# TARGETED GENE DELIVERY FOR DENDRITIC CELL VACCINATION

## BACKGROUND OF THE INVENTION

[0001] The invention relates generally to targeted gene delivery, and more particularly to the use of a recombinant virus comprising a targeting molecule that targets and binds dendritic cells and can thus be used for dendritic cell vaccination.

[0002] Immunization is one of the most productive tools in modern medical practice but remains burdened by limitations. Certain infectious diseases such as HIV/AIDS, malaria, and tuberculosis are not currently controlled at all by immunization, while other infectious diseases are controlled by complex immunization regimens. Cancer is a promising target for immunotherapeutic treatments, but clinical outcomes in experimental trials have been disappointing (Rosenberg, S.A. et al. 2004. *Nat. Med.* 10:909-915, which is incorporated herein by reference in its entirety). Novel methods of immunization are needed, for example, to reliably induce anti-tumor immunity.

[0003] Dendritic cells (DCs) play critical roles in both innate and adaptive immunity. DCs are specialized antigen-presenting cells with the unique capability to capture and process antigens, migrate from the periphery to a lymphoid organ, and present the antigens to resting T cells in a major histocompatibility complex (MHC)-restricted fashion (Banchereau, J. & Steinman, R.M. 1998. *Nature* 392:245-252; Steinman, R.M., et al. 2003. *Ann Rev Immunol* 21: 685-711, each of which is incorporated herein by reference in its entirety). These cells are derived from bone marrow (BM) and are characterized by dendritic morphology and high mobility. Immature DCs are adept at antigen ingestion and are distributed as sentinels in peripheral tissue throughout the body. However, maturation of DCs is required in order to mount an efficient immune response (Steinman, R.M., et al. 2003. *supra*). The matured DCs express high levels of MHC-antigen complex and other costimulatory molecules (such as CD40, B7-1, B7-2 and CD1a) (Steinman, R.M. 1991. *Ann Rev Immunol* 9: 271-296, which is incorporated herein by reference in its entirety; Banchereau, J. and R.M. Steinman. 1998. *supra*). These molecules play key roles in stimulating T cells.

[0004] The discovery of the role of DCs as specialized antigen-presenting cells (APCs) has fueled attempts at DC-based immunization/vaccination that involve loading DCs with specific antigens (Banchereau, J. & Palucka, A.K. 2005. *Nat. Rev. Immunol.* 5:296-306; Figdor, C.G. et al. 2004. *Nat. Med.* 10:475-480, each of which is incorporated herein by reference in its entirety). However, all of these attempts involve ex vivo loading of DCs with specific antigens. Ex vivo generated DCs are then administered to the patient. Ex vivo generation of DCs for each patient is extremely labor intensive process.

[0005] By contrast, the present invention is directed *inter alia* to targeting, antigen loading and activation of DCs in vivo, which results in vivo treatment of diseases by generating a beneficial immune response in the patient. The invention thus fulfills a longstanding need for effective and efficient regimes for immunization/vaccination.

## SUMMARY OF THE INVENTION

**[0005a]** In one aspect, there is provided an in vitro method of delivering a lentiviral vector encoding an antigen to a dendritic cell expressing DC-SIGN (Dendritic Cell Specific ICAM-3 (Intracellular Adhesion Molecules 3)-Grabbing Nonintegrin), the method comprising:

transducing the dendritic cell with a recombinant virus, wherein the recombinant virus comprises said lentiviral vector,
wherein the recombinant virus comprises an alphavirus glycoprotein that targets said cell expressing DC-SIGN,
wherein said glycoprotein is an alphavirus E2 glycoprotein mutated at a heparan sulfate binding site to decrease or eliminate its binding to heparan sulfate.

**[0005b]** In one aspect, there is provided a recombinant virus as defined herein, or a pharmaceutical composition comprising said recombinant virus.

[0005c] In one aspect, there is provided a recombinant virus comprising a lentiviral vector encoding an antigen and an alphavirus glycoprotein that targets cells expressing DC-SIGN wherein said glycoprotein is an alphavirus E2 glycoprotein mutated at a heparan sulfate binding site to decrease or eliminate its binding to heparan sulfate, for use in stimulating an immune response to said antigen in a mammal.

**[0005d]** In one aspect, there is provided a dendritic cell transduced with a recombinant virus, wherein the recombinant virus is as defined herein.

[0006] In one aspect of the invention methods of delivering a polynucleotide to a dendritic cell expressing DC-SIGN are provided. In some embodiments the methods comprise transducing the dendritic cell with a recombinant virus, wherein the recombinant virus comprises the polynucleotide to be delivered and a targeting molecule that binds DC-SIGN. In some embodiments the targeting molecule is specific for DC-SIGN.

[0007] In some embodiments of the invention, the recombinant virus comprises sequences from a lentivirus genome, such as an HIV genome.

[0008] In other embodiments the recombinant virus comprises sequences from a gammaretrovirus genome, such as sequences from a Mouse Stem Cell Virus (MSCV) genome or a Murine Leukemia Virus (MLV) genome.

[0009] In some embodiments of the invention, the methods utilize a targeting molecule comprising a viral glycoprotein derived from at least one virus selected from the group of: Sindbis virus, influenza virus, Lassa fever virus, tick-borne encephalitis virus, Dengue virus, Hepatitis B virus, Rabies virus, Semliki Forest virus, Ross River virus, Aura virus, Borna disease virus, Hantaan virus, and SARS-CoV virus. In more particular embodiments, the targeting molecule comprises a modified viral glycoprotein derived from Sindbis virus (SIN or SVG). In certain embodiments, the targeting molecule is SINmu also known as SVGmu (SEQ ID NO: 11 ).

[0010] In some embodiments, the polynucleotide to be delivered to a dendritic cell comprises at least one of the following: a gene encoding a protein of interest, a gene encoding a siRNA, and a gene encoding a microRNA. The gene encoding a protein of interest may encode an antigen, such as a tumor antigen or an HIV antigen.

[0011] The recombinant virus may be produced by transfecting a packaging cell line with a viral vector comprising the polynucleotide to be delivered and a vector comprising a gene encoding the targeting molecule; culturing the transfected packaging cell line; and recovering the recombinant virus from the packaging cell culture. In some embodiments, the packaging cell line is a 293 cell line.

[0012] In some embodiments of the invention, the polynucleotide is delivered to a dendritic cell *in vitro*, while in other embodiments the polynucleotide is delivered to a dendritic cell in a subject *in vivo*. The subject is typically a mammal, such as a human, mouse or guinea pig.

[0013] In another aspect, recombinant virus comprising: a polynucleotide of interest; and a targeting molecule that binds DC-SIGN are provided. In some embodiments the targeting molecule specifically binds DC-SIGN. The recombinant virus may comprise sequences from a lentivirus genome, such as sequences from an HIV genome. In other embodimentsthe recombinant virus comprises sequences from a gammaretrovirus genome, such as sequences from a Mouse Stem Cell Virus (MSCV) genome or a Murine Leukemia Virus (MLV) genome.

[0014] The targeting molecule may comprise a viral glycoprotein derived from at least one virus selected from the group of: Sindbis virus, influenza virus, Lassa fever virus, tick-borne encephalitis virus, Dengue virus, Hepatitis B virus, Rabies virus, Semliki Forest virus, Ross River virus, Aura virus, Borna disease virus, Hantaan virus, and SARS-CoV virus. In some embodiments the targeting molecule is a viral glycoprotein derived from Sindbis virus. In particular embodiments, the targeting molecule is SVGmu (SEQ ID NO: 11).

[0015] The polynucleotide may be, for example, at least one of the following: a gene encoding a protein of interest, a gene encoding a siRNA, and a gene encoding a

microRNA of interest. In some embodiments the polynucleotide encodes an antigen, such as a tumor antigen or an HIV antigen.

[0016] In another aspect, methods of stimulating an immune response in a mammal are provided. A polynucleotide encoding an antigen to which an immune response is desired is delivered to dendritic cells expressing DC-SIGN by contacting the dendritic cells with a recombinant virus comprising the polynucleotide and a targeting molecule that binds DC-SIGN. In some embodiments the targeting molecule is specific for DC-SIGN and does not bind appreciably to other molecules. In other embodiments the targeting molecule binds preferentially to DC-SIGN.

[0017] In a further aspect, vectors encoding targeting molecules that bind DC-SIGN are provided. In some embodiments, the targeting molecule is a modified viral glycoprotein. In further embodiments, the targeting molecule is SVGmu (SEQ ID NO: 11 ). The targeting molecule specifically binds DC-SIGN in some embodiments. The vector may additionally encode one or more genes of interest, such as a gene encoding an antigen and/or a gene encoding a dendritic cell maturation factor.

[0018] In a still further aspect, methods of treating a patient with a disease are provided. A recombinant virus is administered to the patient, where the recombinant virus comprises a polynucleotide encoding an antigen associated with the disease and a targeting molecule that binds DC-SIGN. The targeting molecule may be derived from a viral glycoprotein. In some embodiments, the targeting molecule is SVGmu (SEQ ID NO: 11).

[0019] The disease to be treated is generally one for which an antigen is known or can be identified. In some embodiments of the invention, the disease to be treated is cancer. In other embodiments, the disease is HIV/AIDS.

[0020] Dendritic cells transduced with a recombinant virus are also provided, where the recombinant virus comprises a polynucleotide of interest and a targeting molecule that binds DC-SIGN. In some embodiments, the targeting molecule comprising a viral glycoprotein derived from at least one virus selected from the group of: Sindbis virus, influenza virus, Lassa fever virus, tick-borne encephalitis virus, Dengue virus, Hepatitis B virus, Rabies virus, Semliki Forest virus, Ross River virus, Aura virus, Borna disease virus,

Hantaan virus, and SARS-CoV virus. In some embodiments, the targeting molecule is SVGmu (SEQ ID NO: 11).

[0021] Further, methods of immunizing a mammal by delivering a polynucleotide encoding an antigen to dendritic cells expressing DC-SIGN are also provided in which the dendritic cells are contacted with a recombinant virus comprising a polynucleotide encoding an antigen and a targeting molecule that binds DC-SIGN. In some embodiments, the dendritic cells are contacted with the recombinant virus ex vivo. In other embodiments, the dendritic cells are contacted with the recombinant virus in vivo.

[0022] The methods disclosed herein can also be used to stimulate an immune response to a specific antigen in a mammal by delivery of a polynucleotide encoding the antigen to dendritic cells using a recombinant virus comprising the polynucleotide and a targeting molecule that binds DC-SIGN. The immune response may be modulated by providing a further polynucleotide whose expression in the dendritic cell modulates the immune response. For example, a polynucleotide encoding a dendritic maturation factor may be delivered.

## BRIEF DESCRIPTION OF THE DRAWINGS

[0023] Figure 1 is a schematic representation of a general strategy to target dendritic cells (DCs) for antigen delivery. Sindbis virus wild-type glycoprotein is mutated at the heparan sulfate binding site to abolish its binding ability. The resulting mutant glycoprotein (SVGmu) binds DC-SIGN but does not bind heparin sulfate. DC-SIGN: Dendritic Cell Specific ICAM-3 (Intracellular Adhesion Molecules 3)-Grabbing Nonintegrin.

[0024] Figure 2 illustrates laser confocal microscope images of virus particles harvested from virus-producing cells transiently transfected with lentiviral vector, plasmids encoding GFP-vpr and SVGmu, and other necessary packaging constructs. The virus particles are labeled with GFP (green). The surface incorporation of SVGmu was detected by immunostaining with an anti-HA tag antibody (red) to label SVGmu. In the "GFP" slide, viral particles labled with GFP are green. In the "SVGmu" slide, viral particles with surface incorporation of SVGmu are stained red. In the "Merged" slide, viral particles where only GFP is expressed are green, viral particles where only SVGmu is incorporated into the surface are red, and viral particles expressing both GFP and containing SVGmu are yellow.

The overlay of the green and red colors (yellow) indicates the viral particles containing SVGmu, which represent the majority of the total virus particles. The scale bar represents 2 μm.

[0025] Figure 3A shows flow cytometric analysis of constructed target cell lines 293T.hDCSIGN expressing human DC-SIGN, and 293T.mDCSIGN expressing murine DC-SIGN. Solid line: expression of DC-SIGN in target cell lines; shaded area: background staining in 293T cells.

[0026] Figure 3B shows flow cytometry results for detection of GFP expressed in 293T cells transduced with lentivector enveloped with wild-type Sindbis glycoprotein (FUGW/SVG) or mutant Sindbis glycoprotein (FUGW/SVGmu). One milliliter of fresh viral supernatants of FUGW/SVG and FUGW/SVGmu were used to transduce 293T cells ($2x10^5$) expressing human DC-SIGN (293T.hDCSIGN) or murine DC-SIGN (293T.mDCSIGN). The parental 293T cells lacking the expression of DC-SIGN were included as controls. As illustrated, lentivector enveloped with the mutant Sindbis virus glycoprotein (SVGmu) is able to specifically transduce 293T cells expressing human or mouse DC-SIGN. The specific transduction titer of FUGW/SVGmu was estimated to be approximately $1x10^6$ TU/ml for 293T.hDC-SIGN and approximately $0.8x10^6$ TU/ml for 293T.mDC-SIGN.

[0027] Figure 4A shows flow cytometry results that illustrate the ability of the FUGW lentivirus enveloped with the mutant Sindbis glycoprotein (FUGW/SVGmu) to specifically transduce mouse dendritic cells expressing DC-SIGN in a primary mixed bone marrow culture. Whole bone marrow cells isolated from B6 mice were exposed to the fresh viral supernatant of FUGW/SVGmu. The FUGW lentivector pseudotyped with the ecotropic glycoprotein (FUGW/Eco) was included as a non-targeting control. Surface antigens of the GFP-positive cells were assessed by staining with anti-CD11c and anti-DC-SIGN antibodies.

[0028] Figure 4B shows flow cytometry results indicating that FUGW lentivirus enveloped with the mutant Sindbis glycoprotein (FUGW/SVGmu) does not transduce other cell types including primary T cells ($CD3^+$, top panel) and B cells ($CD19^+$, bottom panel). Primary $CD3^+$ T cells and $CD19^+$ B cells were isolated from the mouse spleen and transduced with the fresh viral supernatant of either the targeting FUGW/SVGmu or non-targeting FUGW/Eco vector. GFP expression was analyzed by flow cytometry. Solid line: cells

exposed to indicated lentiviral vector; shaded area: cells without transduction (as a negative control).

[0029] Figure 5 shows flow cytometry results that illustrate the ability of the FUGW lentivirus enveloped with the mutant Sindbis glycoprotein (FUGW/SVGmu) to specifically transduce bone marrow-derived DCs (BMDCs). BMDCs were generated by culturing freshly isolated bone marrow cells in the presence of cytokine GM-CSF for 6 days. The cells were then transduced with the fresh viral supernatant of either the targeting FUGW/SVGmu or non-targeting FUGW/Eco vector. GFP and CD11c expression were measured by flow cytometry.

