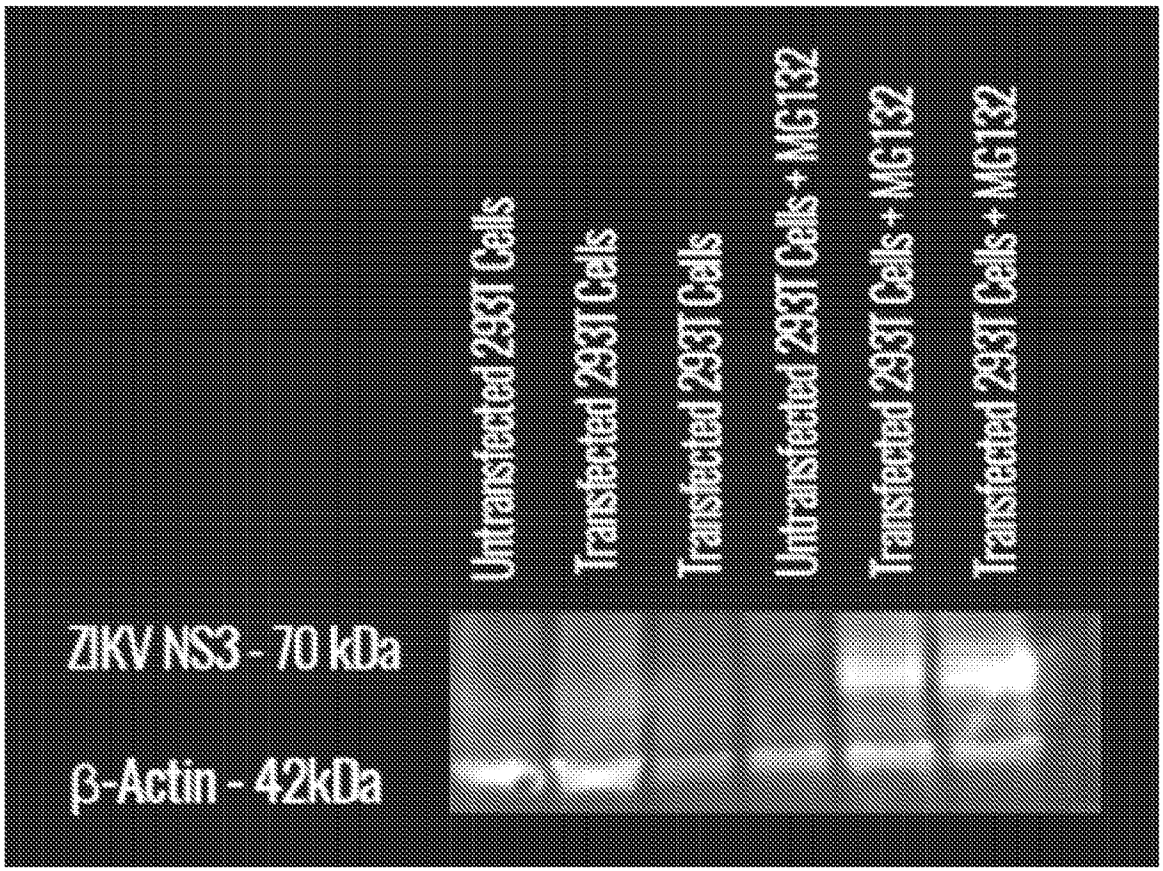

Untransfected 293T Cells
Transfected 293T Cells
Transfected 293T Cells
Untransfected 293T Cells + MG132
Transfected 293T Cells + MG132
Transfected 293T Cells + MG132
ZIKV NS3 - 70 kDa
β-Actin - 42kDa

FIG. 1B (Cont.)

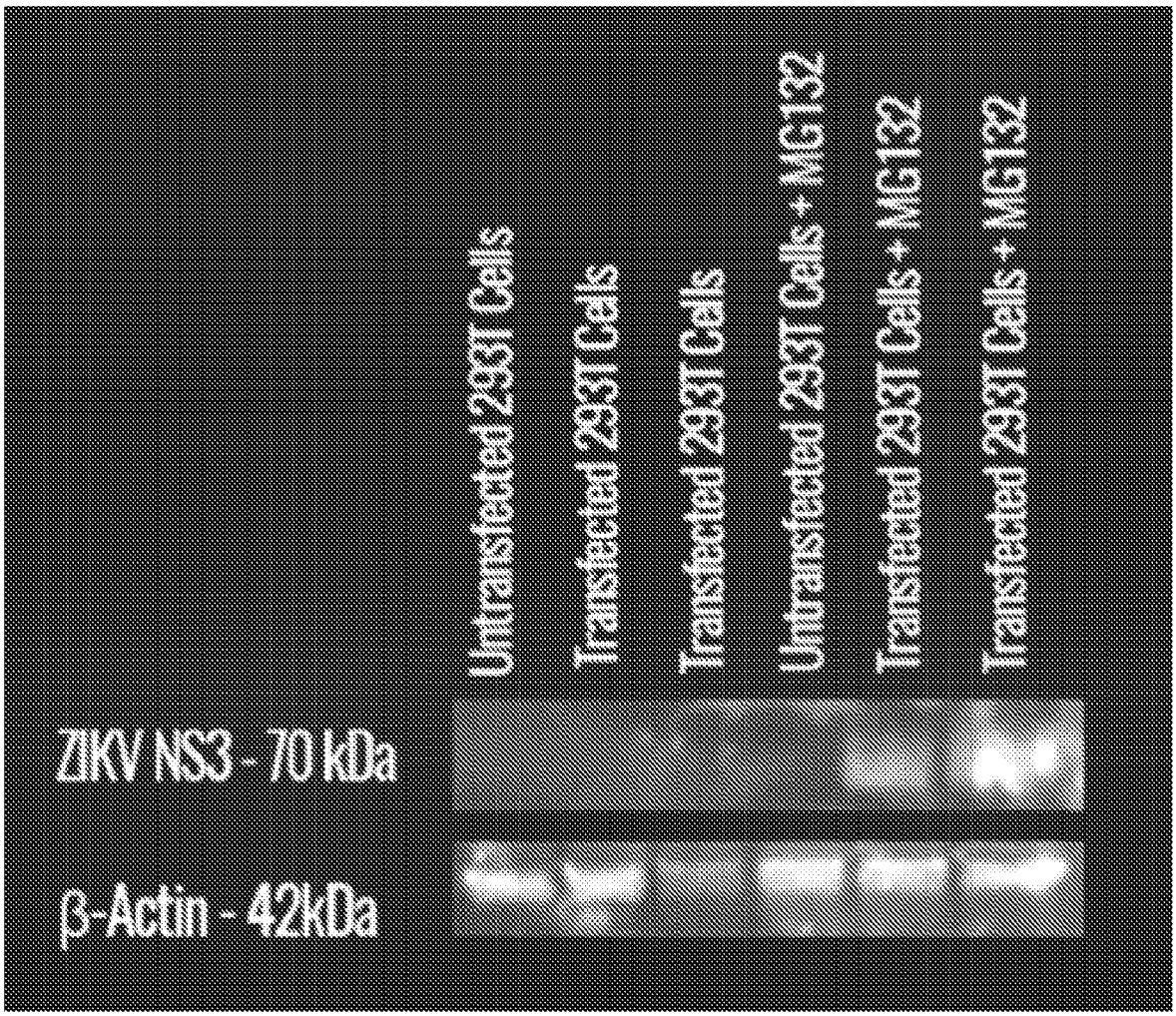

Untransfected 293T Cells
Transfected 293T Cells
Transfected 293T Cells
Untransfected 293T Cells + MG132
Transfected 293T Cells + MG132
Transfected 293T Cells + MG132
ZIKV NS3 - 70 kDa
β-Actin - 42kDa

FIG. 1C

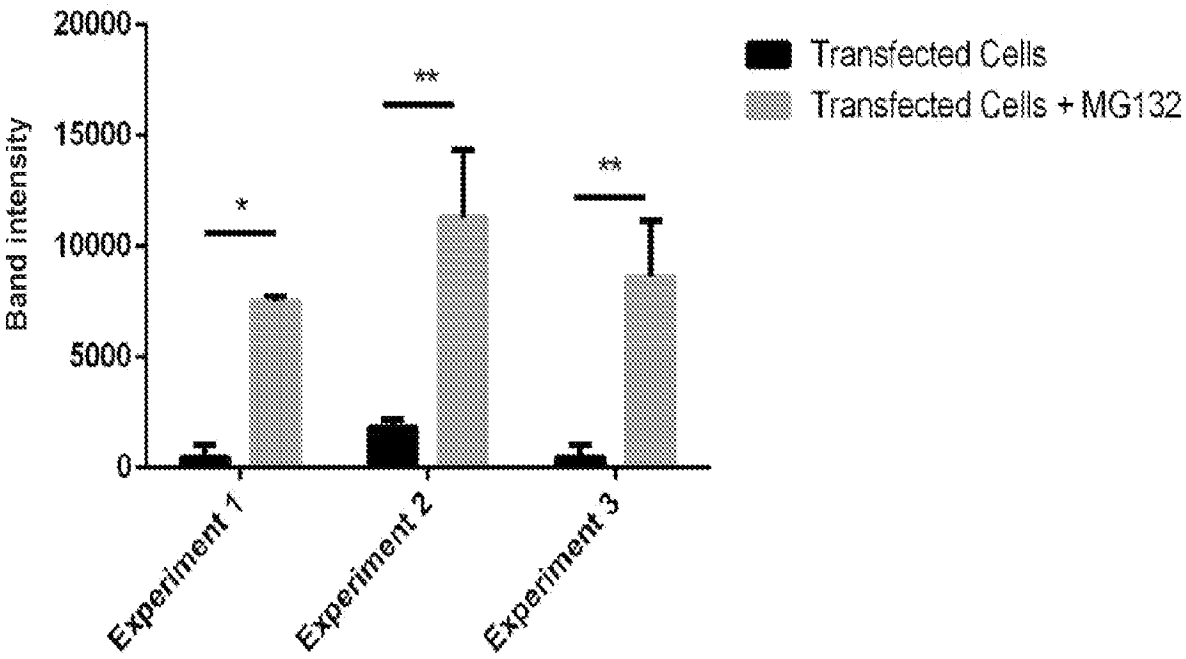

20000
15000
10000
5000
0
Band intensity
*
**
**
Transfected Cells
Transfected Cells + MG132
Experiment 1
Experiment 2
Experiment 3