[0030] Figure 6 shows activation of BMDCs after targeted transduction with FUGW/SVGmu. DC activation was assessed by analyzing the surface expression of CD86 and I-$A^b$ using flow cytometry. The addition of LPS (1 μg/ml) overnight was used as a synergistic stimulator for the activation of transduced BMDCs. Shaded area: GFP negative (untransduced); solid line: GFP positive (transduced).

[0031] Figures 7A, 7B and 7C illustrate targeting of DCs *in vivo* using FUGW/SVGmu lentivirus. B6 mice were injected with $50x10^6$ TU of FUGW/SVGmu and analyzed 3 days later. Non-immunized mice were included as a control. In Figure 7A, the images show the size of a representative inguinal lymph node close to the injection site compared to that of the equivalent lymph node distant from the injection site. Figure 7B illustrates the total cell number counts of the indicated lymph nodes in Figure 7A. Figure 7C illustrates representative flow cytometric analysis of $CD11c^+$ cells from the two lymph nodes shown in Figure 7A. The numbers indicate the fraction of $GFP^+$ DC populations

[0032] Figure 8 provides a schematic representation of the lentivector encoding the OVA antigen (FOVA) (top) and the lentivector encoding GFP (FUGW) as a control (bottom).

[0033] Figure 9 illustrates *in vitro* stimulation of $CD8^+$ OT1 T cells by dendritic cells that were transduced with the FOVA/SVGmu (DC/FOVA) or FUGW/SVGmu lentivector (DC/FUGW), or by non-transduced BMDCs pulsed with OVAp peptide (SIINFEKL) (DC/OVAp). Patterns of surface activation markers of OT1 T cells cocultured with BMDCs were assessed by antibody staining for CD25, CD69, CD62L, and CD44.

Shaded area: naïve OT1 T cells harvested from transgenic animals; solid line: OT1 T cells cocultured with indicated BMDCs.

[0034] Figure 10A illustrates the measurement of IFN-γ by ELISA in OT1 T cells mixed with various dilutions of BMDCs transduced with FOVA/SVGmu (■), FUGW/SVGmu (●), or pulsed with OVAp peptide (▲) and cultured for 3 days.

[0035] Figure 10B illustrates the proliferative responses of treated OT1 T cells from Figure 10A measured by a [$^3$H] thymidine incorporation assay for 12 hours.

[0036] Figure 11 illustrates *in vitro* stimulation of $CD4^+$ OT2 T cells by dendritic cells that were transduced with the FOVA/SVGmu (DC/FOVA) or FUGW/SVGmu lentivector (DC/FUGW), or by non-transduced BMDCs pulsed with OVAp* peptide (ISQAVHAAHAEINEAGR) (DC/OVAp*). Patterns of surface activation markers of OT2 transgenic T cells cocultured with BMDCs were assessed by antibody staining for CD25, CD69, CD62L, and CD44. Shaded area: naïve OT2 T cells harvested from transgenic animals; solid line: OT2 T cells cocultured with BMDCs.

[0037] Figure 12 illustrates the measurement of IFN-γ by ELISA in OT2 T cells mixed with various dilutions of BMDCs transduced with FOVA/SVGmu (■), FUGW/SVGmu (●), or pulsed with OVAp* peptide (▲) and cultured for 3 days.

[0038] Figure 13A provides a schematic representation of the retroviral vector MIG-OT1 used for genetic modification of murine hematopoietic stem cells (HSCs).

[0039] Figure 13B illustrates how $CD8^+$ OT1 T cells derived from the MIG-OT1-modified HSCs in reconstituted mice were identified by the co-expression of GFP and TCR Vα2 or Vβ5. HSCs from B6 mice were infected with MIG-OT1 pseudotyped with Eco (MIG-OT1/Eco) and transferred into irradiated B6 recipient mice. Eight weeks post-transfer, the $CD8^+$ OT1 T cells were identified by flow cytometry.

[0040] Figure 14A illustrates assessment of patterns of surface activation markers on $GFP^+OT1^+$ T cells isolated from the spleens of reconstituted and immunized mice. Mice reconstituted by MIG-OT1 modified HSCs were immunized by direct subcutaneous injection of $10x10^6$ TU of either FOVA/SVGmu or FUGW/SVGmu (as a control) and analyzed seven days later. Detection of surface staining for CD69, CD62L and CD44 was conducted. Solid line: $GFP^+OT1^+$ T cells from FOVA/SVGmu-immunized mice; dotted line: $GFP^+OT1^+$ T

cells from control FUGW/SVGmu-immunized mice; shaded area: $GFP^+OT1^+$ T cells from non-immunized mice.

**[0041]** Figure 14B illustrates the total number of OT 1 cells harvested from lymph nodes (LN, □) or spleens (SP, ■) of non-immunized mice (no imm) or mice immunized with FUGW/SVGmu or FOVA/SVGmu.

**[0042]** Figure 15 illustrates *in vivo* stimulation of antigen specific T cell and antibody responses in wild-type mice following a subcutaneous injection of the DC-targeting lentivector FOVA/SVGmu. B6 mice were immunized subcutaneously with $50x10^6$ TU of either FOVA/SVGmu or FUGW/SVGmu (as a control). Mice without immunization (no imm.) were included as a negative control. Fourteen days post-immunization, spleen cells were harvested and analyzed for the presence of OVA-specific T cells measured by H-$2K^b$-SIINFEKL-PE tetramer and CD44 staining. Indicated percentages are the percent of total $CD8^+$ T cells.

**[0043]** Figures 16A and 16B illustrate *in vivo* OVA-specific T cell responses seen in mice receiving different subcutaneous doses of FOVA/SVGmu. OVA-specific T cells were identified by tetramer staining as in Figure 17. Figure 16A shows the measured percentage of OVA-specific T cells following immunization with $100x10^6$ TU of FOVA/SVGmu. Figure 16B shows the dose responses of OVA-specific T cells following injection of the indicated doses of FOVA/SVGmu.

**[0044]** Figure 17A illustrates the patterns of surface activation markers of OVA-specific $CD8^+$ T cells (identified as tetramer positive cells) isolated from FOVA/SVGmu immunized mice 2 weeks post-injection. The surface activation markers were assessed by antibody staining for CD25, CD69, CD62L and CD44. Solid line: $tetramer^+CD8^+$ T cells from FOVA/SVGmu-immunized mice; shaded area: naïve $CD8^+$ T cells from non-immunized mice.

**[0045]** Figure 17B illustrates the OVA-specific serum IgG titer of B6 mice following immunization with $50x10^6$ TU FOVA/SVGmu. Sera were collected on day 7 and day 14 post-immunization and were analyzed for the titer of OVA-specific IgG using ELISA at serial 10x dilutions, starting at 1:100. The titer values were determined by the highest

dilution at which the optical density was 2x standard derivations higher than that of the baseline serum at the equivalent dilution.

**[0046]** Figure 18 illustrates tumor size as a function of time in a murine E.G7 tumor model. B6 mice were immunized with subcutaneous injection of $50x10^6$ TU of either FOVA/SVGmu (▲) or mock vector FUW/SVGmu (●). No immunization (■) was included as a control. Four mice were included in each group. At day 14 post-immunization, the mice were challenged with $5x10^6$ of either E.G7 tumor cells (expressing the OVA antigen, left panel) or the parental EL4 tumor cells (lacking the OVA antigen, as a control, right panel) subcutaneously. Tumor growth was measured with a fine caliper and is shown as the product of the two largest perpendicular diameters ($mm^2$).

**[0047]** Figure 19 illustrates the *in vivo* the kinetic growth of tumors in a murine E.G7 tumor eradication model. An albino strain of B6 mice were implanted with $5x10^6$ E.G7 tumor cells stably expressing a firefly luciferase imaging gene (E.G7.luc). A mouse (#1) without tumor implantation was included as a control. Mice bearing tumors were treated without immunization (#2), or with immunization by the injection of $50x10^6$ TU of FOVA/SVGmu at days 3 and 10 (#3, #4) post tumor challenge. The kinetic growth of the tumors was monitored by live animal imaging using BLI. The $p/s/cm^2/sr$ represents $photons/sec/cm^2/steridian$.

**[0048]** Figure 20 shows the quantitation of luminescence signals generated by the E.G7 tumors in Figure 19. (□) for mouse #2; (●) for mouse #3; (▲) for mouse #4.

**[0049]** Figure 21 illustrates the percentage of OVA-specific T cells present following immunization with $100x10^6$ TU of FOVA/SVGmu in the albino strain of B6 mice. Albino B6 mice were immunized subcutaneously with $50x10^6$ TU of FOVA/SVGmu. Mice without immunization (no imm.) were included as a negative control. Fourteen days post-immunization, spleen cells were harvested and analyzed for the presence of OVA-specific T cells measured by H-$2K^b$-SIINFEKL-PE tetramer and CD44 staining. Indicated percentages are the percent of total $CD8^+$ T cells.

**[0050]** Figure 22A provides a schematic representation of a DC-targeted lentivector encoding an imaging gene firefly luciferase (Luc), designated as Fluc/SVGmu.

[0051] Figure 22B illustrates bioluminescence imaging of mice injected subcutaneously with $50x10^6$ TU of either the DC-targeting Fluc/SVGmu lentivector (shown in Figure 25A) or a non-targeting Fluc/VSVG lentivector. The representative image was obtained at day 30 post-injection using IVIS200® (Xenogen).

[0052] Figure 23 illustrates that administration of a single dose of recombinant DC-specific lentivector FOVA/SVGmu can generate IFN-$\gamma^+CD8^+$ T cells in B6 mice. Naïve B6 mice are immunized by subcutaneous injection of $50x10^6$ TU of FOVA/SVGmu lentivector, or the same dose of FUGW/SVGmu as a control. The non-immunized B6 mice (no imm.) were included as a negative control. Two weeks later, spleen cells were harvested from the experimental mice, and were analyzed for intracellular IFN-γ production using flow cytometry with or without OVAp peptide restimulation. Indicated percentages are the percent of IFN-$\gamma^+CD8^+$ T cells of the total $CD8^+$ T cells.

[0053] Figure 24 illustrates a schematic representation of lentiviral constructs for preparation of DC-targeting recombinant viruses.

[0054] Figure 25 shows a schematic representation of an embodiment of *in situ* vaccination against HIV/AIDS.

## DETAILED DESCRIPTION OF THE PREFERRED EMBODIMENT

[0055] Genetic engineering has been shown to be an efficient and potent means to convert dendritic cells (DCs) into special immune cells to induce antigen-specific immune responses. A great deal of research involving *in vitro* manipulation of DCs for vaccination/immunization against cancer, HIV and other diseases has been conducted. However, until now, it has not been possible to specifically and efficiently deliver a gene of interest, such as a gene encoding an antigen, to dendritic cells *in vitro* and *in vivo*. The inventors have discovered novel methods and compositions for efficient and specific targeting of DCs *in vitro* and *in vivo*. The methods and compositions can be used to induce antigen-specific immune responses, for example for immunotherapy.

[0056] Embodiments of the invention include methods and compositions for targeting dendritic cells (DCs) by using a recombinant virus to deliver a polynucleotide to the DCs. This is preferably accomplished through targeting the DC-specific surface molecule DC-SIGN (Dendritic Cell Specific ICAM-3 (Intracellular Adhesion Molecules 3)-Grabbing

Nonintegrin; also known as CD209). DC-SIGN is a C-type lectin-like receptor capable of rapid binding and endocytosis of materials (Geijtenbeek, T.B., et al. 2004. *Annu. Rev. Immunol.* 22: 33-54, which is incorporated herein by reference in its entirety). In preferred embodiments, recombinant viruses are enveloped with a designed targeting molecule that is specific in its recognition for DC-SIGN. The polynucleotide can include, but is not limited to, a gene of interest, siRNA(s), and/or microRNA(s). In preferred embodiments, the polynucleotide encodes an antigen. In some embodiments, the recombinant virus delivers more than one gene to DCs. For example, genes encoding two or more antigens could be delivered. The delivery of more than one gene can be achieved, for example, by linking the genes with an Internal Ribosome Entry Site (IRES), and/or with 2A sequences, and driving the expression using a single promoter/enhancer.

[0057] As discussed in more detail below, embodiments of the invention are based on the use of recombinant viruses, such as lentiviruses and gammaretroviruses, because these viruses are able to incorporate into their envelope a large number of proteins are found on the surface of virus-producing cells. However, as also discussed below, other types of viruses may be used and the methods modified accordingly. Generally, a packaging cell line is transfected with a viral vector encoding a polynucleotide of interest (typically encoding an antigen), at least one plasmid encoding virus packaging components (such as gag and pol) and a targeting molecule that is engineered to bind dendritic cells. In preferred embodiments, the targeting molecule is genetically engineered to specifically bind the DC-SIGN cell surface marker of dendritic cells. During budding of the virus, the targeting molecule, which is expressed in the packaging cell membrane, is incorporated into the viral envelope. As a result, the retroviral particles comprise a core including the polynucleotide of interest and an envelope comprising the targeting molecule on its surface.

[0058] The targeting molecule is able to bind DC-SIGN on a dendritic cell, and the virus is able to deliver the gene of interest to the dendritic cell. Without wishing to be bound by theory, it is believed that the binding induces endocytosis, bringing the virus into an endosome, triggering membrane fusion, and allowing the virus core to enter the cytosol. Following reverse transcription and migration of the product to the nucleus, the genome of the virus integrates into the target cell genome, incorporating the polynucleotide of interest

into the genome of the target cell. The DC then expresses the polynucleotide of interest (typically encoding an antigen). The antigen is then processed and presented to T and B cells by DCs, generating an antigen-specific immune response. The specific pathway described above is not required so long as the dendritic cell is able to stimulate an antigen-specific immune response.

[0059] Embodiments of the present invention include methods and compositions for direct targeting of a gene of interest to DCs both *in vitro* and *in vivo*. In some preferred *in vivo* embodiments, the gene of interest is delivered to DCs without *in vitro* culture of DCs. For example, the gene of interest may be delivered to DCs via a direct administration of the targeting virus into a living subject. The gene of interest preferably encodes an antigen against which an immune response is desired. Exemplary antigens include: tumor specific antigens, tumor-associated antigens, tissue-specific antigens, bacterial antigens, viral antigens, yeast antigens, fungal antigens, protozoan antigens, parasite antigens, mitogens, and the like. Other antigens will be apparent to one of skill in the art and can be utilized without undue experimentation.

[0060] The methods disclosed herein may be readily adopted to utilize targeting molecules that are specific for DCs or that can be manipulated to provide the desired specificity. The targeting molecule is preferably an engineered viral glycoprotein that binds DC-SIGN in dendritic cells and that facilitates delivery of the gene of interest into the dendritic cells. Exemplary targeting molecules include, but are not limited to, glycoproteins derived from the following: Sindbis virus, influenza virus, Lassa fever virus, tick-borne encephalitis virus, Dengue virus, Hepatitis B virus, Rabies virus, Semliki Forest virus, Ross River virus, Aura virus, Borna disease virus, Hantaan virus, and SARS-CoV virus. The targeting molecule is preferably membrane bound. If necessary, a DC-SIGN-specific targeting molecule that is designed or derived from a viral glycoprotein for use in the recombinant virus can be modified to a membrane bound form.