FIG. 2A

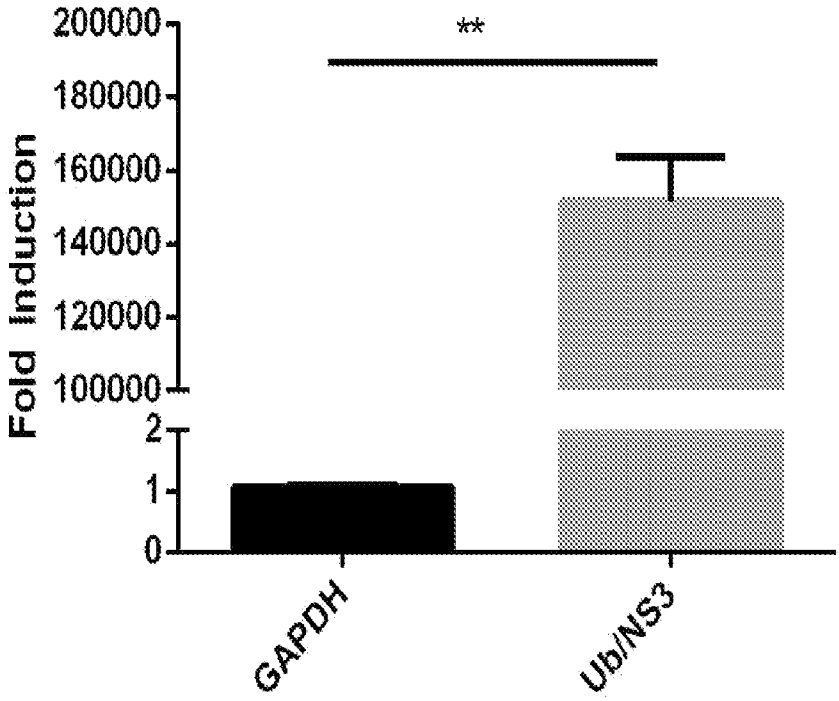
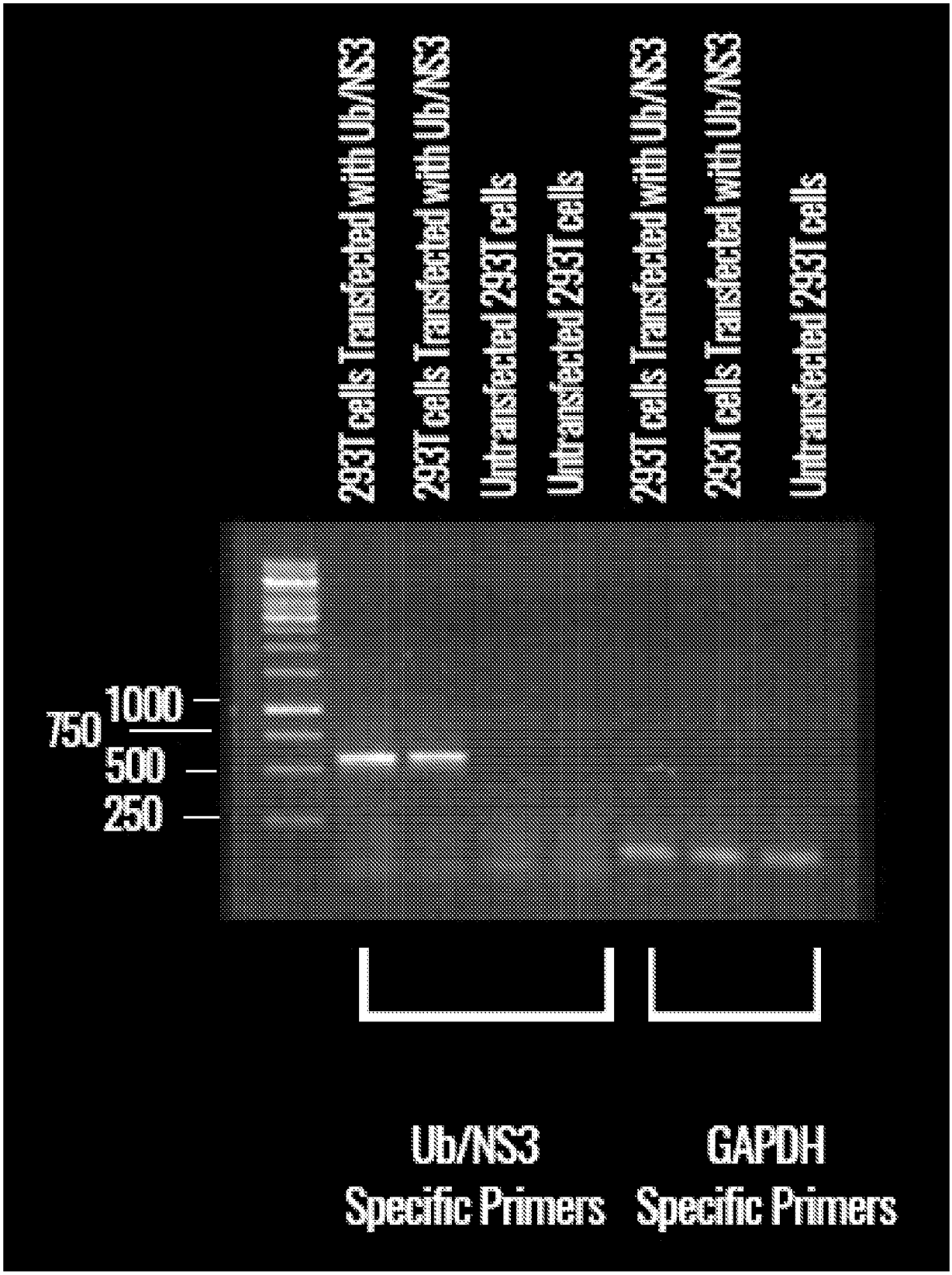

**
Fold Induction
200000
180000
160000
140000
120000
100000
2
1
0
GAPDH
Ub/NS3

FIG. 2B


293T cells Transfected with Ub/NS3
293T cells Transfected with Ub/NS3
Untransfected 293T cells
Untransfected 293T cells
293T cells Transfected with Ub/NS3
293T cells Transfected with Ub/NS3
Untransfected 293T cells
1000
750
500
250
Ub/NS3 Specific Primers
GAPDH Specific Primers

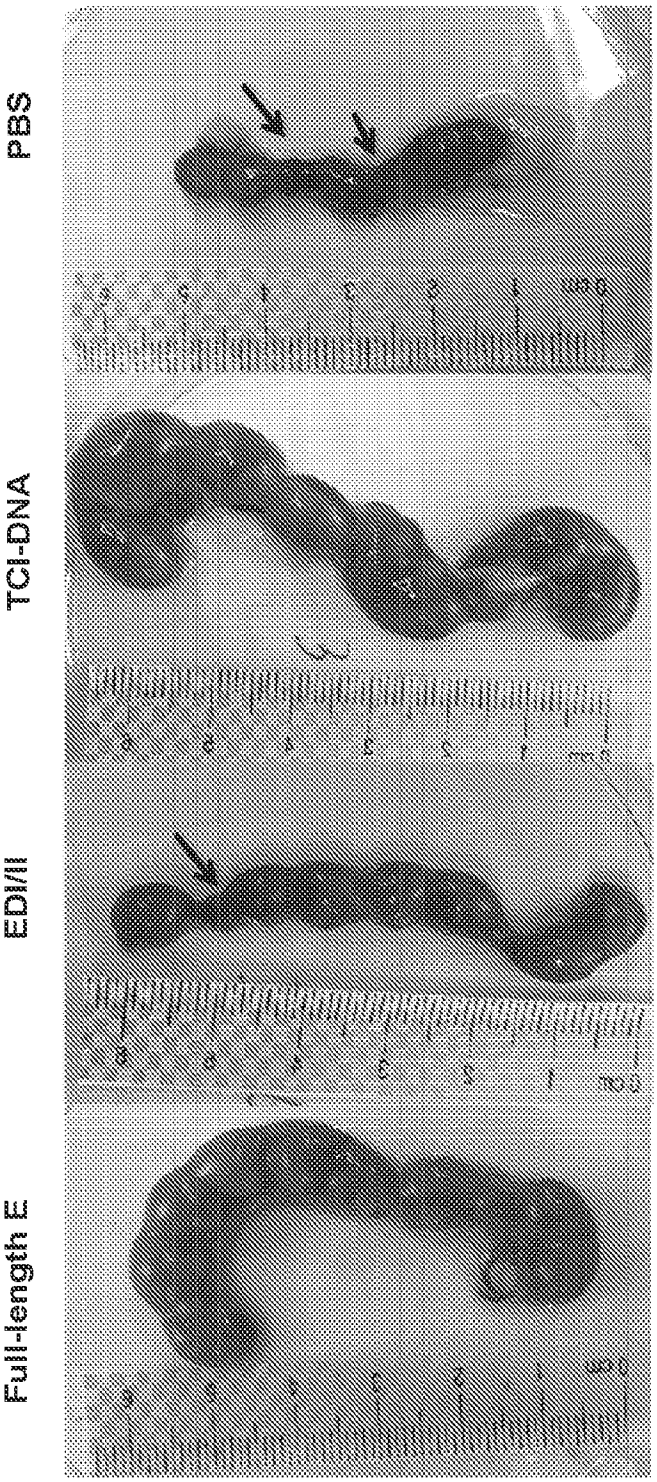


FIG. 3A

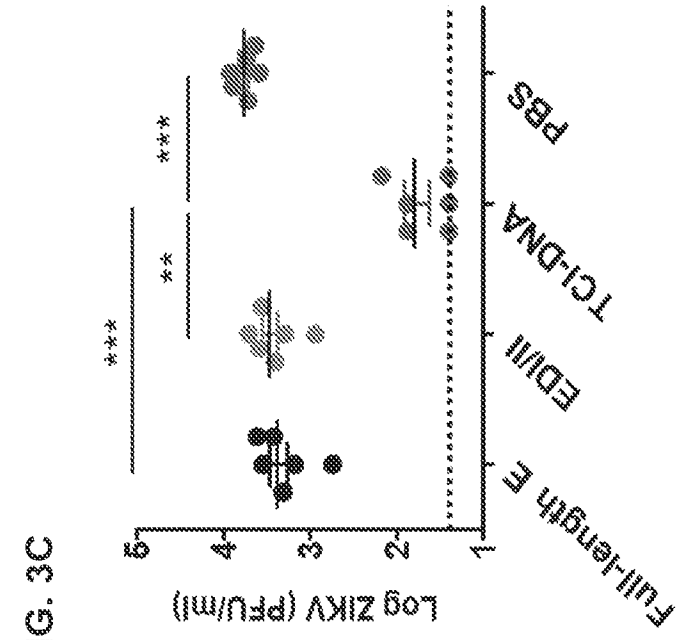

Log ZIKV (PFU/ml)
1
2
3
4
5
Full-length E
EDIII
TCI-DNA
PBS
***
**
***
***

FIG. 3C

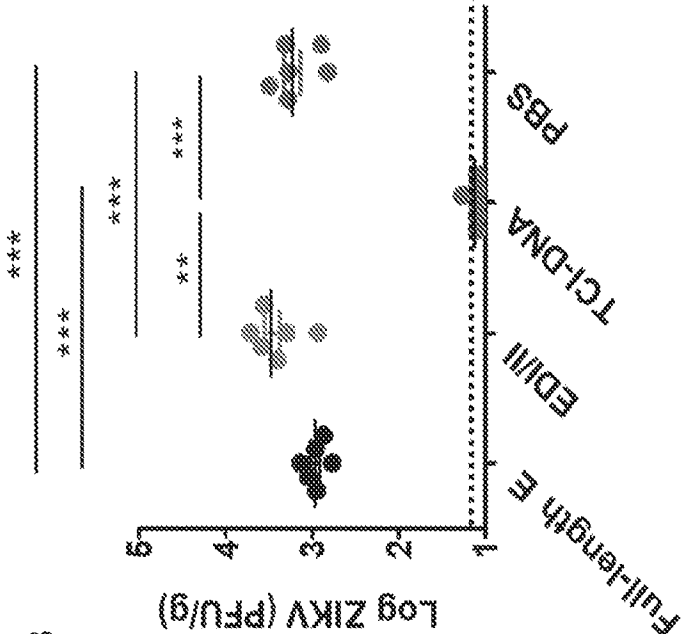

Log ZIKV (PFU/g)
1
2
3
4
5
Full-length E
EDIII
TCI-DNA
PBS
***
***
***
**
***

FIG. 3B

FIG. 4A

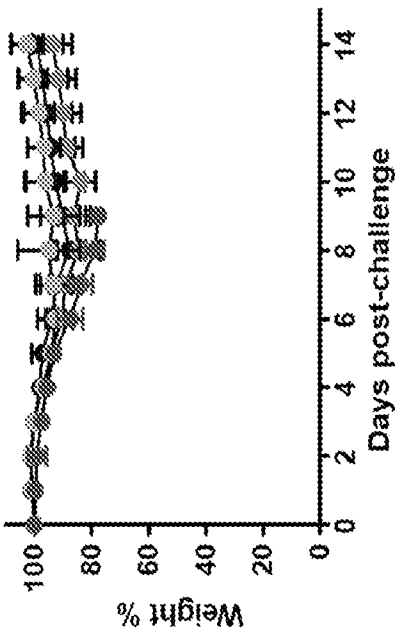
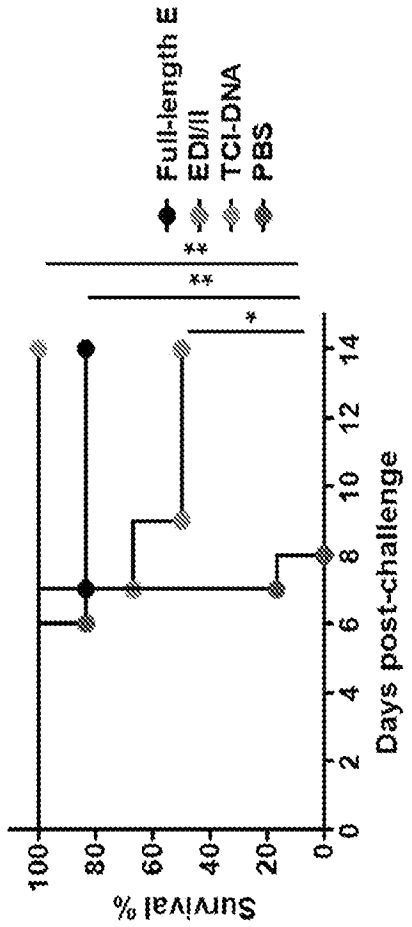

Weight %
100
80
60
40
20
0
0
2
4
6
8
10
12
14
Days post-challenge

FIG. 4B


Survival %
100
80
60
40
20
0
0
2
4
6
8
10
12
14
Days post-challenge
*
**
**
Full-length E
EDI/II
TCI-DNA
PBS

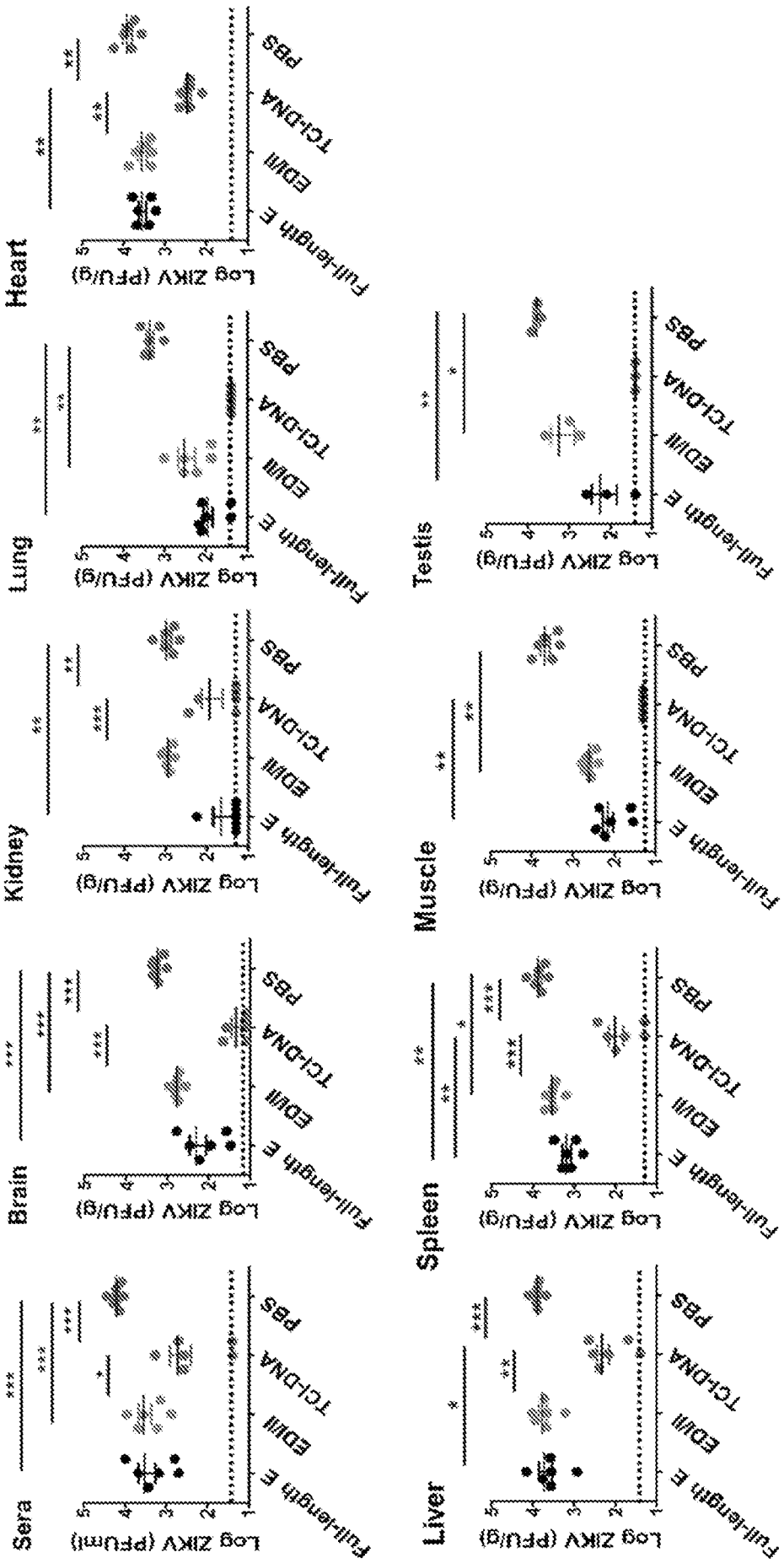

Sera
Brain
Kidney
Lung
Heart
Liver
Spleen
Muscle
Testis
Log ZIKV (PFU/ml)
Log ZIKV (PFU/g)
Full-length E
EDIII
TCI-DNA
PBS