[0061] Any method known in the art can be used to engineer the targeting molecule to provide the desired specificity. Exemplary methods include, but are not limited to, rational protein engineering and DNA shuffling. Generally, to engineer a targeting molecule specific for DCs, a viral glycoprotein that interacts with a dendritic cell-specific

surface marker is provided. Preferably, the viral glycoprotein interacts with DC-SIGN. The viral glycoprotein can also interact with at least a second cell surface marker such as, for example, heparin sulfate (HS), which is expressed on cell types other than DCs. The viral glycoprotein is modified such that its ability to interact with the DC-specific surface marker is maintained while its ability to interact with additional cell surface markers is decreased or eliminated. The modification can be a mutation in at least one residue of the viral glycoprotein amino acid sequence. The mutation can be a deletion, addition or substitution of the residue, and it can be carried out by standard methods known in the art. The desired specificity can readily be confirmed. For example, once the viral glycoprotein is modified, it can be used to prepare a recombinant virus by co-transfection with a viral vector containing a reporter gene and at least one plasmid encoding virus packaging components into a packaging cell line. The glycoprotein is incorporated into the viral envelope during budding of the virus. The virus can be used to transfect both a pure population of DCs as well as a mixed population of cells containing DCs, and specificity of the viral transduction of DCs can be confirmed by assaying the cells for expression of the reporter gene in DCs and not to a significant extent in other cell types. If the specificity is not sufficiently stringent (for example, if undesired levels of infection of other cell types is observed), the viral glycoprotein can be modified further and assayed as described until the desired specificity is achieved.

**[0062]** Embodiments of the present invention include the delivery to DCs of DC activators and/or maturation factors in conjunction with antigens. Exemplary DC activators and maturation factors include, but are not limited to, stimulation molecules, cytokines, chemokines, antibodies and other agents such as Flt-3 ligands. For example, the DC maturation factors can include at least one of the following: GM-CSF, IL-2, IL-4, IL-6, IL-7, IL-15, IL-21, IL-23, TNFα, B7.1, B7.2, 4-1BB, CD40 ligand (CD40L) and drug-inducible CD40 (iCD40) (Hanks, B.A., et al. 2005. *Nat Med* 11:130-137, which is incorporated herein by reference in its entirety).

**[0063]** Embodiments of the present invention also include methods and compositions related to administration of recombinant virus as described above, or DCs infected with recombinant virus, into patients to stimulate antigen-specific immune

responses, such as, for example, T cell responses (cellular immune responses) and B cell responses (humoral immune responses). For example, activated CD4 T cells can coordinate and orchestrate the $CD8^+$ cytotoxic T cells and the B cells in an antigen-specific response. In preferred embodiments, the recombinant virus and/or DCs infected with recombinant virus are used to stimulate immune responses for the prevention and treatment of diseases such as, but not limited to, cancer and AIDS/HIV. Any disease can be treated for which an immune response to a particular antigen is beneficial, including, but not limited to, neoplastic disease, infectious disease, and immune-related diseases.

[0064] As herein described, studies were conducted that resulted in the discovery of methods and compositions that can be used to direct recombinant viruses to provide genes encoding particular antigens into DCs. The genetic modification of DCs in order to elicit productive immune responses can be used in the prevention and treatment of diseases and provides an effective method of inducing effective T cell immunity as well as strong antibody production. The methods and compositions described herein can provide potent means for immunization with desired antigens. Such immunization can prevent and treat diseases such as, for example, cancer and AIDS/ HIV.

Definitions

[0065] Unless defined otherwise, technical and scientific terms used herein have the same meaning as commonly understood by one of ordinary skill in the art to which this invention belongs. See, e.g., Singleton *et al.*, *Dictionary of Microbiology and Molecular Biology 2nd ed.*, J. Wiley & Sons (New York, NY 1994); Sambrook *et al.*, *Molecular Cloning, A Laboratory Manual*, Cold Springs Harbor Press (Cold Springs Harbor, NY 1989). Any methods, devices and materials similar or equivalent to those described herein can be used in the practice of this invention.

[0066] As used herein, the terms nucleic acid, polynucleotide and nucleotide are interchangeable and refer to any nucleic acid, whether composed of phosphodiester linkages or modified linkages such as phosphotriester, phosphoramidate, siloxane, carbonate, carboxymethylester, acetamidate, carbamate, thioether, bridged phosphoramidate, bridged methylene phosphonate, bridged phosphoramidate, bridged phosphoramidate, bridged

methylene phosphonate, phosphorothioate, methylphosphonate, phosphorodithioate, bridged phosphorothioate or sultone linkages, and combinations of such linkages.

[0067] The terms nucleic acid, polynucleotide and nucleotide also specifically include nucleic acids composed of bases other than the five biologically occurring bases (adenine, guanine, thymine, cytosine and uracil).

[0068] As used herein, a nucleic acid molecule is said to be "isolated" when the nucleic acid molecule is substantially separated from contaminant nucleic acid molecules encoding other polypeptides.

[0069] "Immunization" refers to the provision of antigen to a host. In some embodiments, antigen is provided to antigen-presenting cells, such as dendritic cells. As described below, recombinant virus comprising a gene encoding an antigen can be targeted to dendritic cells with an affinity molecule specific to DC-SIGN on dendritic cells. Thus the antigen to which an immune response is desired can be delivered to the dendritic cells. Other methods of immunization are well known in the art.

[0070] The term "immunological" or "immune" response is the development of a beneficial humoral (antibody mediated) and/or a cellular (mediated by antigen-specific T cells or their secretion products) response directed against an amyloid peptide in a recipient patient. Such a response can be an active response induced by administration of immunogen or a passive response induced by administration of antibody or primed T-cells. A cellular immune response is elicited by the presentation of polypeptide epitopes in association with Class I or Class II MHC molecules to activate antigen-specific $CD4^+$ T helper cells and/or $CD8^+$ cytotoxic T cells. The response may also involve activation of monocytes, macrophages, NK cells, basophils, dendritic cells, astrocytes, microglia cells, eosinophils or other components of innate immunity. The presence of a cell-mediated immunological response can be determined by proliferation assays ($CD4^+$ T cells) or CTL (cytotoxic T lymphocyte) assays (Burke et al., *J. Inf. Dis.* 170, 1110-19 (1994)), by antigen-dependent killing (cytotoxic T lymphocyte assay, Tigges et al., *J. Immunol.* 156, 3901-3910) or by cytokine secretion. The relative contributions of humoral and cellular responses to the protective or therapeutic effect of an immunogen can be distinguished by separately isolating

IgG and T-cells from an immunized syngeneic animal and measuring protective or therapeutic effect in a second subject.

[0071] An "immunogenic agent" or "immunogen" is capable of inducing an immunological response against itself on administration to a patient, optionally in conjunction with an adjuvant.

[0072] The term "adjuvant" refers to a compound that when administered in conjunction with an antigen augments, enhances, and/or boosts the immune response to the antigen, but when administered alone does not generate an immune response to the antigen. An adjuvant can be administered with the recombinant virus of the invention as a single composition, or can be administered before, concurrent with or after administration of the recombinant virus of the invention. Adjuvants can enhance an immune response by several mechanisms including lymphocyte recruitment, stimulation of B and/or T cells, and stimulation of macrophages.

[0073] "Antibodies" (Abs) and "immunoglobulins" (Igs) are glycoproteins having the same structural characteristics. While antibodies exhibit binding specificity to a specific antigen, immunoglobulins include both antibodies and other antibody-like molecules that lack antigen specificity. Polypeptides of the latter kind are, for example, produced at low levels by the lymph system and at increased levels by myelomas.

[0074] The term "antibody" is used in the broadest sense and specifically covers human, non-human (e.g. murine), chimeric, and humanized monoclonal antibodies (including full length monoclonal antibodies), polyclonal antibodies, multi-specific antibodies (*e.g.*, bispecific antibodies), single-chain antibodies, and antibody fragments so long as they exhibit the desired biological activity. Typically, fragments compete with the intact antibody from which they were derived for specific binding to an antigen.

[0075] The term "epitope" or "antigenic determinant" refers to a site on an antigen to which B and/or T cells respond. B-cell epitopes can be formed both from contiguous amino acids or noncontiguous amino acids juxtaposed by tertiary folding of a protein. Epitopes formed from contiguous amino acids are typically retained on exposure to denaturing solvents whereas epitopes formed by tertiary folding are typically lost on treatment with denaturing solvents. An epitope typically includes at least 3, and more

usually, at least 5 or 8-10 amino acids in a unique spatial conformation. Methods of determining spatial conformation of epitopes include, for example, x-ray crystallography and 2-dimensional nuclear magnetic resonance. See, e.g., *Epitope Mapping Protocols in Methods in Molecular Biology,* Vol. 66, Glenn E. Morris, Ed. (1996). Antibodies that recognize the same epitope can be identified in a simple immunoassay showing the ability of one antibody to block the binding of another antibody to a target antigen. T-cells recognize continuous epitopes of about nine amino acids for CD8 cells or about 13-15 amino acids for CD4 cells. T cells that recognize the epitope can be identified by *in vitro* assays that measure antigen-dependent proliferation, as determined by $^{3}$H-thymidine incorporation by primed T cells in response to an epitope (see Burke, supra; Tigges, supra).

[0076] "Target cells" are any cells to which delivery of a polynucleotide or in which expression of a gene of interest is desired. Preferably, target cells are dendritic cells, particularly dendritic cells that express DC-SIGN.

[0077] The term "mammal" is defined as an individual belonging to the class Mammalia and includes, without limitation, humans, domestic and farm animals, and zoo, sports, and pet animals, such as sheep, dogs, horses, cats and cows.

[0078] The term "subject" or "patient" includes human and other mammalian subjects that receive either prophylactic or therapeutic treatment.

[0079] As used herein, "treatment" is a clinical intervention that may be therapeutic or prophylactic. In therapeutic applications, pharmaceutical compositions or medicants are administered to a patient suspected of, or already suffering from such a disease in an amount sufficient to cure, or at least partially arrest, the symptoms of the disease and its complications. In prophylactic applications, pharmaceutical compositions or medicants are administered to a patient susceptible to, or otherwise at risk of, a particular disease in an amount sufficient to eliminate or reduce the risk or delay the outset of the disease. An amount adequate to accomplish this is defined as a therapeutically- or pharmaceutically-effective dose. Such an amount can be administered as a single dosage or can be administered according to a regimen, whereby it is effective. The amount can cure a disease but, typically, is administered in order to ameliorate the symptoms of a disease, or to effect prophylaxis of a disease or disorder from developing. In both therapeutic and prophylactic regimes, agents are

usually administered in several dosages until a sufficient immune response has been achieved. Typically, the immune response is monitored and repeated dosages are given if the immune response starts to fade. "Treatment" need not completely eliminate a disease, nor need it completely prevent a subject from becoming ill with the disease or disorder.

[0080] "Tumor," as used herein, refers to all neoplastic cell growth and proliferation, whether malignant or benign, and all pre-cancerous and cancerous cells and tissues.

[0081] The term "cancer" refers to a disease or disorder that is characterized by unregulated cell growth. Examples of cancer include, but are not limited to, carcinoma, lymphoma, blastoma and sarcoma. Examples of specific cancers include, but are not limited to, lung cancer, colon cancer, breast cancer, testicular cancer, stomach cancer, pancreatic cancer, ovarian cancer, liver cancer, bladder cancer, colorectal cancer, and prostate cancer. Additional cancers are well known to those of skill in the art and include, but are not limited to: leukemia, lymphoma, cervical cancer, glioma tumors, adenocarcinomas and skin cancer. Exemplary cancers include, but are not limited to, a bladder tumor, breast tumor, prostate tumor, basal cell carcinoma, biliary tract cancer, bladder cancer, bone cancer, brain and CNS cancer (e.g., glioma tumor), cervical cancer, choriocarcinoma, colon and rectum cancer, connective tissue cancer, cancer of the digestive system; endometrial cancer, esophageal cancer; eye cancer; cancer of the head and neck; gastric cancer; intra-epithelial neoplasm; kidney cancer; larynx cancer; leukemia; liver cancer; lung cancer (e.g. small cell and non-small cell); lymphoma including Hodgkin's and Non-Hodgkin's lymphoma; melanoma; myeloma, neuroblastoma, oral cavity cancer (e.g., lip, tongue, mouth, and pharynx); ovarian cancer; pancreatic cancer, retinoblastoma; rhabdomyosarcoma; rectal cancer, renal cancer, cancer of the respiratory system; sarcoma, skin cancer; stomach cancer, testicular cancer, thyroid cancer; uterine cancer, cancer of the urinary system, as well as other carcinomas and sarcomas. Cancer also includes neoplasias and malignant disorders in mammals that are well known in the art.

[0082] A "vector" is a nucleic acid that is capable of transporting another nucleic acid. Vectors may be, for example, plasmids, cosmids or phage. An "expression vector" is a

vector that is capable of directing expression of a protein or proteins encoded by one or more genes carried by the vector when it is present in the appropriate environment.

[0083] The term "regulatory element" and "expression control element" are used interchangeably and refer to nucleic acid molecules that can influence the transcription and/or translation of an operably linked coding sequence in a particular environment. These terms are used broadly and cover all elements that promote or regulate transcription, including promoters, core elements required for basic interaction of RNA polymerase and transcription factors, upstream elements, enhancers, and response elements (see, e.g., Lewin, "Genes V" (Oxford University Press, Oxford) pages 847-873). Exemplary regulatory elements in prokaryotes include promoters, operator sequences and a ribosome binding sites. Regulatory elements that are used in eukaryotic cells may include, without limitation, promoters, enhancers, splicing signals and polyadenylation signals.

[0084] The term "transfection" refers to the introduction of a nucleic acid into a host cell.

[0085] "Retroviruses" are viruses having an RNA genome.

[0086] "Lentivirus" refers to a genus of retroviruses that are capable of infecting dividing and non-dividing cells. Several examples of lentiviruses include HIV (human immunodeficiency virus: including HIV type 1, and HIV type 2), the etiologic agent of the human acquired immunodeficiency syndrome (AIDS); visna-maedi, which causes encephalitis (visna) or pneumonia (maedi) in sheep, the caprine arthritis-encephalitis virus, which causes immune deficiency, arthritis, and encephalopathy in goats; equine infectious anemia virus, which causes autoimmune hemolytic anemia, and encephalopathy in horses; feline immunodeficiency virus (FIV), which causes immune deficiency in cats; bovine immune deficiency virus (BIV), which causes lymphadenopathy, lymphocytosis, and possibly central nervous system infection in cattle; and simian immunodeficiency virus (SIV), which cause immune deficiency and encephalopathy in sub-human primates.