FIG. 4C

FIG. 5A

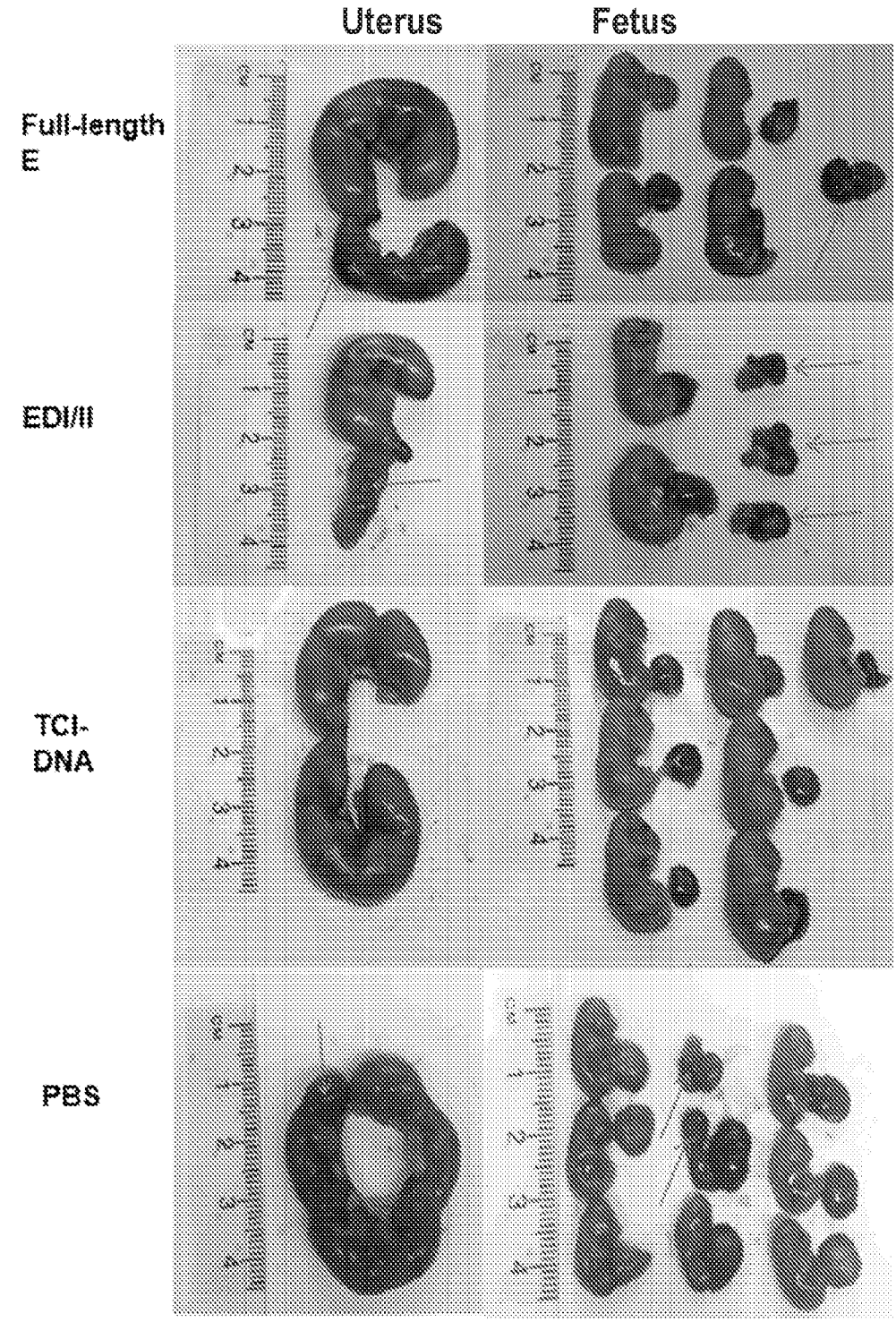


FIG. 5B

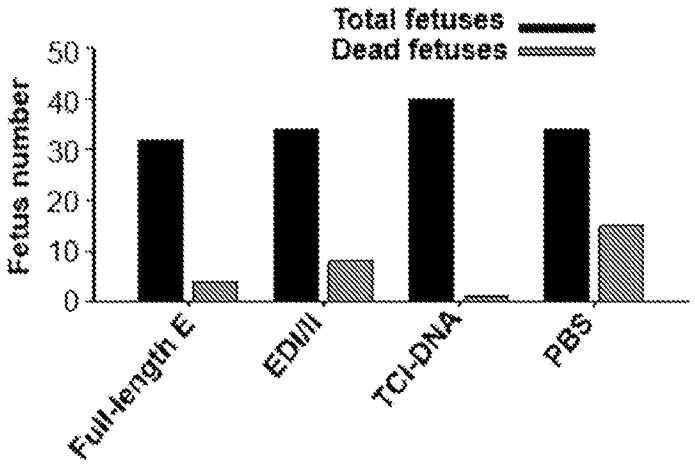


FIG. 5C

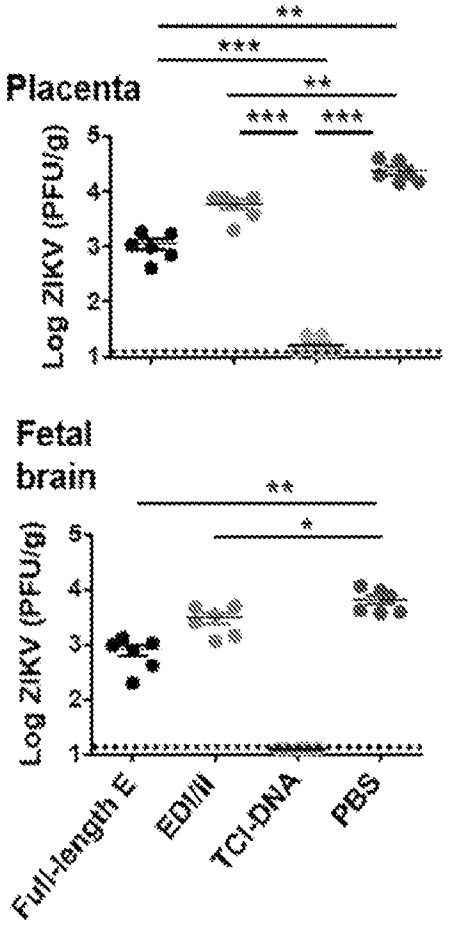


FIG. 5D

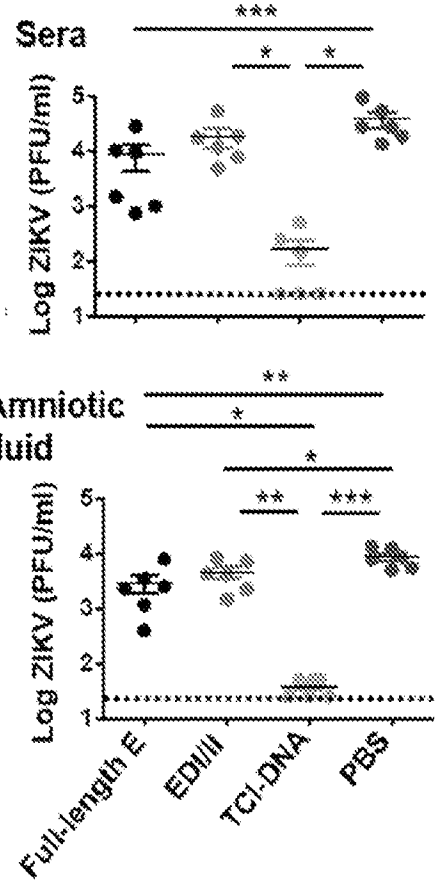


FIG. 5E

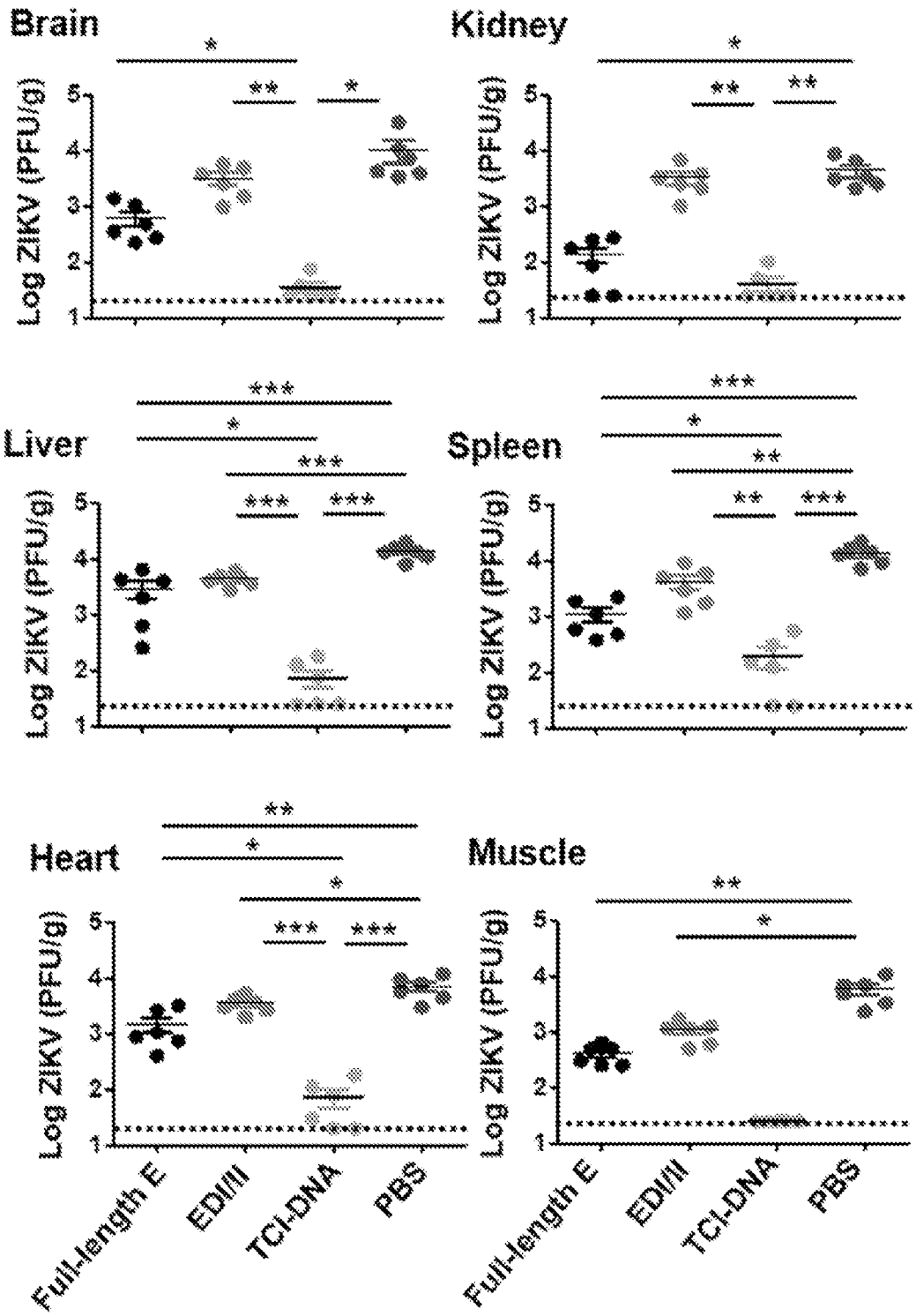

Brain
Kidney
Liver
Spleen
Heart
Muscle
Log ZIKV (PFU/g)
Full-length E
EDI/II
TCI-DNA
PBS

FIG. 6A

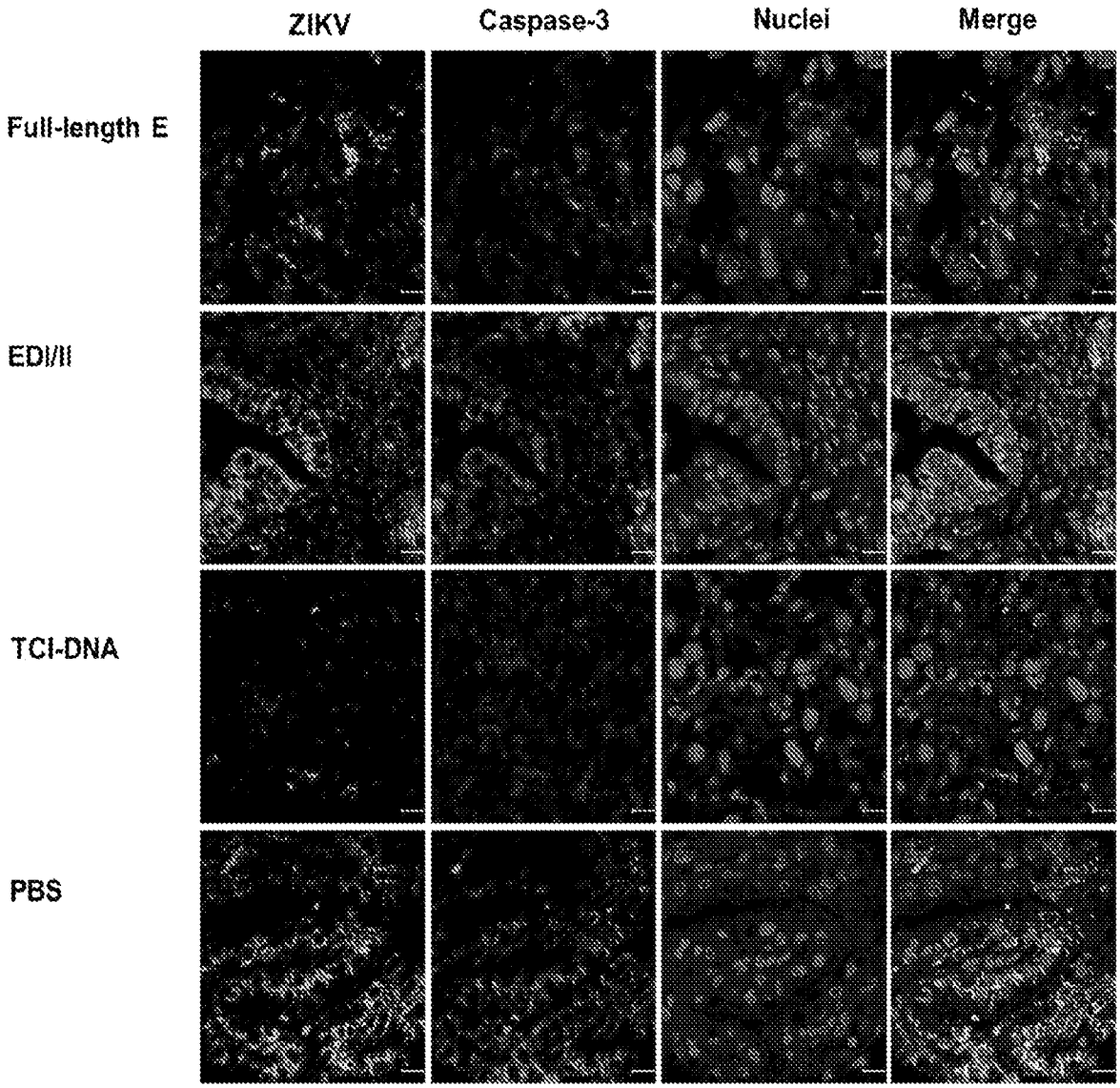


FIG. 6B

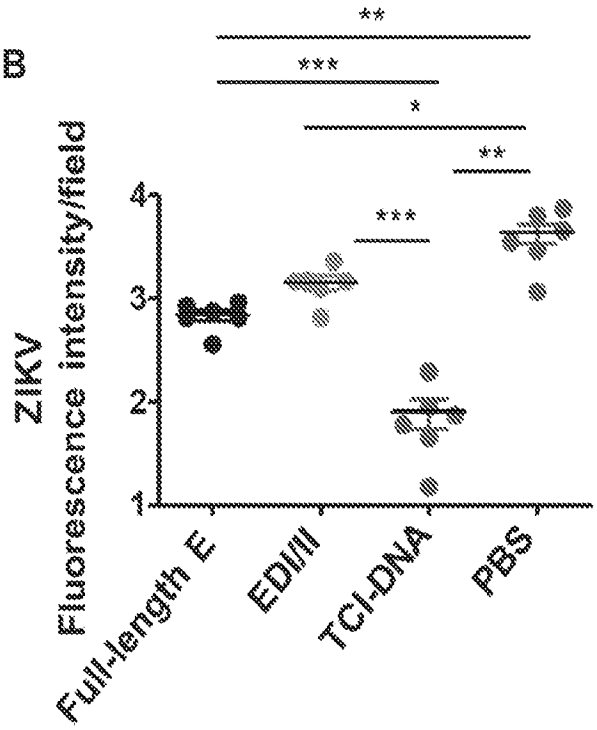

**
***
*
**
***
ZIKV
Fluorescence intensity/field
1
2
3
4
Full-length E
EDI/II
TCI-DNA
PBS

FIG. 6C

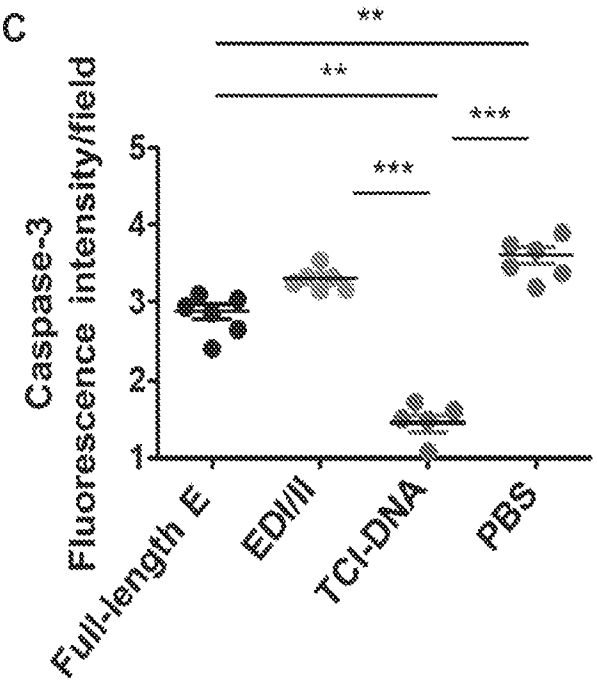

**
**
***
***
Caspase-3
Fluorescence intensity/field
1
2
3
4
5
Full-length E
EDI/II
TCI-DNA
PBS

FIG. 7A

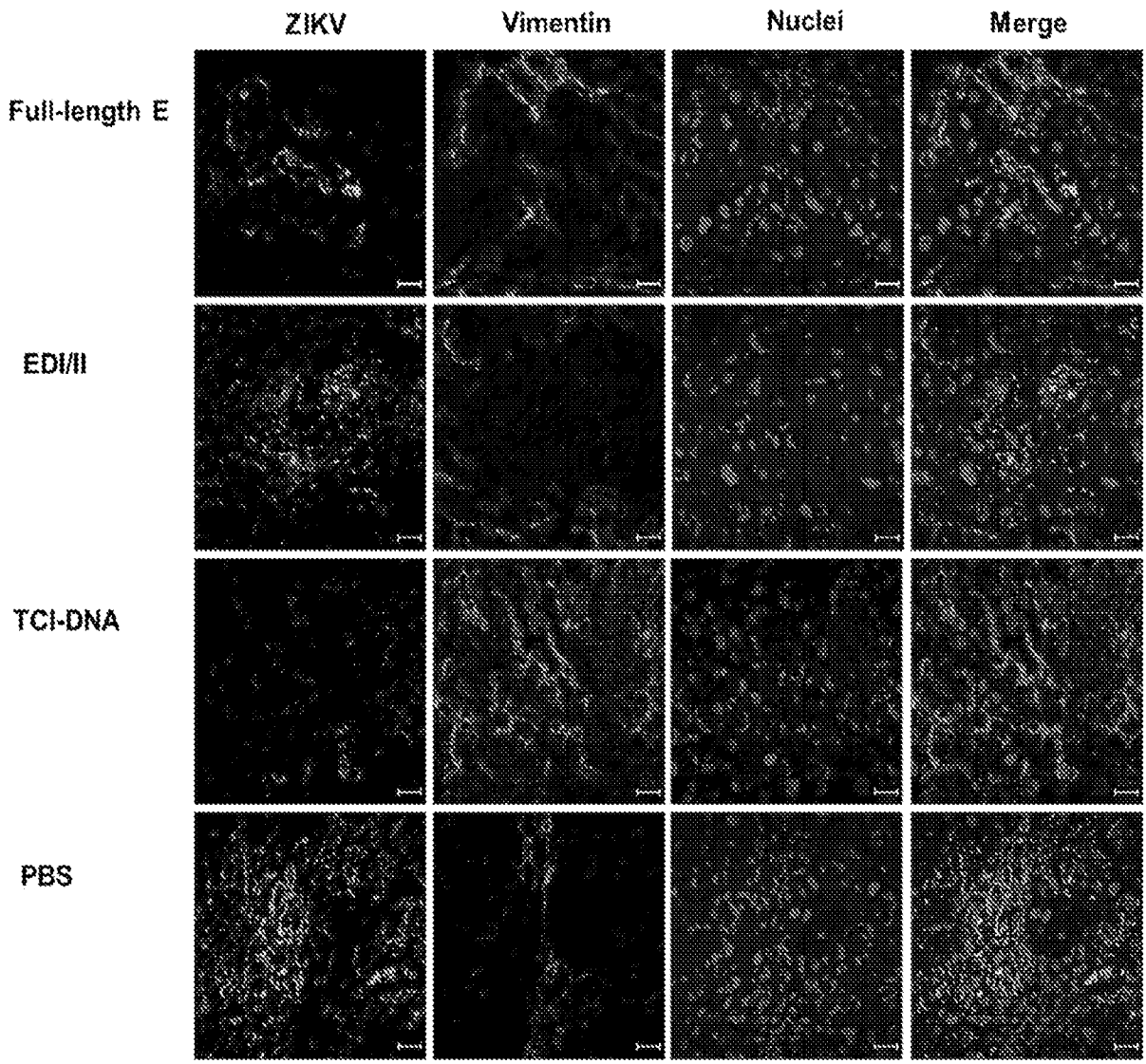


FIG. 7B

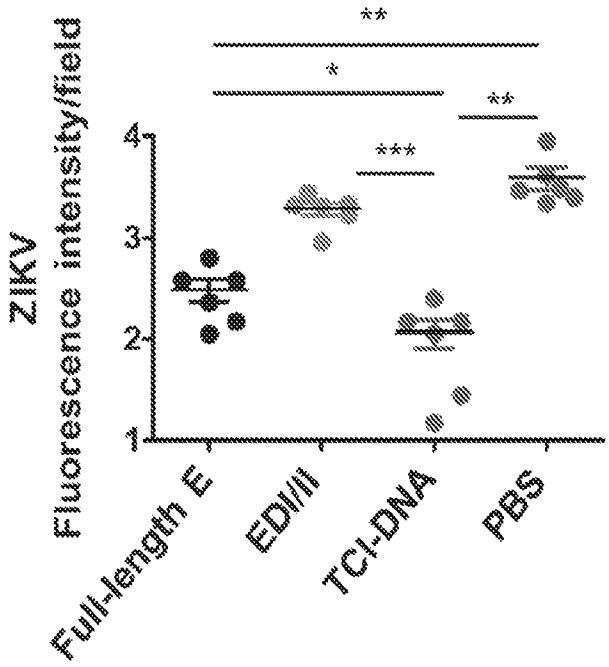

ZIKV
Fluorescence intensity/field
**
*
**
***
4
3
2
1
Full-length E
EDI/II
TCI-DNA
PBS

FIG. 7C

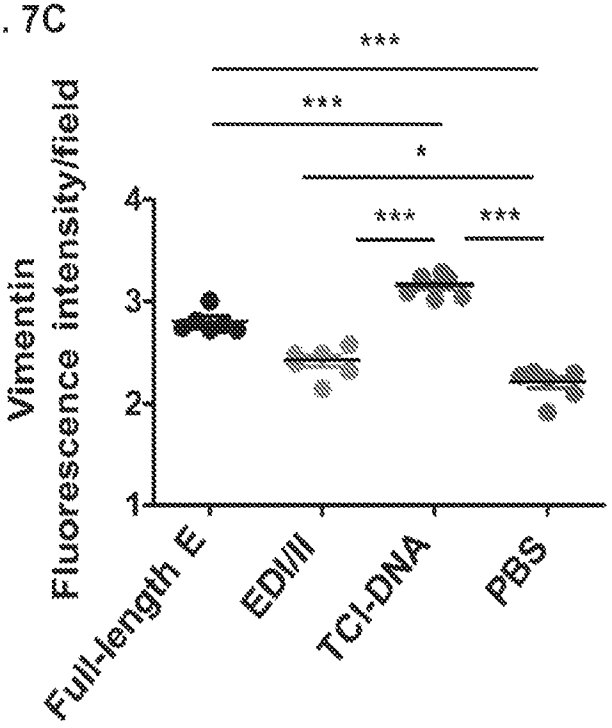

Vimentin
Fluorescence intensity/field
***
***
*
***
***
4
3
2
1
Full-length E
EDI/II
TCI-DNA
PBS

FIG. 8A

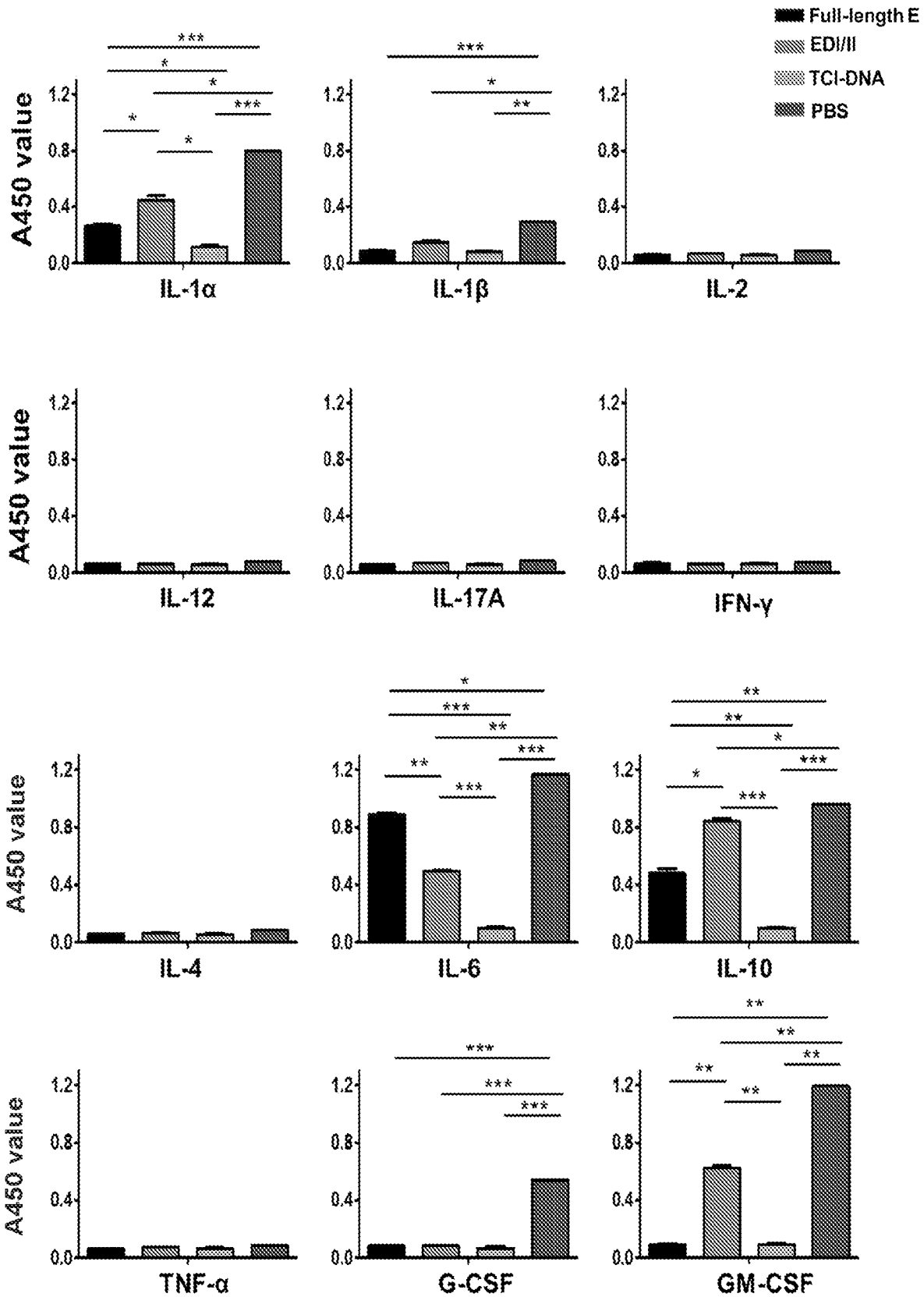

Full-length E
EDI/II
TCI-DNA
PBS
A450 value
IL-1α
IL-1β
IL-2
IL-12
IL-17A
IFN-γ
IL-4
IL-6
IL-10
TNF-α
G-CSF
GM-CSF

FIG. 8B

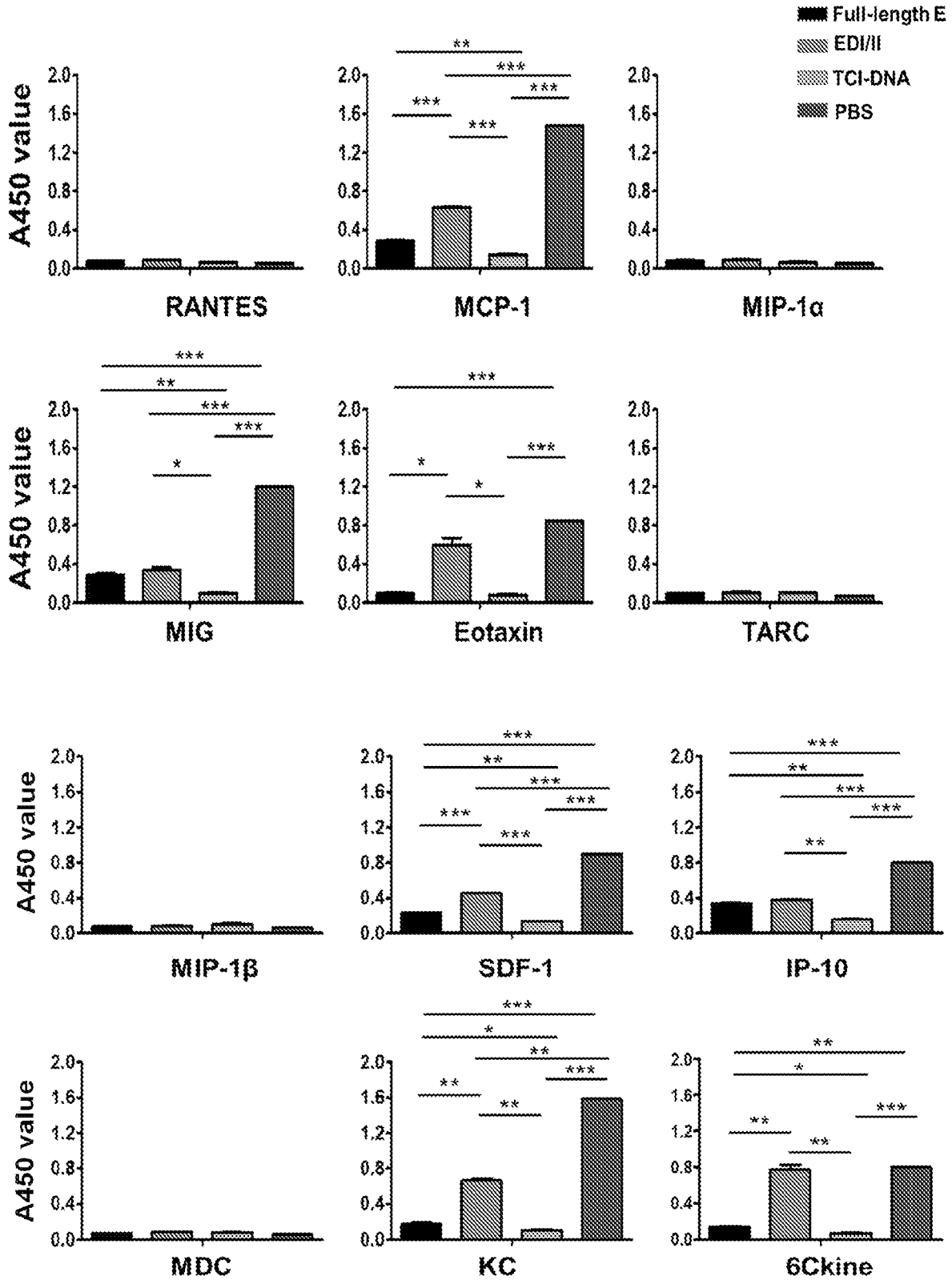

Full-length E
EDI/II
TCI-DNA
PBS
A450 value
RANTES
MCP-1
MIP-1α
MIG
Eotaxin
TARC
MIP-1β
SDF-1
IP-10
MDC
KC
6Ckine