[0087] A lentiviral genome is generally organized into a 5' long terminal repeat (LTR), the gag gene, the pol gene, the env gene, the accessory genes (nef, vif, vpr, vpu) and a 3' LTR. The viral LTR is divided into three regions called U3, R and U5. The U3 region contains the enhancer and promoter elements. The U5 region contains the polyadenylation

signals. The R (repeat) region separates the U3 and U5 regions and transcribed sequences of the R region appear at both the 5' and 3' ends of the viral RNA. See, for example, "RNA Viruses: A Practical Approach" (Alan J. Cann, Ed., Oxford University Press, (2000)), O Narayan and Clements J. Gen. Virology 70:1617-1639 (1989), Fields et al. Fundamental Virology Raven Press. (1990), Miyoshi H, Blomer U, Takahashi M, Gage FH, Verma IM. *J Virol.* 72(10):8150-7 (1998), and U.S. Patent No. 6,013,516.

**[0088]** "Gammaretrovirus" refers to a genus of the retroviridae family. Exemplary gammaretroviruses include, but are not limited to, mouse stem cell virus, murine leukemia virus, feline leukemia virus, feline sarcoma virus, and avian reticuloendotheliosis viruses.

**[0089]** A "hybrid virus" as used herein refers to a virus having components from one or more other viral vectors, including element from non-retroviral vectors, for example, adenoviral-retroviral hybrids. As used herein hybrid vectors having a retroviral component are to be considered within the scope of the retroviruses.

**[0090]** "Virion," "viral particle" and "retroviral particle" are used herein to refer to a single virus comprising an RNA genome, *pol* gene derived proteins, *gag* gene derived proteins and a lipid bilayer displaying an envelope (glyco)protein. The RNA genome is usually a recombinant RNA genome and thus may contain an RNA sequence that is exogenous to the native viral genome. The RNA genome may also comprise a defective endogenous viral sequence.

**[0091]** A "pseudotyped" retrovirus is a retroviral particle having an envelope protein that is from a virus other than the virus from which the RNA genome is derived. The envelope protein can be, for example and without limitation, from a different retrovirus or from a non-retroviral origin. The envelope protein can be a native envelope protein or an envelope protein that is modified, mutated or engineered as described herein. In some embodiments, an envelope protein is a DC-SIGN-specific viral glycoprotein that is derived from a glycoprotein from one of the following: Sindbis virus, influenza virus, Lassa fever virus, tick-borne encephalitis virus, Dengue virus, Hepatitis B virus, Rabies virus, Semliki Forest virus, Ross River virus, Aura virus, Borna disease virus, Hantaan virus, and SARS-CoV virus.

[0092] "Transformation," as defined herein, describes a process by which exogenous DNA enters a target cell. Transformation may rely on any known method for the insertion of foreign nucleic acid sequences into a prokaryotic or eukaryotic host cell and may include, but is not limited to, viral infection, electroporation, heat shock, lipofection, and particle bombardment. "Transformed" cells include stably transformed cells in which the inserted nucleic acid is capable of replication either as an autonomously replicating plasmid or as part of the host chromosome. Also included are cells that transiently express a gene of interest.

[0093] A "fusogenic molecule," as described herein, is any molecule that can trigger membrane fusion when present on the surface of a virus and allows a virus core to pass through the membrane and, typically, enter the cytosol of a target cell. Fusogenic molecules can be, for example, viral glycoproteins. Exemplary viral glycoproteins contemplated as fusogenic molecules include, but are not limited to hemagglutinin, mutant hemagglutinin, SIN and viral glycoproteins from the following viruses: Sindbis virus, influenza virus, Lassa fever virus, tick-borne encephalitis virus, Dengue virus, Hepatitis B virus, Rabies virus, Semliki Forest virus, Ross River virus, Aura virus, Borna disease virus, Hantaan virus, and SARS-CoV virus. Glycoproteins can be native or modified to have desired activity.

[0094] By "transgene" is meant any nucleotide sequence, particularly a DNA sequence, that is integrated into one or more chromosomes of a host cell by human intervention, such as by the methods of the present invention. The transgene preferably comprises a "gene of interest."

[0095] A "gene of interest" is not limited in any way and may be any nucleic acid, without limitation, that is desired to be delivered to, integrated, transcribed, translated, and/or expressed in a target cell. The gene of interest may encode a functional product, such as a protein or an RNA molecule. Preferably the gene of interest encodes a protein or other molecule, the expression of which is desired in the target cell. The gene of interest is generally operatively linked to other sequences that are useful for obtaining the desired expression of the gene of interest, such as transcriptional regulatory sequences. In some embodiments a gene of interest is preferably one that encodes an antigen to which an immune

response is desired. Other genes of interest that may be used in some embodiments are genes that encode dendritic cell activators and/or maturation factors.

[0096] A "functional relationship" and "operably linked" mean, with respect to the gene of interest, that the gene is in the correct location and orientation with respect to the promoter and/or enhancer that expression of the gene will be affected when the promoter and/or enhancer is contacted with the appropriate molecules.

[0097] "2A sequences" or elements are small peptides introduced as a linker between two proteins, allowing autonomous intraribosomal self-processing of polyproteins (de Felipe. Genetic Vaccines and Ther. 2:13 (2004); deFelipe et al. Traffic 5:616-626 (2004)). The short peptides allow co-expression of multiple proteins from a single vector, such as co-expression of a fusogenic molecule and affinity molecule from the same vector. Thus, in some embodiments polynucleotides encoding the 2A elements are incorporated into a vector between polynucleotides encoding proteins to be expressed.

[0098] "DC maturation factors" (also known as "DC activators") are compounds that can induce activation or stimulation of DCs such that DCs facilitate the elicitation of cellular and humoral immune responses. Typical DC maturation factors are known in the art and include, but are not limited to, stimulation molecules, cytokines, chemokines, antibodies and other agents such as Flt-3 ligands (Figdor, C.G., et al. 2004. *Nat Med* 10:475-480; Pulendran, B., et al. 2000. *J Immunol* 165: 566-572; Maraskovsky, E., et al. 2000. *Blood* 96:878-884, each of which is incorporated herein by reference in its entirety). Exemplary DC maturation factors can include, but are not limited to, GM-CSF, IL-2, IL-4, IL-6, IL-7, IL-15, IL-21, IL-23, TNFα, B7.1, B7.2, 4-1BB, CD40 ligand (CD40L) and drug-inducible CD40 (iCD40).

Targeting Molecules

[0099] As discussed above, a targeting molecule is incorporated into a recombinant virus to target the virus to dendritic cells that express DC-SIGN. The targeting molecule preferably also mediates fusion with the cell membrane and efficient transduction and delivery of the desired polynucleotide(s) into the dendritic cell. Thus, the targeting molecule is typically a fusogenic molecule (FM) with the desired binding specificity. The targeting molecule is modified, if necessary, such that it binds to DC-SIGN on dendritic cells.

In some embodiments, the targeting molecule specifically binds to DC-SIGN. That is, the targeting molecule preferentially directs the recombinant virus to dendritic cells that express DC-SIGN relative to other cell types. Thus, in some embodiments, targeting molecules are created by eliminating the ability of a FM to bind to other targets, such as hemagglutinin, while retaining the ability to bind DC-SIGN. In other embodiments, the targeting molecule can be modified to eliminate native binding specificity to non-DC-SIGN molecules and components thereof and add or improve binding specificity for DC-SIGN. While some nonspecific binding to other molecules, and thus other cell types, may occur even if the targeting molecule is specific for DC-SIGN, the targeting molecules are modified to have sufficient specificity to avoid undesired side effects, such as side effects that may reduce the desired immune response.

**[0100]** Targeting molecules are generally molecules that are able to pseudotype virus and thus be incorporated in the envelope of recombinant viruses, target dendritic cells and, under the right conditions, induce membrane fusion and allow entry of a gene of interest to the dendritic cells. Preferred targeting molecules are viral glycoproteins. In addition, targeting molecules are preferably resistant to ultracentrifugation to allow concentration, which can be important for *in vivo* gene delivery.

**[0101]** Targeting molecules preferably induce membrane fusion at a low pH, independently of binding. Thus, in preferred embodiments, targeting molecule-induced membrane fusion occurs once the virus comprising the targeting molecule is inside the endosome of a target cell and the viral core component, including a polynucleotide of interest, is delivered to the cytosol.

**[0102]** In some embodiments a tag sequence is incorporated into a targeting molecule to allow detection of targeting molecule expression and the presence of the targeting molecule in viral particles.

**[0103]** There are two recognized classes of viral fusogens and both can be used as targeting molecules (D. S. Dimitrov, Nature Rev. Microbio. 2, 109 (2004)). The class I fusogens trigger membrane fusion using helical coiled-coil structures whereas the class II fusogens trigger fusion with β barrels. These two structures have different mechanics and kinetics (D. S. Dimitrov, Nature Rev. Microbio. 2, 109 (2004)). In some embodiments, class

I fusogens are used. In other embodiments, class II fusogens are used. In still other embodiments, both class I and class II fusogens are used.

[0104] Some non-limiting examples of surface glycoproteins that may be used as targeting molecules (or as fusogenic molecules in embodiments where the viral binding and fusion functions are separate), either in the wild type or in modified form, include glycoproteins from alphaviruses, such as Semliki Forest virus (SFV), Ross River virus (RRV) and Aura virus (AV), which comprise surface glycoproteins such as E1, E2, and E3. The E2 glycoproteins derived from the Sindbis virus (SIN) and the hemagglutinin (HA) of influenza virus are non-retroviral glycoproteins that specifically bind particular molecules on cell surfaces (heparin sulfate glycosaminoglycan for E2, sialic acid for HA) and can be used to create targeting molecules in some embodiments. Their fusion is relatively independent of binding to receptor molecules, and the activation of fusion is accomplished through acidification in the endosome (Skehel and Wiley, Annu. Rev. Biochem. 69, 531-569 (2000); Smit, J. et al. J. Virol. 73, 8476-8484 (1999)). Moreover, they can tolerate certain genetic modifications and remain efficiently assembled on the retroviral surface (Morizono et al. J. Virol. 75, 8016-8020).

[0105] In other embodiments of the invention, surface glycoproteins of Lassa fever virus, Hepatitis B virus, Rabies virus, Borna disease virus, Hantaan virus, or SARS-CoV virus can be utilized as fusion molecules.

[0106] In other embodiments of the invention, flavivirus-based surface glycoproteins may be used as the basis for targeting molecules. Like alphaviruses, flaviviruses use the class II fusion molecule to mediate infection (Mukhopadhyay et al. (2005) Rev. Microbio. 3, 13-22). prM (about 165 amino acids) and E (about 495 amino acids) are the glycoproteins of flaviviruses. Also, the ligand-binding pocket for one flavivirus, Dengue virus (DV), has been well-characterized. Of interest, DC-SIGN has been suggested to specifically interact with the carbohydrate residues on the DV E protein to enhance viral entry (Mukhopadhyay et al. (2005) Nat. Rev. Microbio. 3, 13-22). Thus, lentiviruses enveloped only by DV E protein, or by modified DV E protein, can be used to target DCs. The TBE and DV E proteins, as well as other fusion molecules described, may be

engineered to provide the desired binding specificity or to be binding deficient and fusion competent if necessary.

[0107] In some embodiments, a form of hemagglutinin (HA) from influenza A/fowl plague virus/Rostock/34 (FPV), a class I fusogen, is used (T. Hatziioannou, S. Valsesia-Wittmann, S. J. Russell, F. L. Cosset, J. Virol. 72, 5313 (1998)). In some embodiments, a form of FPV HA is used (A. H. Lin et al., Hum. Gene. Ther. 12, 323 (2001)). HA-mediated fusion is generally considered to be independent of receptor binding (D. Lavillette, S. J. Russell, F. L. Cosset, Curr. Opin. Biotech. 12, 461 (2001)).

[0108] In other embodiments, a class II FM is used, preferably the Sindbis virus glycoprotein from the alphavirus family (K. S. Wang, R. J. Kuhn, E. G. Strauss, S. Ou, J. H. Strauss, J. Virol. 66, 4992 (1992)), herein also referred to as SVG. SVG includes two transmembrane proteins (S. Mukhopadhyay, R. J. Kuhn, M. G. Rossmann, Nature Rev. Microbio. 3, 13 (2005)), a first protein responsible for fusion (E1), and a second protein for cell binding (E2). SVG is known to pseudotype both oncoretroviruses and lentiviruses.

[0109] As discussed below, in some preferred embodiments a modified SVG that preferentially binds DC-SIGN is utilized. In other embodiments, a binding-deficient and fusion-competent SVG, SVGmu, can be used as the fusogenic molecule in combination with a separate targeting molecule, such as an antibody to DC-SIGN or another dendritic cell specific protein. For example, a SVG fusogenic molecule can be used in which the immunoglobulin G binding domain of protein A (ZZ domain) is incorporated into the E2 protein and one or more additional mutations are made to inactivate the receptor binding sites (K. Morizono et al., Nature Med. 11, 346 (2005)).

[0110] The gene encoding the targeting molecule is preferably cloned into an expression vector, such as pcDNA3 (Invitrogen). Packaging cells, such as 293T cells are then co-transfected with the viral vector encoding a gene of interest (typically encoding an antigen), at least one plasmid encoding virus packing components, and a vector for expression of the targeting molecule. If the targeting function is separated from the fusogenic function, one or more vectors encoding an affinity molecule and any associated components is also provided, The targeting molecule is expressed on the membrane of the packaging cell

and incorporated into the recombinant virus. Expression of targeting molecules on the packaging cell surface can be analyzed, for example, by FACS.

[0111] Based on information obtained, for example from structural studies and molecular modeling, mutagenesis may be employed to generate the mutant forms of glycoproteins that maintain their fusogenic ability but have the desired binding specificity and/or level of binding. Several mutants may be created for each glycoprotein and assayed using the methods described below, or other methods known in the art, to identify FMs with the most desirable characteristics. For example, targeting molecules can be tested for the ability to specifically deliver antigens to dendritic cells by determining their ability to stimulate an immune response without causing undesired side effects in a mammal. The ability to specifically target dendritic cells can also be tested directly, for example, in cell culture as described below.

[0112] To select suitable targeting molecules (either wild-type or mutant), viruses bearing the targeting molecule (and an affinity molecule where appropriate) are prepared and tested for their selectivity and/or their ability to facilitate penetration of the target cell membrane. Viruses that display a wild-type glycoprotein can be used as controls for examining titer effects in mutants. Cells expressing the binding partner of the targeting molecule (or affinity molecule, where appropriate) are transduced by the virus using a standard infection assay. After a specified time, for example 48 hours post-transduction, cells can be collected and the percentage of cells infected by the virus comprising the targeting molecule (or affinity molecule and fusogenic molecule) can be determined by, for example, FACS. The selectivity can be scored by calculating the percentage of cells infected by virus. Similarly, the effect of mutations on viral titer can be quantified by dividing the percentage of cells infected by virus comprising a mutant targeting molecule by the percentage of cells infected by virus comprising the corresponding wild type targeting molecule. A preferred mutant will give the best combination of selectivity and infectious titer. Once an targeting molecule is selected, viral concentration assays may be performed to confirm that viruses enveloped by the FM can be concentrated. Viral supernatants are collected and concentrated by ultracentrifugation. The titers of viruses can be determined by

limited dilution of viral stock solution and transduction of cells expressing the binding partner of the affinity molecule.