FIG. 9A

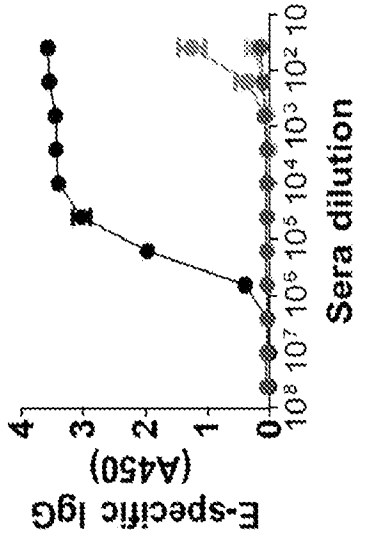


FIG. 9B

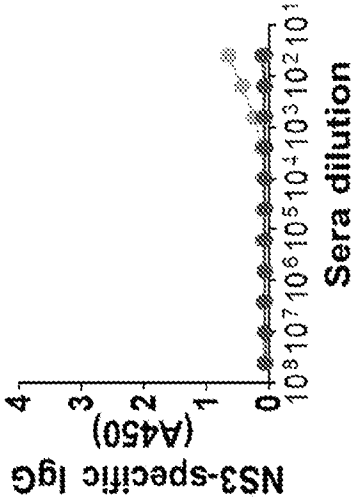


FIG. 9C

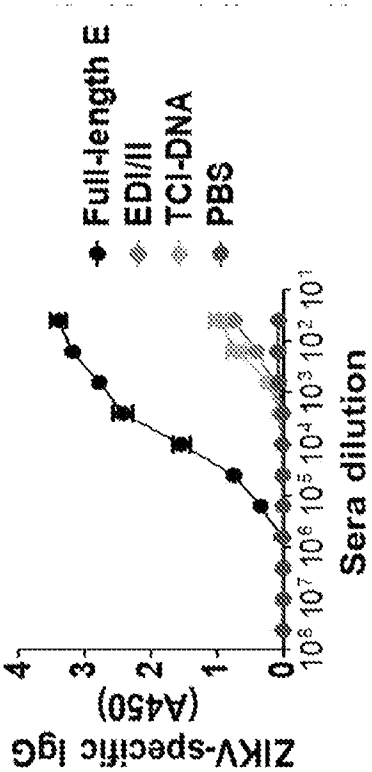


FIG. 9D

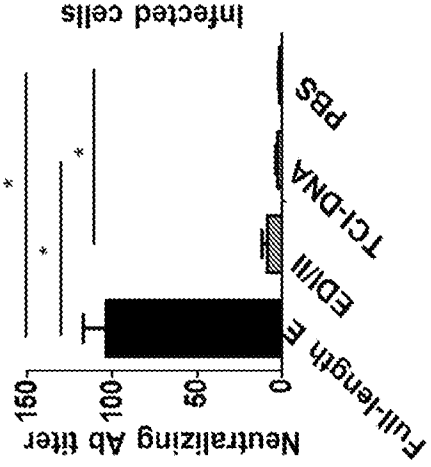


FIG. 9E

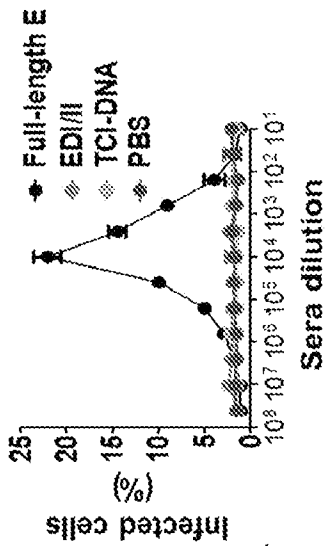


FIG. 10A

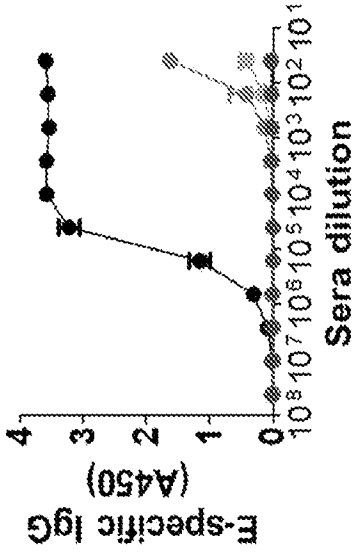


FIG. 10B

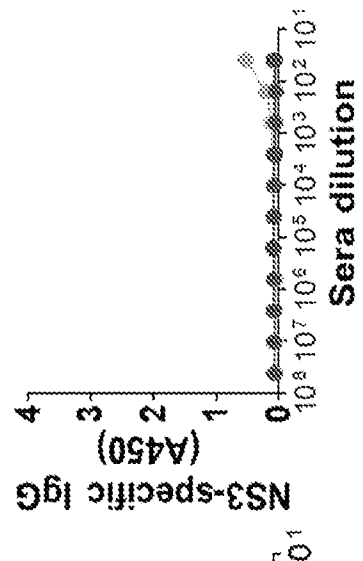


FIG. 10C

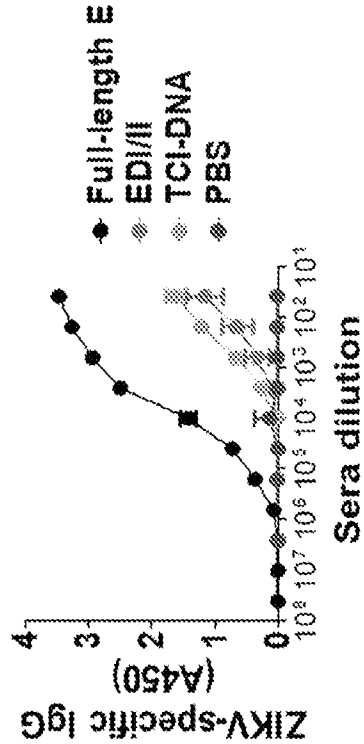


FIG. 10D

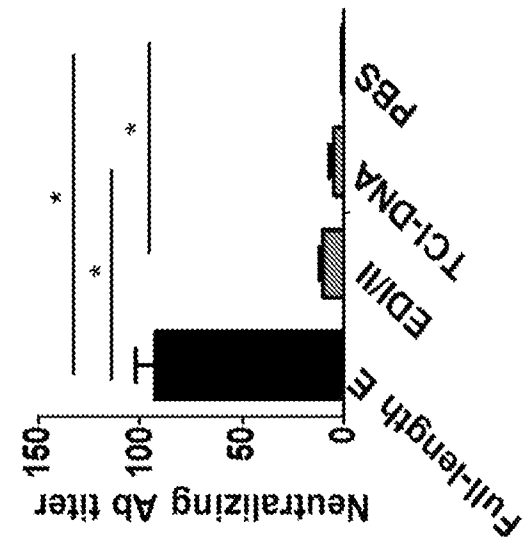


FIG. 10E

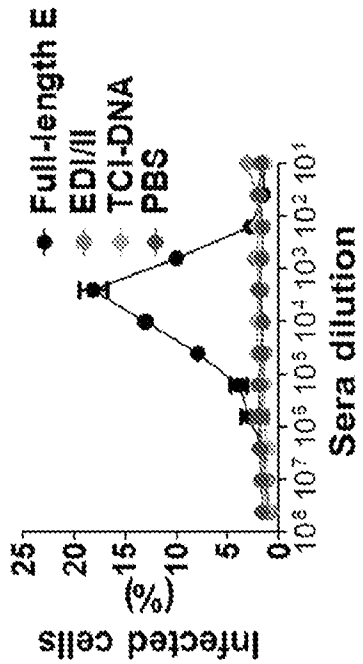


FIG. 11A

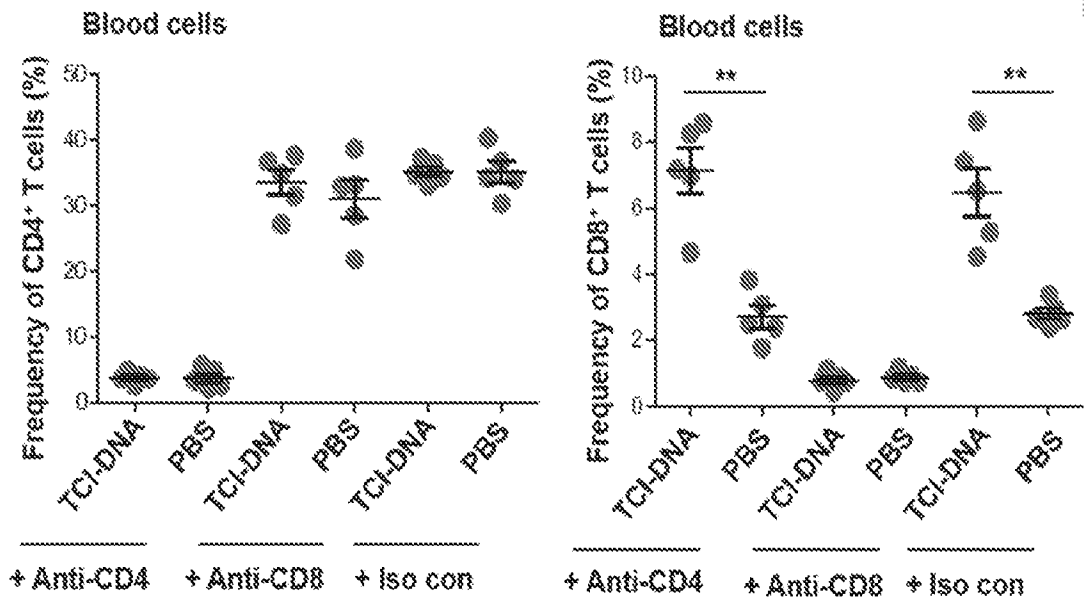


FIG. 11B

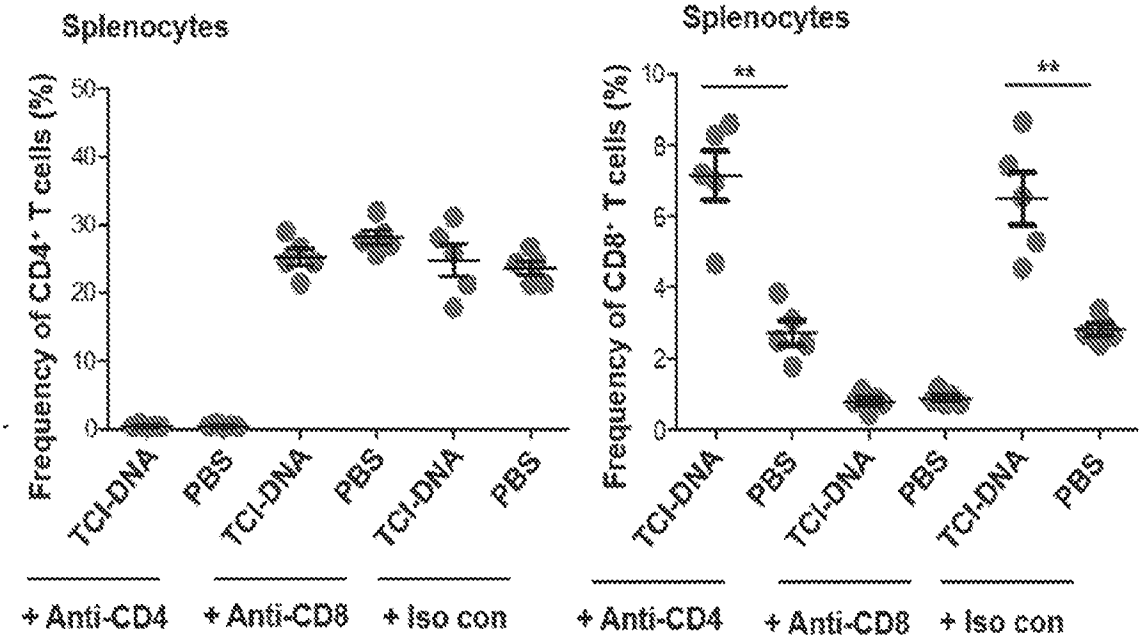


FIG. 11C

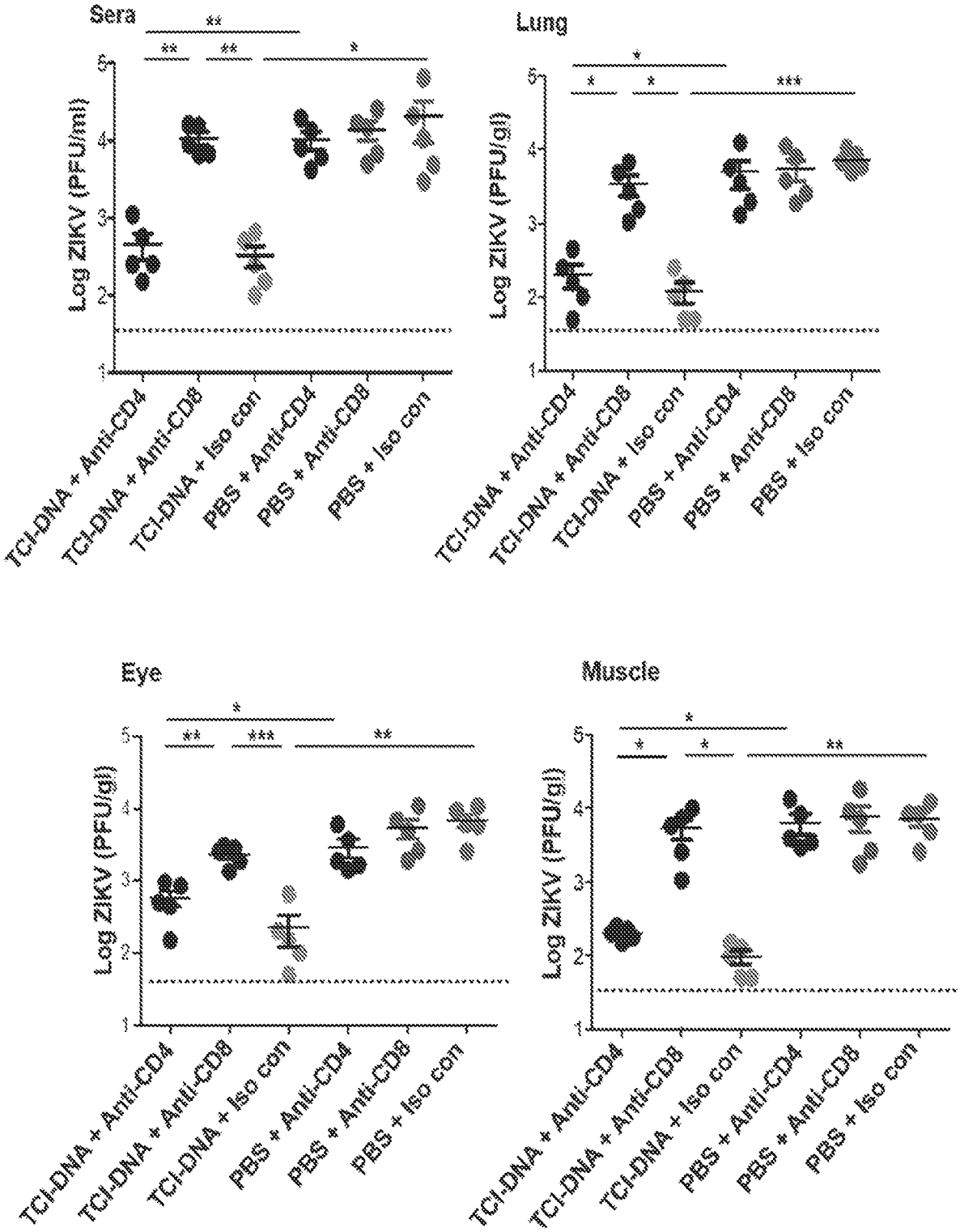

Sera
Lung
Eye
Muscle
Log ZIKV (PFU/ml)
Log ZIKV (PFU/gl)
TCI-DNA + Anti-CD4
TCI-DNA + Anti-CD8
TCI-DNA + Iso con
PBS + Anti-CD4
PBS + Anti-CD8
PBS + Iso con

FIG. 12A

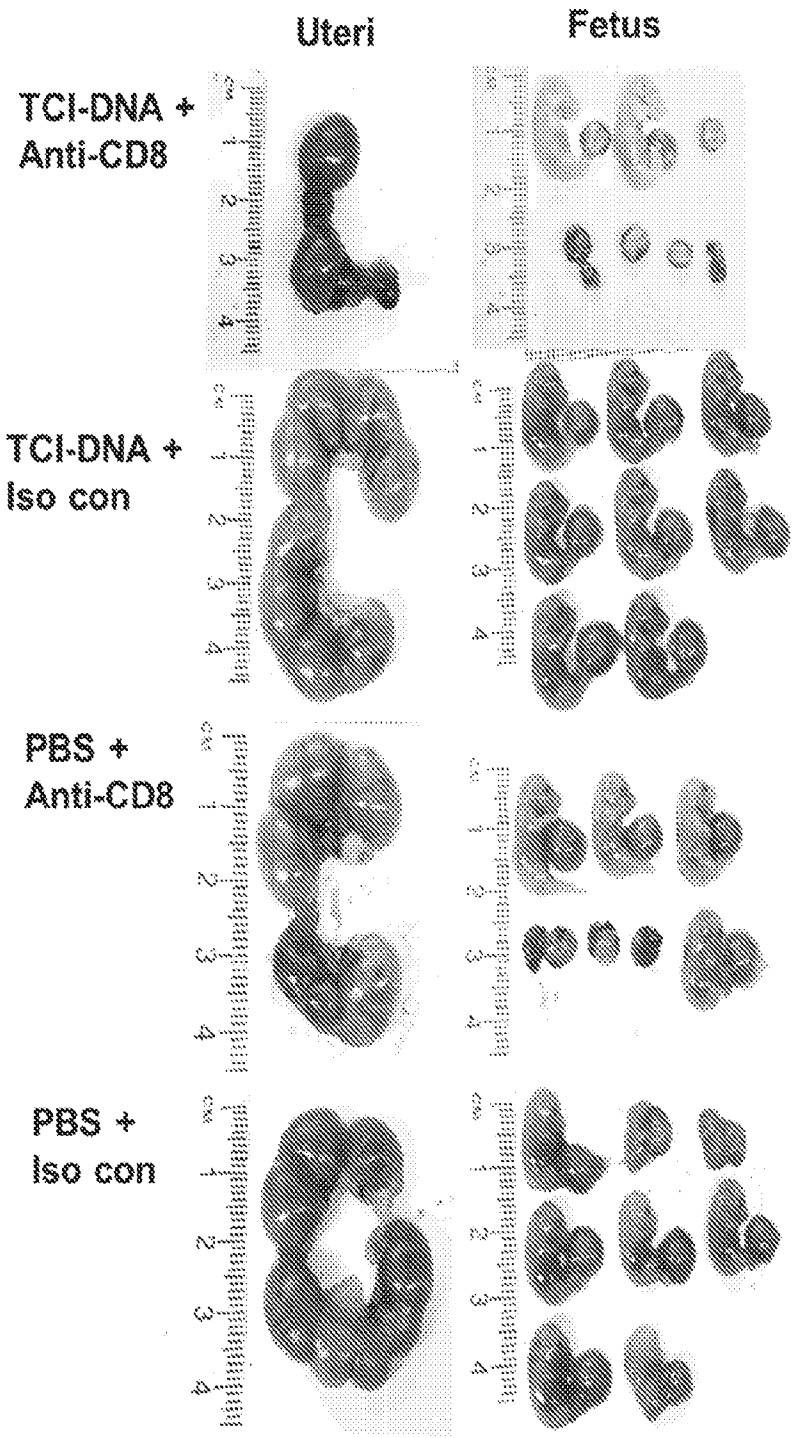

Uteri
Fetus
TCI-DNA + Anti-CD8
TCI-DNA + Iso con
PBS + Anti-CD8
PBS + Iso con

FIG. 12B

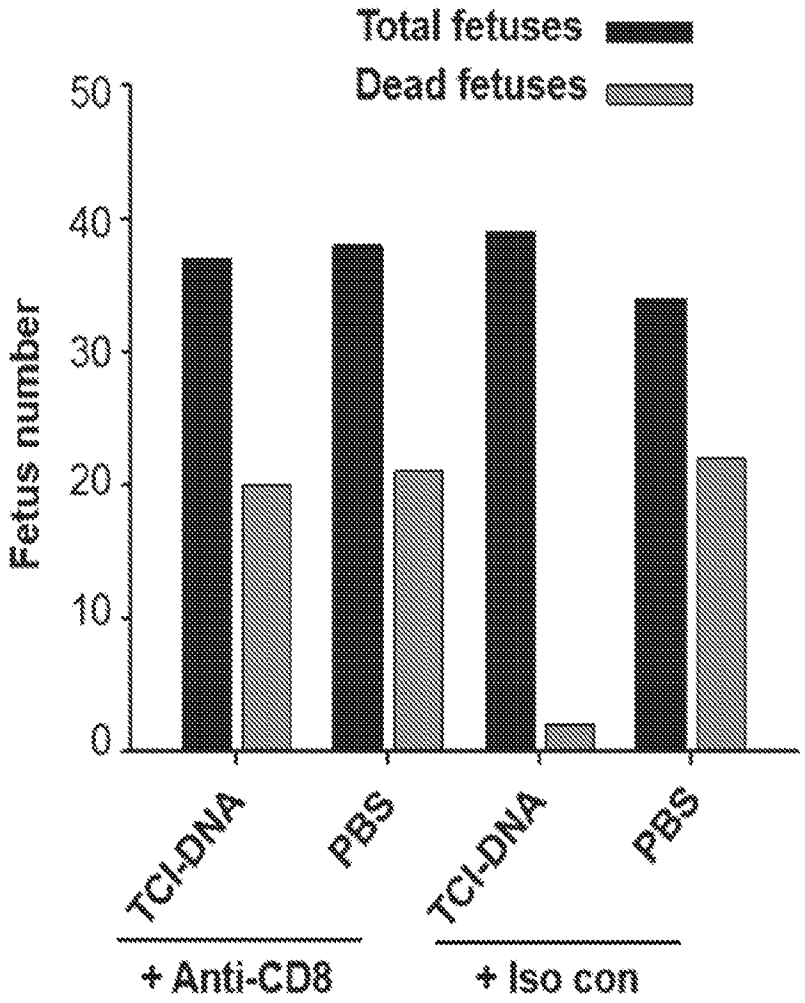

Total fetuses
Dead fetuses
Fetus number
50
40
30
20
10
0
TCI-DNA
PBS
TCI-DNA
PBS
+ Anti-CD8
+ Iso con