[0113] In some embodiments, BlaM-Vpr fusion protein may be utilized to evaluate viral penetration, and thus the efficacy of a fusion molecule (wild-type or mutant). Virus may be prepared, for example, by transient transfection of packaging cells with one or more vectors comprising the viral elements, BlaM-Vpr, and the FM of interest (and an affinity molecule if appropriate). The resulting viruses can be used to infect cells expressing a molecule the targeting molecule (or affinity molecule) specifically binds in the absence or presence of the free inhibitor of binding (such as an antibody). Cells can then be washed with $CO_2$-independent medium and loaded with CCF2 dye (Aurora Bioscience). After incubation at room temperature to allow completion of the cleavage reaction, the cells can be fixed by paraformaldehyde and analyzed by FACS and microscopy. The presence of blue cells indicates the penetration of viruses into the cytoplasm; fewer blue cells would be expected when blocking antibody is added.

[0114] To investigate whether penetration is dependent upon a low pH, and select targeting molecules (or fusogenic molecules) with the desired pH dependence, $NH_4Cl$ or other compound that alters pH can be added at the infection step ($NH_4Cl$ will neutralize the acidic compartments of endosomes). In the case of $NH_4Cl$, he disappearance of blue cells will indicate that penetration of viruses is low pH-dependent.

[0115] In addition, to confirm that the activity is pH-dependent, lysosomotropic agents, such as ammonium chloride, chloroquine, concanamycin, bafilomycin A1, monensin, nigericin, etc., may be added into the incubation buffer. These agents can elevate the pH within the endosomal compartments (e.g., Drose and Altendorf, J. Exp. Biol. 200, 1-8, 1997). The inhibitory effect of these agents will reveal the role of pH for viral fusion and entry. The different entry kinetics between viruses displaying different fusogenic molecules may be compared and the most suitable selected for a particular application.

[0116] PCR entry assays may be utilized to monitor reverse transcription and thus measure kinetics of viral DNA synthesis as an indication of the kinetics of viral entry. For example, viral particles comprising a particular targeting molecule may be incubated with packaging cells, such as 293T cells, expressing the appropriate cognate for the targeting

molecule (or a separate affinity molecule in some embodiments). Either immediately, or after incubation (to allow infection to occur) unbound viruses are removed and aliquots of the cells are analyzed. DNA may then be extracted from these aliquots and semi-quantitative performed using LTR-specific primers. The appearance of LTR-specific DNA products will indicate the success of viral entry and uncoating.

[0117] Although the targeting molecule can have both viral binding and fusion functions, in another aspect of the invention, the viral binding and fusion functions are separated into two distinct components. Typically, the recombinant virus comprises both (i) an affinity molecule that mediates viral binding and precisely targets the virus to dendritic cells, and (ii) a distinct fusogenic molecule (FM) that mediates efficient transduction and delivery of the desired polynucleotide into the dendritic cells. The methods disclosed herein may be readily adopted to utilize any of a variety of affinity molecules and fusogenic molecules. In addition to those described herein, other exemplary fusogenic molecules and related methods are described, for example, in U.S. Patent Application No. 11/071,785, filed March 2, 2005 (published as U.S. Patent Application Publication 2005-0238626), and in U.S. Patent Application No. 11/446,353, filed June 1, 2006 (published as U.S. Patent Application Publication 2007/0020238), each of which is incorporated herein by reference in its entirety.

[0118] The affinity molecule is one that binds a dendritic cell surface marker. In preferred embodiments, the affinity molecule binds DC-SIGN with specificity. That is, the binding of the affinity molecule to DC-SIGN is preferably specific enough to avoid undesired side effects due to interaction with markers on other cell types. The affinity molecule can be, for example, an antibody that specifically binds DC-SIGN.

[0119] In some preferred embodiments, the fusion molecule is a viral glycoprotein that mediates fusion or otherwise facilitates delivery of the gene of interest to the dendritic cell, preferably in response to the low pH environment of the endosome. The fusion molecule preferably exhibits fast enough kinetics that the viral contents can empty into the cytosol before the degradation of the viral particle. In addition, the fusion molecule can be modified to reduce or eliminate any binding activity and thus reduce or eliminate any non-specific binding. That is, by reducing the binding ability of the fusion molecules, binding of the virus to the target cell is determined predominantly or entirely by the affinity molecule,

allowing for high target specificity and reducing undesired effects. Exemplary fusion molecules include, but are not limited to viral glycoproteins derived from one of the following viruses: Sindbis virus, influenza virus, Lassa fever virus, tick-borne encephalitis virus, Dengue virus, Hepatitis B virus, Rabies virus, Semliki Forest virus, Ross River virus, Aura virus, Borna disease virus, Hantaan virus, and SARS-CoV virus.

[0120] The methods disclosed herein can be readily adopted to utilize any of a variety of molecules as targeting molecules, or as fusogenic molecules in combination with affinity molecules. In addition to those described herein, other exemplary molecules and related methods are described, for example, in U.S. Patent Application Publication 2005/0238626 and in U.S. Patent Application Publication 2007/0020238).

Vectors

[0121] In a preferred embodiment, one or more vectors are used to introduce polynucleotide sequences into a packaging cell line for the preparation of a recombinant virus as described herein. The vectors can contain polynucleotide sequences encoding the various components of the recombinant virus including the DC-specific targeting molecule, a gene(s) of interest (typically encoding an antigen), and any components necessary for the production of the virus that are not provided by the packaging cell. In some embodiments, vectors containing polynucleotide sequences that encode a DC-specific affinity molecule and a separate fugosenic molecule are substituted for a vector that encodes a DC-specific targeting molecule in the preparation of the virus. Eukaryotic cell expression vectors are well known in the art and are available from a number of commercial sources.

[0122] In one aspect of the invention, vectors containing polynucleotide sequences that encode DC maturation factors are also used in the preparation of the virus. These polynucleotides are typically under the control of one or more regulatory elements that direct the expression of the coding sequences in the packaging cell and the target cell, as appropriate. Several lines of evidence have shown the success of DC vaccination is dependent on the maturation state of DCs (Banchereau, J and Palucka, A.K. *Nat. Rev. Immunol.* 5:296-306 (2005); Schuler, G. et al. *Curr. Opin. Immunol.*15:138-147 (2003); Figdor, C.G. et al. *Nat. Med.* 10:475-480 (2004), each of which is incorporated herein by reference). Maturation can transform DCs from cells actively involved in antigen capture

into cells specialized for T cell priming. In one aspect of the invention, the vector includes genes that encode the stimulatory molecules to trigger the desired DC maturation. Such stimulatory molecules are also referred to as maturation factors or maturation stimulatory factors.

[0123] In some embodiments, packaging cells are co-transfected with a viral vector encoding an antigen and one or more additional vectors. For example, in addition to the viral vector encoding an antigen, a second vector preferably carries a gene encoding a targeting molecule that binds dendritic cells, such SVGmu, as described elsewhere in the application. In some preferred embodiments, the targeting molecule encodes a modified viral glycoprotein that is specific for DC-SIGN. The modified viral glycoprotein is preferably one derived from at least one of the following: Sindbis virus, influenza virus, Lassa fever virus, tick-borne encephalitis virus, Dengue virus, Hepatitis B virus, Rabies virus, Semliki Forest virus, Ross River virus, Aura virus, Borna disease virus, Hantaan virus, and SARS-CoV virus. In some embodiments, the viral vector encoding an antigen also includes a polynucleotide sequence encoding a DC maturation factor. In some embodiments, the polynucleotide sequence encoding a DC maturation factor is contained in a third vector that is co-transfected with the viral vector encoding an antigen and the one or more additional vectors into the packaging cells.

[0124] In other embodiments, one or more multicistronic expression vectors are utilized that include two or more of the elements (e.g., the viral genes, gene(s) of interest, the targeting molecule, DC maturation factors) necessary for production of the desired recombinant virus in packaging cells. The use of multicistronic vectors reduces the total number of vectors required and thus avoids the possible difficulties associated with coordinating expression from multiple vectors. In a multicistronic vector the various elements to be expressed are operably linked to one or more promoters (and other expression control elements as necessary). In other embodiments a multicistronic vector comprising a gene of interest, a reporter gene, and viral elements is used. The gene of interest typically encodes an antigen and, optionally, a DC maturation factor. Such a vector may be cotransfected, for example, along with a vector encoding a targeting molecule, or, in some embodiments, a multicistronic vector encoding both an FM and an affinity molecule. In

some embodiments the multicistronic vector comprises a gene encoding an antigen, a gene encoding a DC maturation factor and viral elements.

[0125] Each component to be expressed in a multicistronic expression vector may be separated, for example, by an IRES element or a viral 2A element, to allow for separate expression of the various proteins from the same promoter. IRES elements and 2A elements are known in the art (U.S. Patent No. 4,937,190; de Felipe et al. 2004. *Traffic* 5: 616-626, each of which is incorporated herein by reference in its entirety). In one embodiment, oligonucleotides encoding furin cleavage site sequences (RAKR) (Fang et al. 2005. *Nat. Biotech* 23: 584-590, which is incorporated herein by reference in its entirety) linked with 2A-like sequences from foot-and-mouth diseases virus (FMDV), equine rhinitis A virus (ERAV), and thosea asigna virus (TaV) (Szymczak et al. 2004. *Nat. Biotechnol.* 22: 589-594, which is incorporated herein by reference in its entirety) are used to separate genetic elements in a multicistronic vector. The efficacy of a particular multicistronic vector for use in synthesizing the desired recombinant virus can readily be tested by detecting expression of each of the genes using standard protocols.

[0126] Generation of the vector(s) can be accomplished using any suitable genetic engineering techniques known in the art, including, without limitation, the standard techniques of restriction endonuclease digestion, ligation, transformation, plasmid purification, and DNA sequencing, for example as described in Sambrook et al. (1989. Molecular Cloning: A Laboratory Manual. Cold Spring Harbor Laboratory Press, N.Y.), Coffin et al. (Retroviruses. Cold Spring Harbor Laboratory Press, N.Y. (1997)) and "RNA Viruses: A Practical Approach" (Alan J. Cann, Ed., Oxford University Press, (2000), each of the foregoing which is incorporated herein by reference in its entirety.

[0127] The vector(s) may incorporate sequences from the genome of any known organism. The sequences may be incorporated in their native form or may be modified in any way. For example, the sequences may comprise insertions, deletions or substitutions.

[0128] Expression control elements that may be used for regulating the expression of the components are known in the art and include, but are not limited to, inducible promoters, constitutive promoters, secretion signals, enhancers and other regulatory elements.

[0129] In one embodiment, a vector can include a prokaryotic replicon, *i.e.*, a DNA sequence having the ability to direct autonomous replication and maintenance of the recombinant DNA molecule extrachromosomally in a prokaryotic host cell, such as a bacterial host cell, transformed therewith. Such replicons are well known in the art. In addition, vectors that include a prokaryotic replicon may also include a gene whose expression confers a detectable marker such as a drug resistance. Typical bacterial drug resistance genes are those that confer resistance to ampicillin or tetracycline.

[0130] The vector(s) may include one or more genes for selectable markers that are effective in a eukaryotic cell, such as a gene for a drug resistance selection marker. This gene encodes a factor necessary for the survival or growth of transformed host cells grown in a selective culture medium. Host cells not transformed with the vector containing the selection gene will not survive in the culture medium. Typical selection genes encode proteins that confer resistance to antibiotics or other toxins, *e.g.*, ampicillin, neomycin, methotrexate, or tetracycline, complement auxotrophic deficiencies, or supply critical nutrients withheld from the media. The selectable marker can optionally be present on a separate plasmid and introduced by co-transfection.

[0131] Vectors will usually contain a promoter that is recognized by the packaging cell and that is operably linked to the polynucleotide(s) encoding the targeting molecule, viral components, and the like. A promoter is an expression control element formed by a nucleic acid sequence that permits binding of RNA polymerase and transcription to occur. Promoters are untranslated sequences that are located upstream (5') to the start codon of a structural gene (generally within about 100 to 1000 bp) and control the transcription and translation of the antigen-specific polynucleotide sequence to which they are operably linked. Promoters may be inducible or constitutive. The activity of the inducible promoters is induced by the presence or absence of biotic or abiotic factors. Inducible promoters can be a useful tool in genetic engineering because the expression of genes to which they are operably linked can be turned on or off at certain stages of development of an organism or in a particular tissue. Inducible promoters can be grouped as chemically-regulated promoters, and physically-regulated promoters. Typical chemically-regulated promoters include, not are not limited to, alcohol-regulated promoters (e.g. alcohol

dehydrogenase I (alcA) gene promoter), tetracycline-regulated promoters (e.g. tetracycline-responsive promoter), steroid-regulated promoter (e.g. rat glucocorticoid receptor (GR)-based promoter, human estrogen receptor (ER)-based promoter, moth ecdysone receptor-based promoter, and the promoters based on the steroid/retinoid/thyroid receptor superfamily), metal-regulated promoters (e.g. metallothionein gene-based promoters), and pathogenesis-related promoters (e.g. Arabidopsis and maize pathogen-related (PR) protein-based promoters). Typical physically-regulated promoters include, but are not limited to, temperature-regulated promoters (e.g. heat shock promoters), and light-regulated promoters (e.g. soybean SSU promoter). Other exemplary promoters are described elsewhere, for example, in hyper text transfer protocol://www.patentlens.net/daisy/promoters/768/271.html, which is incorporated herein by reference in its entirety.

[0132] One of skill in the art will be able to select an appropriate promoter based on the specific circumstances. Many different promoters are well known in the art, as are methods for operably linking the promoter to the gene to be expressed. Both native promoter sequences and many heterologous promoters may be used to direct expression in the packaging cell and target cell. However, heterologous promoters are preferred, as they generally permit greater transcription and higher yields of the desired protein as compared to the native promoter.

[0133] The promoter may be obtained, for example, from the genomes of viruses such as polyoma virus, fowlpox virus, adenovirus, bovine papilloma virus, avian sarcoma virus, cytomegalovirus, a retrovirus, hepatitis-B virus and Simian Virus 40 (SV40). The promoter may also be, for example, a heterologous mammalian promoter, *e.g.*, the actin promoter or an immunoglobulin promoter, a heat-shock promoter, or the promoter normally associated with the native sequence, provided such promoters are compatible with the target cell. In one embodiment, the promoter is the naturally occurring viral promoter in a viral expression system. In some embodiments, the promoter is a dendritic cell-specific promoter. The dendritic cell-specific promoter can be, for example, CD11c promoter.

[0134] Transcription may be increased by inserting an enhancer sequence into the vector(s). Enhancers are typically cis-acting elements of DNA, usually about 10 to 300 bp in length, that act on a promoter to increase its transcription. Many enhancer sequences are now

known from mammalian genes (globin, elastase, albumin, α-fetoprotein, and insulin). Preferably an enhancer from a eukaryotic cell virus will be used. Examples include the SV40 enhancer on the late side of the replication origin (bp 100-270), the cytomegalovirus early promoter enhancer, the polyoma enhancer on the late side of the replication origin, and adenovirus enhancers. The enhancer may be spliced into the vector at a position 5' or 3' to the antigen-specific polynucleotide sequence, but is preferably located at a site 5' from the promoter.

[0135] Expression vectors will also contain sequences necessary for the termination of transcription and for stabilizing the mRNA. These sequences are often found in the 5' and, occasionally 3', untranslated regions of eukaryotic or viral DNAs or cDNAs and are well known in the art.

[0136] Plasmid vectors containing one or more of the components described above are readily constructed using standard techniques well known in the art.

[0137] For analysis to confirm correct sequences in plasmids constructed, the plasmid may be replicated in *E. coli*, purified, and analyzed by restriction endonuclease digestion, and/or sequenced by conventional methods.

[0138] Vectors that provide for transient expression in mammalian cells may also be used. Transient expression involves the use of an expression vector that is able to replicate efficiently in a host cell, such that the host cell accumulates many copies of the expression vector and, in turn, synthesizes high levels of a the polypeptide encoded by the antigen-specific polynucleotide in the expression vector. See Sambrook et al., *supra*, pp. 16.17 - 16.22.

[0139] Other vectors and methods suitable for adaptation to the expression of the viral polypeptides are well known in the art and are readily adapted to the specific circumstances.

[0140] Using the teachings provided herein, one of skill in the art will recognize that the efficacy of a particular expression system can be tested by transforming packaging cells with a vector comprising a gene encoding a reporter protein and measuring the expression using a suitable technique, for example, measuring fluorescence from a green fluorescent protein conjugate. Suitable reporter genes are well known in the art.

[0141] Transformation of packaging cells with vectors of the present invention is accomplished by well-known methods, and the method to be used is not limited in any way. A number of non-viral delivery systems are known in the art, including for example, electroporation, lipid-based delivery systems including liposomes, delivery of "naked" DNA, and delivery using polycyclodextrin compounds, such as those described in Schatzlein AG. (2001. Non-Viral Vectors in Cancer Gene Therapy: Principles and Progresses. *Anticancer Drugs*, which is incorporated herein by reference in its entirety). Cationic lipid or salt treatment methods are typically employed, see, for example, Graham *et al.* (1973. *Virol.* 52:456; Wigler *et al.* (1979. *Proc. Natl. Acad. Sci. USA* 76:1373-76), each of the foregoing which is incorporated herein by reference in its entirety. The calcium phosphate precipitation method is preferred. However, other methods for introducing the vector into cells may also be used, including nuclear microinjection and bacterial protoplast fusion.

Viral Vector and Packaging Cells

[0142] One of the vectors encodes the core virus (the "viral vector"). There are a large number of available viral vectors that are suitable for use with the invention, including those identified for human gene therapy applications, such as those described by Pfeifer and Verma (Pfeifer, A. and I.M. Verma. 2001. *Annu. Rev. Genomics Hum. Genet.* 2:177-211, which is incorporated herein by reference in its entirety). Suitable viral vectors include vectors based on RNA viruses, such as retrovirus-derived vectors, e.g., Moloney murine leukemia virus (MLV)-derived vectors, and include more complex retrovirus-derived vectors, e.g., lentivirus-derived vectors. Human Immunodeficiency virus (HIV-1)-derived vectors belong to this category. Other examples include lentivirus vectors derived from HIV-2, feline immunodeficiency virus (FIV), equine infectious anemia virus, simian immunodeficiency virus (SIV) and maedi/visna virus.

[0143] The viral vector preferably comprises one or more genes encoding components of the recombinant virus as well as one or more genes of interest, such as, for example, an antigen and/or a DC maturation factor. The viral vector may also comprise genetic elements that facilitate expression of the gene of interest in a target cell, such as promoter and enhancer sequences. In order to prevent replication in the target cell,

endogenous viral genes required for replication may be removed and provided separately in the packaging cell line.

[0144] In a preferred embodiment the viral vector comprises an intact retroviral 5' LTR and a self-inactivating 3' LTR.

[0145] Any method known in the art may be used to produce infectious retroviral particles whose genome comprises an RNA copy of the viral vector. To this end, the viral vector (along with other vectors encoding the gene of interest, the DC-specific targeting molecule, etc.) is preferably introduced into a packaging cell line that packages viral genomic RNA based on the viral vector into viral particles.

[0146] The packaging cell line provides the viral proteins that are required in *trans* for the packaging of the viral genomic RNA into viral particles. The packaging cell line may be any cell line that is capable of expressing retroviral proteins. Preferred packaging cell lines include 293 (ATCC CCL X), HeLa (ATCC CCL 2), D17 (ATCC CCL 183), MDCK (ATCC CCL 34), BHK (ATCC CCL-10) and Cf2Th (ATCC CRL 1430). The packaging cell line may stably express the necessary viral proteins. Such a packaging cell line is described, for example, in U.S. Patent No. 6,218,181, which is incorporated herein by reference in its entirety. Alternatively a packaging cell line may be transiently transfected with plasmids comprising nucleic acid that encodes one or more necessary viral proteins, including the DC-specific targeting molecule (or alternatively, a DC-specific affinity molecule and fusogenic molecule) along with the viral vectors encoding the gene of interest, which typically encodes an antigen and can additionally encode a DC maturation factor.

[0147] Viral particles comprising a polynucleotide with the gene of interest and a targeting molecule that is specific for dendritic cells are collected and allowed to infect the target cell. In some preferred embodiments, the virus is pseudotyped to achieve target cell specificity. Methods for pseudotyping are well known in the art and also described herein.

[0148] In one embodiment, the recombinant virus used to deliver the gene of interest is a modified lentivirus and the viral vector is based on a lentivirus. As lentiviruses are able to infect both dividing and non-dividing cells, in this embodiment it is not necessary for target cells to be dividing (or to stimulate the target cells to divide).

[0149] In another embodiment, the recombinant virus used to deliver the gene of interest is a modified gammaretrovirus and the viral vector is based on a gammaretrovirus.

[0150] In another embodiment the vector is based on the murine stem cell virus (MSCV; (Hawley, R. G., et al. (1996) Proc. Natl. Acad. Sci. USA 93:10297–10302; Keller, G., et al. (1998) Blood 92:877–887; Hawley, R. G., et al. (1994) Gene Ther. 1:136–138, each of the foregoing which is incorporated herein by reference in its entirety). The MSCV vector provides long-term stable expression in target cells, particularly hematopoietic precursor cells and their differentiated progeny.

[0151] In another embodiment, the vector is based on a modified Moloney virus, for example a Moloney Murine Leukemia Virus. The viral vector can also can be based on a hybrid virus such as that described in Choi, J.K., et al. (2001. *Stem Cells* 19, No. 3, 236-246, which is incorporated herein by reference in its entirety).

[0152] A DNA viral vector may be used, including, for example adenovirus-based vectors and adeno-associated virus (AAV)-based vectors. Likewise, retroviral-adenoviral vectors also can be used with the methods of the invention.

[0153] Other vectors also can be used for polynucleotide delivery including vectors derived from herpes simplex viruses (HSVs), including amplicon vectors, replication-defective HSV and attenuated HSV (Krisky DM, Marconi PC, Oligino TJ, Rouse RJ, Fink DJ, et al. 1998. Development of herpes simplex virus replication-defective multigene vectors for combination gene therapy applications. *Gene Ther.* 5: 1517-30, which is incorporated herein by reference in its entirety).

[0154] Other vectors that have recently been developed for gene therapy uses can also be used with the methods of the invention. Such vectors include those derived from baculoviruses and alpha-viruses. (Jolly DJ. 1999. Emerging viral vectors. pp 209-40 in Friedmann T, ed. 1999. The development of human gene therapy. New York: Cold Spring Harbor Lab, which is incorporated herein by reference in its entirety).

[0155] In some preferred embodiments, the viral construct comprises sequences from a lentivirus genome, such as the HIV genome or the SIV genome. The viral construct preferably comprises sequences from the 5' and 3' LTRs of a lentivirus. More preferably the viral construct comprises the R and U5 sequences from the 5' LTR of a lentivirus and an

inactivated or self-inactivating 3' LTR from a lentivirus. The LTR sequences may be LTR sequences from any lentivirus from any species. For example, they may be LTR sequences from HIV, SIV, FIV or BIV. Preferably the LTR sequences are HIV LTR sequences.

[0156] The viral construct preferably comprises an inactivated or self-inactivating 3' LTR. The 3' LTR may be made self-inactivating by any method known in the art. In the preferred embodiment the U3 element of the 3' LTR contains a deletion of its enhancer sequence, preferably the TATA box, Spl and NF-kappa B sites. As a result of the self-inactivating 3' LTR, the provirus that is integrated into the host cell genome will comprise an inactivated 5' LTR.

[0157] Optionally, the U3 sequence from the lentiviral 5' LTR may be replaced with a promoter sequence in the viral construct. This may increase the titer of virus recovered from the packaging cell line. An enhancer sequence may also be included. Any enhancer/promoter combination that increases expression of the viral RNA genome in the packaging cell line may be used. In a preferred embodiment the CMV enhancer/promoter sequence is used.

[0158] In some preferred embodiments, the viral construct comprises sequences from a gammaretrovirus genome, such as the mouse stem cell virus (MSCV) genome or the murine leukemia virus (MLV) genome. The viral construct preferably comprises sequences from the 5' and 3' LTRs of a gammaretrovirus. The LTR sequences may be LTR sequences from any gammaretrovirus from any species. For example, they may be LTR sequences from mouse stem cell virus (MSCV), murine leukemia virus (MLV), feline leukemia virus (FLV), feline sarcoma virus (FAV), and avian reticuloendotheliosis viruses (ARV).. Preferably the LTR sequences are MSCV and MLV LTR sequences.

[0159] In some embodiments, the viral construct preferably comprises an inactivated or self-inactivating 3' LTR. The 3' LTR may be made self-inactivating by any method known in the art. In the preferred embodiment the U3 element of the 3' LTR contains a deletion of its enhancer sequence, preferably the TATA box, Spl and NF-kappa B sites. As a result of the self-inactivating 3' LTR, the provirus that is integrated into the host cell genome will comprise an inactivated 5' LTR.

[0160] Optionally, the U3 sequence from the gammaretroviral 5' LTR may be replaced with a promoter sequence in the viral construct. This may increase the titer of virus recovered from the packaging cell line. An enhancer sequence may also be included. Any enhancer/promoter combination that increases expression of the viral RNA genome in the packaging cell line may be used. In a preferred embodiment the CMV enhancer/promoter sequence is used.

[0161] The viral construct generally comprises a gene that encodes an antigen that is desirably expressed in one or more target cells. Preferably the gene of interest is located between the 5' LTR and 3' LTR sequences. Further, the gene of interest is preferably in a functional relationship with other genetic elements, for example transcription regulatory sequences such as promoters and/or enhancers, to regulate expression of the gene of interest in a particular manner once the gene is incorporated into the target cell. In certain embodiments, the useful transcriptional regulatory sequences are those that are highly regulated with respect to activity, both temporally and spatially.

[0162] In some embodiments, the gene of interest is in a functional relationship with internal promoter/enhancer regulatory sequences. An "internal" promoter/enhancer is one that is located between the 5' LTR and the 3' LTR sequences in the viral construct and is operably linked to the gene that is desirably expressed.

[0163] The internal promoter/enhancer may be any promoter, enhancer or promoter/enhancer combination known to increase expression of a gene with which it is in a functional relationship. A "functional relationship" and "operably linked" mean, without limitation, that the gene is in the correct location and orientation with respect to the promoter and/or enhancer that expression of the gene will be affected when the promoter and/or enhancer is contacted with the appropriate molecules.

[0164] The internal promoter/enhancer is preferably selected based on the desired expression pattern of the gene of interest and the specific properties of known promoters/enhancers. Thus, the internal promoter may be a constitutive promoter. Non-limiting examples of constitutive promoters that may be used include the promoter for ubiquitin, CMV (Karasuyama et al. 1989. *J. Exp. Med.* 169:13, which is incorporated herein by reference in its entirety), beta-actin (Gunning et al. 1989. *Proc. Natl. Acad. Sci. USA*

84:4831-4835, which is incorporated herein by reference in its entirety) and pgk (see, for example, Adra et al. 1987. *Gene* 60:65-74; Singer-Sam et al. 1984. *Gene* 32:409-417; and Dobson et al. 1982. *Nucleic Acids Res.* 10:2635-2637, each of the foregoing which is incorporated herein by reference in its entirety).

**[0165]** Alternatively, the promoter may be a tissue specific promoter. In some preferred embodiments, the promoter is a target cell-specific promoter. For example, the promoter can be the dendritic cell-specific promoter CD11c (Masood, R., et al. 2001. *Int J Mol Med* 8:335-343; Somia, N.V., et al. 1995. *Proc Acad Sci USA* 92:7570-7574, each of which is incorporated herein by reference in its entirety.) In addition, promoters may be selected to allow for inducible expression of the gene. A number of systems for inducible expression are known in the art, including the tetracycline responsive system and the lac operator-repressor system. It is also contemplated that a combination of promoters may be used to obtain the desired expression of the gene of interest. The skilled artisan will be able to select a promoter based on the desired expression pattern of the gene in the organism and/or the target cell of interest.

**[0166]** In some embodiments the viral construct preferably comprises at least one RNA Polymerase II or III promoter. The RNA Polymerase II or III promoter is operably linked to the gene of interest and can also be linked to a termination sequence. In addition, more than one RNA Polymerase II or III promoters may be incorporated.

**[0167]** RNA polymerase II and III promoters are well known to one of skill in the art. A suitable range of RNA polymerase III promoters can be found, for example, in Paule and White. *Nucleic Acids Research.*, Vol 28, pp 1283-1298 (2000), which is incorporated herein by reference in its entirety. The definition of RNA polymerase II or III promoters, respectively, also include any synthetic or engineered DNA fragment that can direct RNA polymerase II or III, respectively, to transcribe its downstream RNA coding sequences. Further, the RNA polymerase II or III (Pol II or III) promoter or promoters used as part of the viral vector can be inducible. Any suitable inducible Pol II or III promoter can be used with the methods of the invention. Particularly suited Pol II or III promoters include the tetracycline responsive promoters provided in Ohkawa and Taira *Human Gene Therapy*, Vol.

11, pp 577-585 (2000) and in Meissner *et al. Nucleic Acids Research,* Vol. 29, pp 1672-1682 (2001), each of which is incorporated herein by reference in its entirety.