FIG. 13A

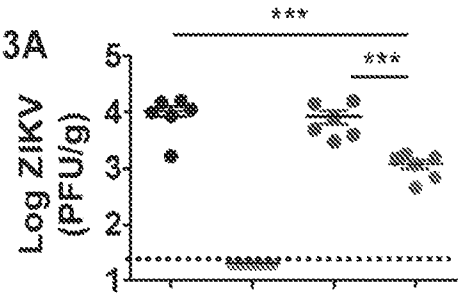


FIG. 13B

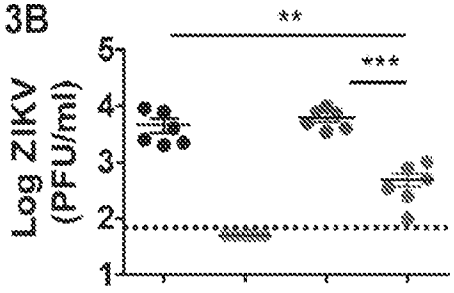


FIG. 13C

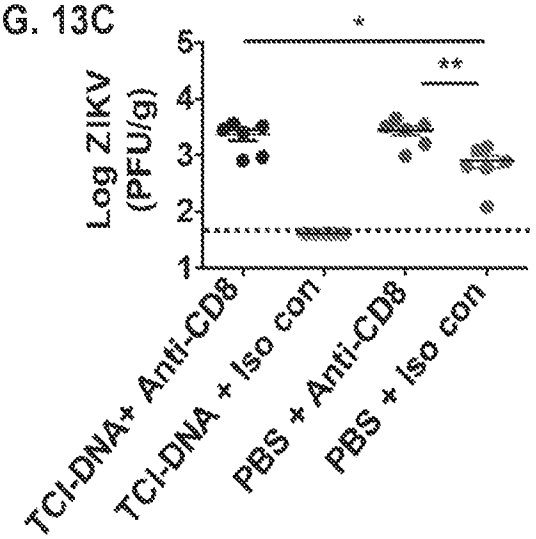


FIG. 13D

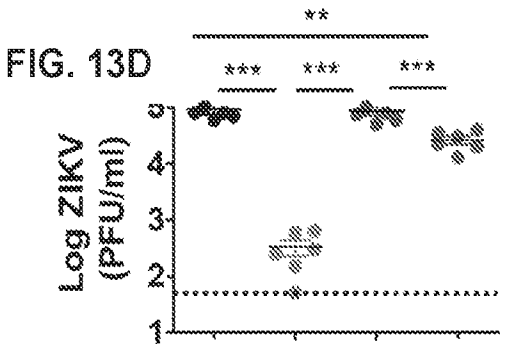


FIG. 13E

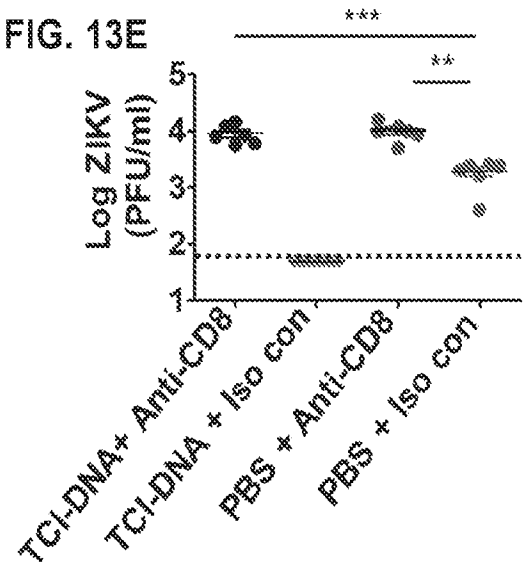


FIG. 14A

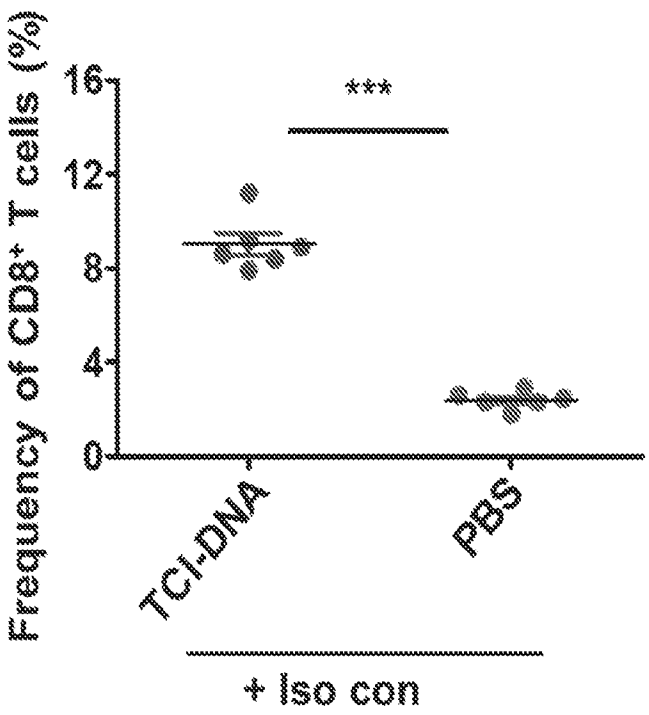
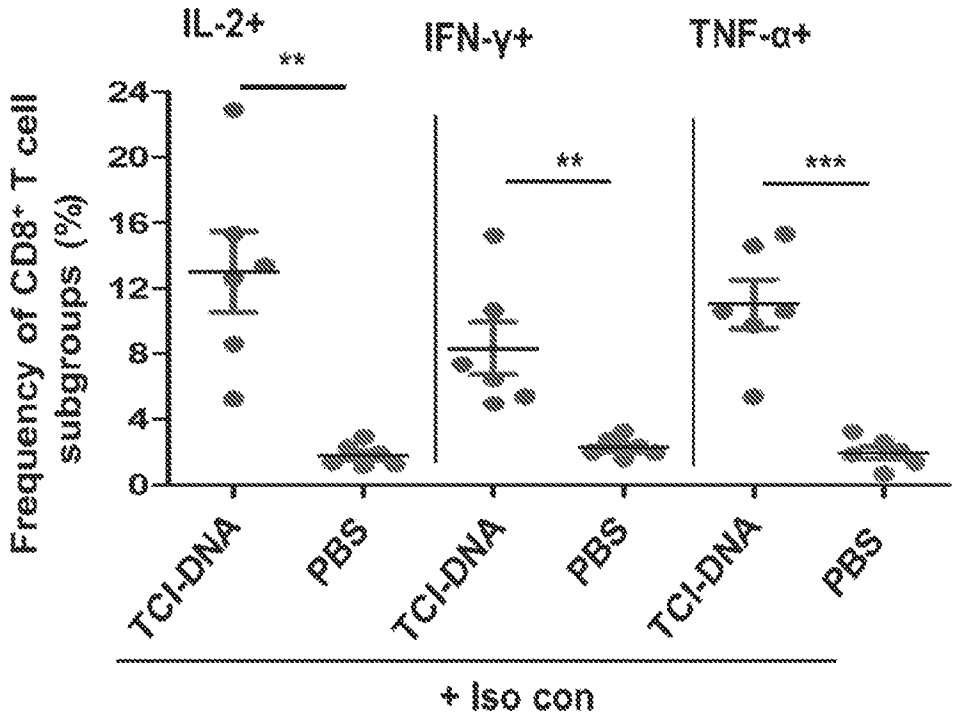


FIG. 14B



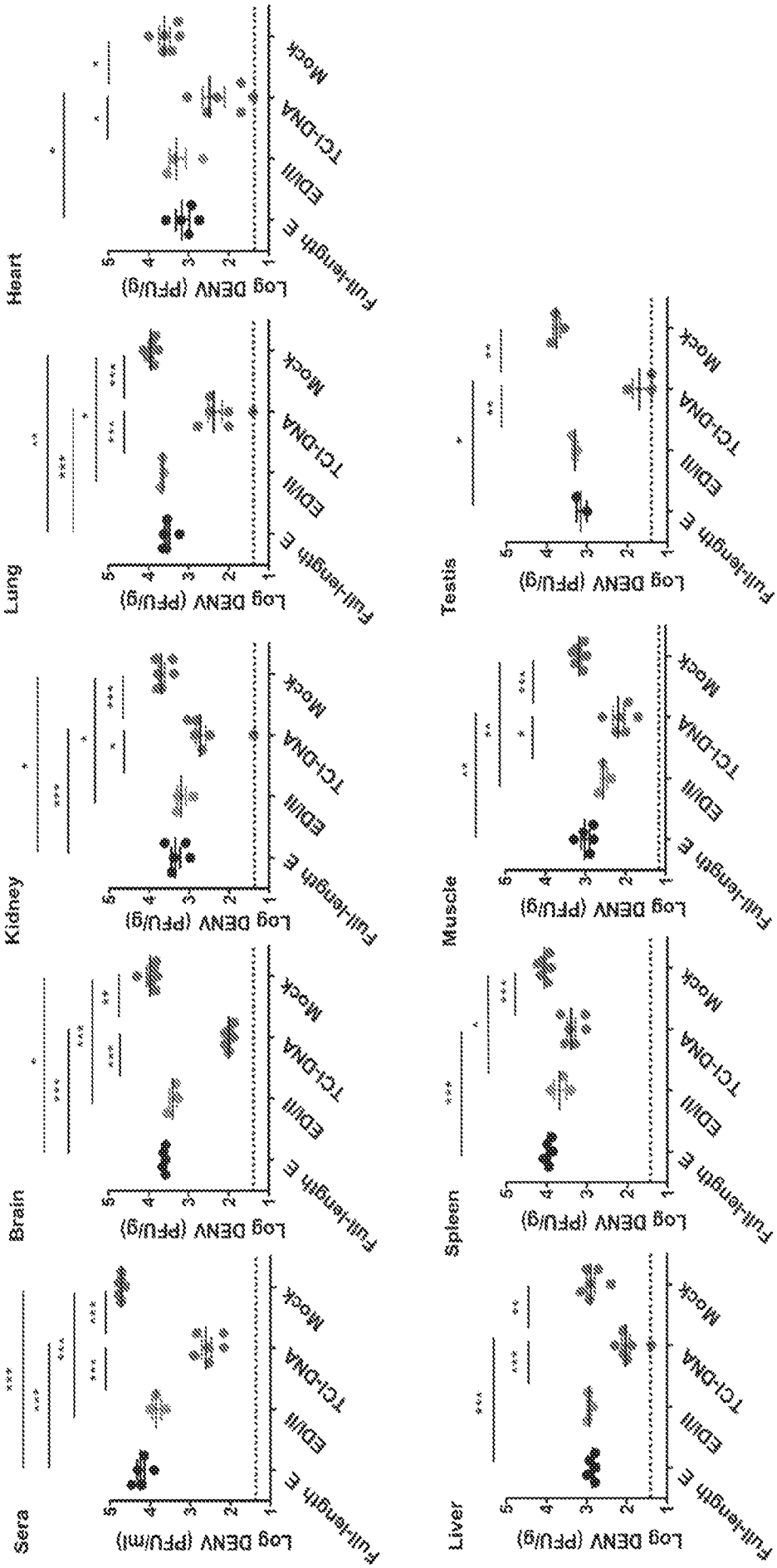

Sera
Brain
Kidney
Lung
Heart
Liver
Spleen
Muscle
Testis
Log DENV (PFU/ml)
Log DENV (PFU/g)
Full-length E
EDIII
TCI-DNA
Mock

FIG. 15

INTERNATIONAL SEARCH REPORT

International application No.
PCT/US2021/016654

A. CLASSIFICATION OF SUBJECT MATTER

IPC(8) - A61K 39/12; A61P 31/14 (2021.01)
CPC - A61K 39/12; A61K 2039/5254; A61P 31/14; C12N 2770/24134 (2021.02)

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)
see Search History document

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched
see Search History document

Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)
see Search History document

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
A	WO 2019/126690 A1 (CODAGENIX INC. et al) 27 June 2019 (27.06.2019) entire document	1-5, 7-11, 14-17
A	WO 2017/140905 A1 (CUREVAC AG et al) 24 August 2017 (24.08.2017) entire document	1-5, 7-11, 14-17
A	WO 2018/129160 A1 (THE UNITED STATES OF AMERICA, AS REPRESENTED BY THE SECRETARY, DEPARTMENT OF HEALTH AND HUMAN SERVICES) 12 July 2018 (12.07.2018) entire document	1-5, 7-11, 14-17
A	US 2019/0175716 A1 (OXFORD UNIVERSITY INNOVATION LIMITED) 13 June 2019 (13.06.2019) entire document	1-5, 7-11, 14-17
A	US 2019/0083601 A1 (THEMIS BIOSCIENCE GMBH) 21 March 2019 (21.03.2019) entire document	1-5, 7-11, 14-17
A	US 2019/0008945 A1 (VALNEVA AUSTRIA GMBH) 10 January 2019 (10.01.2019) entire document	1-5, 7-11, 14-17

☐ Further documents are listed in the continuation of Box C. ☐ See patent family annex.

* Special categories of cited documents:
"A" document defining the general state of the art which is not considered to be of particular relevance
"D" document cited by the applicant in the international application
"E" earlier application or patent but published on or after the international filing date
"L" document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified)
"O" document referring to an oral disclosure, use, exhibition or other means
"P" document published prior to the international filing date but later than the priority date claimed
"T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention
"X" document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone
"Y" document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art
"&" document member of the same patent family

Date of the actual completion of the international search	Date of mailing of the international search report
20 April 2021	MAY 03 2021
Name and mailing address of the ISA/US Mail Stop PCT, Attn: ISA/US, Commissioner for Patents P.O. Box 1450, Alexandria, VA 22313-1450 Facsimile No. 571-273-8300	Authorized officer Blaine R. Copenheaver Telephone No. PCT Helpdesk: 571-272-4300

INTERNATIONAL SEARCH REPORT

International application No.
PCT/US2021/016654

Box No. II Observations where certain claims were found unsearchable (Continuation of item 2 of first sheet)

This international search report has not been established in respect of certain claims under Article 17(2)(a) for the following reasons:

1. ☐ Claims Nos.:
because they relate to subject matter not required to be searched by this Authority, namely:

2. ☐ Claims Nos.:
because they relate to parts of the international application that do not comply with the prescribed requirements to such an extent that no meaningful international search can be carried out, specifically:

3. ☒ Claims Nos.: 6, 12, 13
because they are dependent claims and are not drafted in accordance with the second and third sentences of Rule 6.4(a).

Box No. III Observations where unity of invention is lacking (Continuation of item 3 of first sheet)

This International Searching Authority found multiple inventions in this international application, as follows:

1. ☐ As all required additional search fees were timely paid by the applicant, this international search report covers all searchable claims.

2. ☐ As all searchable claims could be searched without effort justifying additional fees, this Authority did not invite payment of additional fees.

3. ☐ As only some of the required additional search fees were timely paid by the applicant, this international search report covers only those claims for which fees were paid, specifically claims Nos.:

4. ☐ No required additional search fees were timely paid by the applicant. Consequently, this international search report is restricted to the invention first mentioned in the claims; it is covered by claims Nos.:

Remark on Protest

☐ The additional search fees were accompanied by the applicant's protest and, where applicable, the payment of a protest fee.

☐ The additional search fees were accompanied by the applicant's protest but the applicable protest fee was not paid within the time limit specified in the invitation.

☐ No protest accompanied the payment of additional search fees.