[0168] An internal enhancer may also be present in the viral construct to increase expression of the gene of interest. For example, the CMV enhancer (Karasuyama et al. 1989. *J. Exp. Med.* 169:13, which is incorporated herein by reference in its entirety) may be used. In some embodiments, the CMV enhancer can be used in combination with the chicken β-actin promoter. One of skill in the art will be able to select the appropriate enhancer based on the desired expression pattern.

[0169] The polynucleotide or gene of interest is not limited in any way and includes any nucleic acid that the skilled practitioner desires to have integrated, transcribed, translated, and/or expressed in the target cell. In some embodiments, the polynucleotide can be a gene that encodes an antigen against which an immune response is desired. In some embodiments, the polynucleotide can be a gene encoding a small inhibiting RNA (siRNA) or a microRNA (miRNA) of interest that down-regulates expression of a molecule. For example, the gene encoding an siRNA or a microRNA can be used to down-regulate expression of negative regulators in a cell, including those that inhibit activation or maturation of dendritic cells. siRNAs and microRNAs are known in the art and describe elsewhere (Shen, L. et al. 2004. *Nat Biotech* 22(12): 1546-1553; Zhou, H. et al. 2006. *Biochemical and Biophysical Research Communications* 347:200-207; Song, X-T., et al. 2006. *PLoS Medicine* 3(1):e11; Kobayashi, T. and A. Yoshimura. 2005. *TRENDS in Immunology* 26(4):177-179; Taganov, K., et al. 2007. *Immunity* 26:133-137; Dahlberg, J.E. and E. Lund. 2007. *Sci. STKE* 387:pe25, each of which is incorporated herein by reference in its entirety).

[0170] In addition, in some embodiments, the polynucleotide can contain more than one gene of interest, which can be placed in functional relationship with the viral promoter. The gene of interest can encode a protein, a siRNA, or a microRNA. In some embodiments, the polynucleotide to be delivered can comprise multiple genes encoding at least one protein, at least one siRNA, at least one microRNA, or any combinations thereof. For example, the polynucleotide to be delivered can include one or more genes that encode one or more antigens against which an immune response is desired. The one or more antigens

can be associated with a single disease or disorder, or the can be associated with multiple diseases and/or disorders. In some embodiments, a gene encoding an immune regulatory protein can be constructed with a primary gene encoding an antigen against which an immune response is desired, and the combination can elicit and regulate the immune response to the desired direction and magnitude. In some embodiments, a gene encoding an siRNA or microRNA can be constructed with a primary gene encoding an antigen against which an immune response is desired, and the combination can regulate the scope of the immune response. (See, for example, embodiments of polynucleotides in Figure 24c and Figure 24d, with accompanying sequences in SEQ ID NO: 9 and SEQ ID NO: 10, respectively.) In some embodiments, a gene encoding a marker protein can be placed after a primary gene of interest to allow for identification of cells that are expressing the desired protein. In one embodiment a fluorescent marker protein, preferably green fluorescent protein (GFP), is incorporated into the construct along with the gene of interest (typically encoding an antigen). If more than one gene is included, internal ribosomal entry site (IRES) sequences, or 2A elements are also preferably included, separating the primary gene of interest from a reporter gene and/or any other gene of interest. The IRES or 2A sequences may facilitate the expression of the reporter gene, or other genes.

[0171] The viral construct may also contain additional genetic elements. The types of elements that may be included in the construct are not limited in any way and will be chosen by the skilled practitioner to achieve a particular result. For example, a signal that facilitates nuclear entry of the viral genome in the target cell may be included. An example of such a signal is the HIV-1 flap signal.

[0172] Further, elements may be included that facilitate the characterization of the provirus integration site in the target cell. For example, a tRNA amber suppressor sequence may be included in the construct.

[0173] In addition, the construct may contain one or more genetic elements designed to enhance expression of the gene of interest. For example, a woodchuck hepatitis virus responsive element (WRE) may be placed into the construct (Zufferey et al. 1999. *J. Virol.* 74:3668-3681; Deglon et al. 2000. *Hum. Gene Ther.* 11:179-190, each of which is incorporated herein by reference in its entirety).

[0174] A chicken β-globin insulator may also be included in the viral construct. This element has been shown to reduce the chance of silencing the integrated provirus in the target cell due to methylation and heterochromatinization effects. In addition, the insulator may shield the internal enhancer, promoter and exogenous gene from positive or negative positional effects from surrounding DNA at the integration site on the chromosome.

[0175] Any additional genetic elements are preferably inserted 3' of the gene of interest.

[0176] In a specific embodiment, the viral vector comprises: a cytomegalovirus (CMV) enhancer/promoter sequence; the R and U5 sequences from the HIV 5' LTR; the HIV-1 flap signal; an internal enhancer; an internal promoter; a gene of interest; the woodchuck hepatitis virus responsive element; a tRNA amber suppressor sequence; a U3 element with a deletion of its enhancer sequence; the chicken beta-globin insulator; and the R and U5 sequences of the 3' HIV LTR.

[0177] The viral construct is preferably cloned into a plasmid that may be transfected into a packaging cell line. The preferred plasmid preferably comprises sequences useful for replication of the plasmid in bacteria.

Delivery of the Virus

[0178] The virus may be delivered to a target cell in any way that allows the virus to contact the target dendritic cells (DCs) in which delivery of a polynucleotide of interest is desired. In preferred embodiments, a suitable amount of virus is introduced into an animal directly (*in vivo*), for example though injection into the body. In some preferred embodiments, the viral particles are injected into a mammal's peripheral blood stream. In other preferred embodiments, the viral particles are injected into a mammal through intra-dermal injection, subcutaneous injection, intra-peritoneal cavity injection, or intra-venal injection. The virus may be delivered using a subdermal injection device such the devices disclosed in US Patent Nos. 7,241,275, 7,115,108, 7,108,679, 7,083,599, 7,083,592, 7,047,070, 6,971,999, 6,808,506, 6,780,171, 6,776,776, 6,689,118, 6,670,349, 6,569,143, 6,494,865, 5,997,501, 5,848,991, 5,328,483, 5,279,552, 4,886,499, all of which are incorporated by reference in their entirety for all purposes.Other injection locations also are suitable, such as directly into organs comprising target cells. For example intra-lymph node

injection, intra-spleen injection, or intra-bone marrow injection may be used to deliver virus to the lymph node, the spleen and the bone marrow, respectively. Depending on the particular circumstances and nature of the target cells, introduction can be carried out through other means including for example, inhalation, or direct contact with epithelial tissues, for example those in the eye, mouth or skin.

[0179] In other embodiments, target cells are provided and contacted with the virus *in vitro*, such as in culture plates. The target cells are typically dendritic cells obtained from a healthy subject or a subject in need of treatment. Preferably, the target cells are dendritic cells obtained from a subject in whom it is desired to stimulate an immune response to an antigen. Methods to obtain cells from a subject are well known in the art. The virus may be suspended in media and added to the wells of a culture plate, tube or other container. The media containing the virus may be added prior to the plating of the cells or after the cells have been plated. Preferably cells are incubated in an appropriate amount of media to provide viability and to allow for suitable concentrations of virus in the media such that infection of the host cell occurs.

[0180] The cells are preferably incubated with the virus for a sufficient amount of time to allow the virus to infect the cells. Preferably the cells are incubated with virus for at least 1 hour, more preferably at least 5 hours and even more preferably at least 10 hours.

[0181] In both *in vivo* and *in vitro* delivery embodiments, any concentration of virus that is sufficient to infect the desired target cells may be used, as can be readily determined by the skilled artisan. When the target cell is to be cultured, the concentration of the viral particles is at least 1 PFU/μl, more preferably at least 10 PFU/μl, even more preferably at least 400 PFU/μl and even more preferably at least $1 \times 10^4$ PFU/μl.

[0182] In some embodiments, following infection with the virus *in vitro*, target cells can be introduced (or re-introduced) into an animal. In some embodiments, the cells can be introduced into the dermis, under the dermis, or into the peripheral blood stream. The cells introduced into an animal are preferably cells derived from that animal, to avoid an adverse immune response. Cells also can be used that are derived from a donor animal having a similar immune background. Other cells also can be used, including those designed to avoid an adverse immunogenic response.

[0183] The target cells may be analyzed, for example for integration, transcription and/or expression of the polynucleotide or gene(s) of interest, the number of copies of the gene integrated, and the location of the integration. Such analysis may be carried out at any time and may be carried out by any methods known in the art.

[0184] Subjects in which a recombinant virus or virus-infected DCs are administered can be analyzed for location of infected cells, expression of the virus-delivered polynucleotide or gene of interest, stimulation of an immune response, and monitored for symptoms associated with a disease or disorder by any methods known in the art.

[0185] The methods of infecting cells disclosed above do not depend upon individual-specific characteristics of the cells. As a result, they are readily extended to all mammals. In some embodiments the recombinant virus is delivered to a human or to human dendritic cells. In other embodiments, the recombinant virus is delivered to a mouse or to mouse dendritic cells. In still other embodiments, the recombinant virus is delivered to an animal other than a human or a mouse, or to dendritic cells from an animal other than a human or a mouse.

[0186] As discussed above, the recombinant virus can be pseudotyped to confer upon it a broad host range as well as target cell specificity. One of skill in the art would also be aware of appropriate internal promoters to achieve the desired expression of a polynucleotide or gene of interest in a particular animal species. Thus, one of skill in the art will be able to modify the method of infecting dendritic cells derived from any species.

[0187] The recombinant virus can be evaluated to determine the specificity of the targeting molecule incorporated into the virus that targets dendritic cells. For example, a mixed population of bone marrow cells can be obtained from a subject and cultured *in vitro*. The recombinant virus can be administered to the mixed population of bone marrow cells, and expression of a reporter gene incorporated into the virus can be assayed in the cultured cells. In some embodiments, at least about 50%, more preferably at least about 60%, 70%, 80% or 90%, still more preferably at least about 95% of transduced cells in the mixed cell population are dendritic cells that express DC-SIGN.

Therapy

[0188] The methods of the present invention can be used to prevent or treat a wide variety of diseases or disorders, particularly those for which activation of an immune response in a patient would be beneficial. Many such diseases are well known in the art. For example, diseases or disorders that are amenable to treatment or prevention by the methods of the present invention include, without limitation, cancers, autoimmune diseases, and infections, including viral, bacterial, fungal and parasitic infections. In embodiments of the invention, a disease is treated by using recombinant viruses to deliver a gene of interest to dendritic cells, wherein expression of the gene produces a disease-specific antigen and leads to stimulation of antigen-specific cellular immune responses and humoral immune responses.

[0189] In embodiments of the invention, a recombinant virus is used to deliver polynucleotides encoding an antigen against which an immune response is desired to dendritic cells. In some embodiments, the delivery can be achieved by contacting dendritic cells with the recombinant virus *in vitro*, whereupon the transduced dendritic cells are provided to a patient. In some embodiments, the delivery can be achieved by delivering the virus to a subject for contact with dendritic cells *in vivo*. The dendritic cells then stimulate antigen-specific T cells or B cells in a patient to induce cellular and humoral immune responses to the expressed antigen. In such embodiments, a patient that is suffering from a disease or disorder is treated by generating immune cells with a desired specificity.

[0190] Any antigen that is associated with a disease or disorder can be delivered to dendritic cells using the recombinant viruses as described herein. An antigen that is associated with the disease or disorder is identified for preparation of a recombinant virus that targets dendritic cells. Antigens associated with many diseases and disorders are well known in the art. An antigen may be previously known to be associated with the disease or disorder, or may be identified by any method known in the art. For example, an antigen to a type of cancer from which a patient is suffering may be known, such as a tumor associated antigen. In one aspect, the invention provides a method to deliver genes encoding tumor antigens and other necessary proteins to DCs in vivo using engineered recombinant lentivirus. In other embodiments, an antigen related to the disease or disorder is identified from the patient to be treated. For example, an antigen associated with a tumor may be identified from the tumor itself by any method known in the art. Tumor associated antigens

are not limited in any way and include, for example, antigens that are identified on cancerous cells from the patient to be treated.

**[0191]** Tumor associated antigens are known for a variety of cancers including, for example, prostate cancer and breast cancer. In some breast cancers, for example, the Her-2 receptor is overexpressed on the surface of cancerous cells. Exemplary tumor antigens include, but are not limited to: MAGE, BAGE, RAGE, and NY-ESO, which are nonmutated antigens expressed in the immune-privileged areas of the testes and in a variety of tumor cells; lineage-specific tumor antigens such as the melanocyte-melanoma lineage antigens MART-1/Melan-A, gp100, gp75, mda-7, tyrosinase and tyrosinase-related protein, or the prostate specific membrane antigen (PSMA) and prostate-specific antigen (PSA), which are antigens expressed in normal and neoplastic cells derived from the same tissue; epitope proteins/peptides derived from genes mutated in tumor cells or genes transcribed at different levels in tumor compared to normal cells, such as mutated ras, bcr/abl rearrangement, Her2/neu, mutated or wild-type p53, cytochrome P450 1B1, and abnormally expressed intron sequences such as *N*-acetylglucosaminyltransferase-V; clonal rearrangements of immunoglobulin genes generating unique idiotypes in myeloma and B-cell lymphomas; epitope proteins/peptides derived from oncoviral processes, such as human papilloma virus proteins E6 and E7; nonmutated oncofetal proteins with a tumor-selective expression, such as carcinoembryonic antigen and alpha-fetoprotein. A number of tumor associated antigens have been reviewed (see, for example, "Tumor-Antigens Recognized By T-Lymphocytes," Boon T, Cerottini J C, Vandeneynde B, Vanderbruggen P, Vanpel A, Annual Review Of Immunology 12: 337-365, 1994; "A listing of human tumor antigens recognized by T cells," Renkvist N, Castelli C, Robbins P F, Parmiani G. Cancer Immunology Immunotherapy 50: (1) 3-15 MAR 2001, each of which is incorporated herein by reference in its entirety.)

**[0192]** The antigen can also be an antigen associated with an infectious disease, such as, for example, HIV/AIDS. The antigen can be, for example, gp120 (Klimstra, W.B., et al. 2003. *J Virol* 77:12022-12032; Bernard, K.A., et al. 2000. *Virology* 276:93-103; Bymes, A.P., et al. 1998. *J Virol* 72: 7349-7356, each of which is incorporated herein by reference in its entirety). Other exemplary antigens include, but are not limited to: gag, pol, env, tat, nef and rev (Lieberman, J. et al. 1997. *AIDS Res Hum Retroviruses* 13(5): 383-392;

Menendez-Arias, L. et al. 1998. *Viral Immunol* 11(4): 167-181, each of which is incorporated herein by reference in its entirety).

[0193] Examples of viral antigens include, but are not limited to, adenovirus polypeptides, alphavirus polypeptides, calicivirus polypeptides, e.g., a calicivirus capsid antigen, coronavirus polypeptides, distemper virus polypeptides, Ebola virus polypeptides, enterovirus polypeptides, flavivirus polypeptides, hepatitis virus (AE) polypeptides, e.g., a hepatitis B core or surface antigen, herpesvirus polypeptides, e.g., a herpes simplex virus or varicella zoster virus glycoprotein, immunodeficiency virus polypeptides, e.g., the human immunodeficiency virus envelope or protease, infectious peritonitis virus polypeptides, influenza virus polypeptides, e.g., an influenza A hemagglutinin, neuraminidase, or nucleoprotein, leukemia virus polypeptides, Marburg virus polypeptides, orthomyxovirus polypeptides, papilloma virus polypeptides, parainfluenza virus polypeptides, e.g., the hemagglutinin/neuraminidase, paramyxovirus polypeptides, parvovirus polypeptides, pestivirus polypeptides, picorna virus polypeptides, e.g., a poliovirus capsid polypeptide, pox virus polypeptides, e.g., a vaccinia virus polypeptide, rabies virus polypeptides, e.g., a rabies virus glycoprotein G, reovirus polypeptides, retrovirus polypeptides, and rotavirus polypeptides.

[0194] Examples of bacterial antigens include, but are not limited to, Actinomyces polypeptides, Bacillus polypeptides, Bacteroides polypeptides, Bordetella polypeptides, Bartonella polypeptides, Borrelia polypeptides, e.g., B. burgdorferi OspA, Brucella polypeptides, Campylobacter polypeptides, Capnocytophaga polypeptides, Chlamydia polypeptides, Clostridium polypeptides, Corynebacterium polypeptides, Coxiella polypeptides, Dermatophilus polypeptides, Enterococcus polypeptides, Ehrlichia polypeptides, Escherichia polypeptides, Francisella polypeptides, Fusobacterium polypeptides, Haemobartonella polypeptides, Haemophilus polypeptides, e.g., H. influenzae type b outer membrane protein, Helicobacter polypeptides, Klebsiella polypeptides, L-form bacteria polypeptides, Leptospira polypeptides, Listeria polypeptides, Mycobacteria polypeptides, Mycoplasma polypeptides, Neisseria polypeptides, Neorickettsia polypeptides, Nocardia polypeptides, Pasteurella polypeptides, Peptococcus polypeptides, Peptostreptococcus polypeptides, Pneumococcus polypeptides, Proteus polypeptides,

Pseudomonas polypeptides, Rickettsia polypeptides, Rochalimaea polypeptides, Salmonella polypeptides, Shigella polypeptides, Staphylococcus polypeptides, Streptococcus polypeptides, e.g., S. pyogenes M proteins, Treponema polypeptides, and Yersinia polypeptides, e.g., Y. pestis F1 and V antigens.

**[0195]** Examples of fungal antigens include, but are not limited to, Absidia polypeptides, Acremonium polypeptides, Alternaria polypeptides, Aspergillus polypeptides, Basidiobolus polypeptides, Bipolaris polypeptides, Blastomyces polypeptides, Candida polypeptides, Coccidioides polypeptides, Conidiobolus polypeptides, Cryptococcus polypeptides, Curvalaria polypeptides, Epidermophyton polypeptides, Exophiala polypeptides, Geotrichum polypeptides, Histoplasma polypeptides, Madurella polypeptides, Malassezia polypeptides, Microsporum polypeptides, Moniliella polypeptides, Mortierella polypeptides, Mucor polypeptides, Paecilomyces polypeptides, Penicillium polypeptides, Phialemonium polypeptides, Phialophora polypeptides, Prototheca polypeptides, Pseudallescheria polypeptides, Pseudomicrodochium polypeptides, Pythium polypeptides, Rhinosporidium polypeptides, Rhizopus polypeptides, Scolecobasidium polypeptides, Sporothrix polypeptides, Stemphylium polypeptides, Trichophyton polypeptides, Trichosporon polypeptides, and Xylohypha polypeptides.

**[0196]** Examples of protozoan parasite antigens include, but are not limited to, Babesia polypeptides, Balantidium polypeptides, Besnoitia polypeptides, Cryptosporidium polypeptides, Eimeria polypeptides, Encephalitozoon polypeptides, Entamoeba polypeptides, Giardia polypeptides, Hammondia polypeptides, Hepatozoon polypeptides, Isospora polypeptides, Leishmania polypeptides, Microsporidia polypeptides, Neospora polypeptides, Nosema polypeptides, Pentatrichomonas polypeptides, Plasmodium polypeptides, e.g., P. falciparum circumsporozoite (PfCSP), sporozoite surface protein 2 (PfSSP2), carboxyl terminus of liver state antigen 1 (PfLSA1 c-term), and exported protein 1 (PfExp-1), Pneumocystis polypeptides, Sarcocystis polypeptides, Schistosoma polypeptides, Theileria polypeptides, Toxoplasma polypeptides, and Trypanosoma polypeptides.

**[0197]** Examples of helminth parasite antigens include, but are not limited to, Acanthocheilonema polypeptides, Aelurostrongylus polypeptides, Ancylostoma polypeptides, Angiostrongylus polypeptides, Ascaris polypeptides, Brugia polypeptides, Bunostomum

polypeptides, Capillaria polypeptides, Chabertia polypeptides, Cooperia polypeptides, Crenosoma polypeptides, Dictyocaulus polypeptides, Dioctophyme polypeptides, Dipetalonema polypeptides, Diphyllobothrium polypeptides, Diplydium polypeptides, Dirofilaria polypeptides, Dracunculus polypeptides, Enterobius polypeptides, Filaroides polypeptides, Haemonchus polypeptides, Lagochilascaris polypeptides, Loa polypeptides, Mansonella polypeptides, Muellerius polypeptides, Nanophyetus polypeptides, Necator polypeptides, Nematodirus polypeptides, Oesophagostomum polypeptides, Onchocerca polypeptides, Opisthorchis polypeptides, Ostertagia polypeptides, Parafilaria polypeptides, Paragonimus polypeptides, Parascaris polypeptides, Physaloptera polypeptides, Protostrongylus polypeptides, Setaria polypeptides, Spirocerca polypeptides Spirometra polypeptides, Stephanofilaria polypeptides, Strongyloides polypeptides, Strongylus polypeptides, Thelazia polypeptides, Toxascaris polypeptides, Toxocara polypeptides, Trichinella polypeptides, Trichostrongylus polypeptides, Trichuris polypeptides, Uncinaria polypeptides, and Wuchereria polypeptides.

**[0198]** Examples of ectoparasite antigens include, but are not limited to, polypeptides (including protective antigens as well as allergens) from fleas; ticks, including hard ticks and soft ticks; flies, such as midges, mosquitos, sand flies, black flies, horse flies, horn flies, deer flies, tsetse flies, stable flies, myiasis-causing flies and biting gnats; ants; spiders, lice; mites; and true bugs, such as bed bugs and kissing bugs.

**[0199]** Once an antigen has been identified and/or selected, a polynucleotide that encodes the desired antigen is identified. Preferably the polynucleotide comprises a cDNA. The polynucleotides encoding the antigen are preferably introduced into target dendritic cells using a recombinant virus, more preferably a recombinant lentivirus or gammaretrovirus, including a targeting molecule that binds DC-SIGN as described above. The recombinant virus first binds to the dendritic cell membrane by way of the DC-SIGN targeting molecule, and the viral core containing a polynucleotide encoding the antigen subsequently enters the cytosol. The polynucleotide (e.g., one encoding the antigen) is then preferably integrated into the cell's genome and expressed. If contacted *ex vivo*, the target dendritic cells are then transferred back to the patient, for example by injection, where they interact with immune cells that are capable of generating an immune response against the desired antigen. In

preferred embodiments, the recombinant virus is injected into the patient where it transduces the targeted dendritic cells *in situ*. The dendritic cells then express the particular antigen associated with a disease or disorder to be treated, and the patient is able to mount an effective immune response against the disease or disorder.

[0200] In some embodiments, the recombinant virus contains a polynucleotide sequence encoding more than one antigen, and upon transduction of a target dendritic cell, generates immune responses to the multitude of antigens delivered to the cell. In some embodiments, the antigens are related to a single disease or disorder. In other embodiments, the antigens are related to multiple diseases or disorders.

[0201] In embodiments of the invention, DC maturation factors that activate and/or stimulate maturation of the DCs are delivered in conjunction with the recombinant virus carrying the polynucleotide or gene of interest. In some embodiments, the DCs are activated by delivery of DC maturation factors prior to delivery of the virus. In some embodiments, the DCs are activated by delivery of DC maturation factors after delivery of the virus. In some embodiments, the DCs are activated by delivery of DC maturation factors simultaneously with delivery of the virus. In some embodiments, DC maturation factors are provided together with administration of the virus. In other embodiments, DC maturation factors are provided separately from administration of the virus.

[0202] In certain embodiments, one or more DC maturation factors can be encoded by one or more genes that are contained in the virus and expressed after the virus transduces a dendritic cell. In some embodiments, the one or more genes encoding DC maturation factors can be included in a viral vector encoding an antigen. In further embodiments, the one or more genes encoding DC maturation factors can be included in a viral vector that encodes more than one antigen. In some embodiments, the one or more genes encoding DC maturation factors can be provided in a separate vector that is co-transfected with the viral vector encoding one or more antigens in a packaging cell line.

[0203] In some embodiments, the methods of the present invention can be used for adoptive immunotherapy in a patient. As described above, an antigen against which an immune response is desired is identified. A polynucleotide encoding the desired antigen is obtained and packaged into a recombinant virus. Target dendritic cells are obtained from the

patient and transduced with a recombinant virus containing a polynucleotide that encodes the desired antigen. The dendritic cells are then transferred back into the patient.

Vaccination

**[0204]** As discussed above, various engineered targeting molecules that bind the DC-SIGN surface dendritic cell marker are contemplated for use in producing recombinant virus that delivers a gene encoding an antigen to DCs. The virus can be used to transduce DCs *in vitro* or *in vivo* for prevention of a disease or disorder. For example, the Sindbis virus envelope glycoprotein can be engineered to bind preferentially to DC-SIGN and used to pseudotype a recombinant virus. A gene encoding an antigen against which an immune response is desired, such as for cancer (for example, Mart-1), or another disease/disorder (such as viral infection) may be delivered to DCs using the methods described herein. In some embodiments, multiple genes encoding multiple antigens can be delivered to DCs using the methods described herein, through the use of multiple viral vectors, or, preferably, a multicistronic vector system. The one or more genes for the one or more antigens may be accompanied by genes encoding stimulatory molecules (such as GM-CSF, IL-2, IL-4, IL-6, IL-7, IL-15, IL-21, IL-23, TNFα, B7.1, B7.2, 4-1BB, CD40 ligand (CD40L), drug-inducible CD40 (iCD40), and the like) and/or a reporter molecule (such as GFP, luciferase and the like) using multiple vectors or, preferably, a multicistronic vector system.

**[0205]** In some embodiments of the invention, human DCs are generated by obtaining CD34α+ human hematopoietic progenitors and using an *in vitro* culture method as described elsewhere (e.g., Banchereau et al. Cell 106, 271-274 (2001)). Viruses bearing a targeting molecule that binds DC-SIGN are generated comprising a gene encoding an antigen against which an immune response is desired and are used to transduce human DCs. Transduction specificity and efficiency may be quantified by FACS. Maturation of DCs can be characterized by FACS analysis of up-regulation of surface marker such as MHC II.

**[0206]** In other embodiments, virus may be injected *in vivo*, where it contacts natural DCs and delivers a polynucleotide of interest, typically a gene encoding an antigen. The amount of viral particles is at least $50 \times 10^6$ TU, and can be at least $1 \times 10^7$ TU, at least $2 \times 10^7$ TU, at least $3 \times 10^7$, at least $4 \times 10^7$ TU, or at least $5 \times 10^7$ TU. At selected intervals, DCs from the recipient's lymphoid organs may be used to measure expression, for example,

by observing marker expression, such as GFP or luciferase. T cells from lymph nodes and spleens of virus-treated recipients may be measured from the magnitude and durability of response to antigen stimulation. Tissue cells other than DCs, such as epithelial cells and lymphoid cells, may be analyzed for the specificity of *in vivo* gene delivery.

**[0207]** It is widely agreed that the most effective potential method to end the AIDS epidemic (and other viral diseases) is a vaccine. To date, no vaccination method against HIV has successfully passed a phase III trial. Thus, there is an urgent need for novel and effective vaccination strategies. In some embodiments of the invention, DC vaccination is used. A gene is cloned encoding a viral protein, such as those described above, into a viral vector. Patients are infected with viruses comprising a targeting molecule that binds DC-SIGN in DCs, preferably with specificity such that undesired side effects are avoided. The targeting molecule can be, for example, an engineered Sindbis virus envelope glycoprotein, and the administration of virus can be carried out, for example, by injection. In an animal model, molecularly cloned HIV reporter viruses (NFNSZ-r-HSAS, NL-r-HSAS) and clinical isolates may be used to challenge the animals by tail vein injection. Evidence of infection may be monitored over time in splenocytes, lymph nodes, and peripheral blood. PCR for HIV-gag protein and FACS for HAS in the reporter viruses may be used to test for viral integration and replication. Productive *in situ* DC vaccination may increase resistance to a HIV challenge. See Examples 17-20.

**[0208]** In some embodiments, dendritic cells transduced with a recombinant virus as described herein are provided for the prevention of or treatment of a disease or disorder. In preferred embodiments, the dendritic cells express an antigen against which an immune response is desired. The antigen is typically one that is not normally expressed in a dendritic cell but is expressed after the target cell is transduced with the recombinant virus containing a polynucleotide encoding the antigen. In some embodiments, the dendritic cells further express a DC maturation factor which is provided to the dendritic cell by a recombinant virus as described herein.

**[0209]** In some aspects of the invention, an adjuvant is administered in conjunction with a recombinant virus of the invention. The adjuvant may be administered with the recombinant virus, before the recombinant virus, or after the recombinant virus.

[0210] A variety of adjuvants can be used in combination with the recombinant virus of the invention to elicit an immune response to the antigen encoded to the recombinant virus. Preferred adjuvants augment the intrinsic response to an antigen without causing conformational changes in the antigen that affect the qualitative form of the response. Preferred adjuvants include alum, 3 De-O-acylated monophosphoryl lipid A (MPL) (see GB 2220211). QS21 is a triterpene glycoside or saponin isolated from the bark of the Quillaja Saponaria Molina tree found in South America (see Kensil et al., *in Vaccine Design: The Subunit and Adjuvant Approach* (eds. Powell & Newman, Plenum Press, NY, 1995); US Patent No. 5,057,540). Other adjuvants are oil in water emulsions (such as squalene or peanut oil), optionally in combination with immune stimulants, such as monophosphoryl lipid A (see Stoute et al., *N. Engl. J. Med.* 336, 86-91 (1997)). Another adjuvant is CpG (*Bioworld Today*, Nov. 15, 1998). Alternatively, Aβ can be coupled to an adjuvant. For example, a lipopeptide version of Aβ can be prepared by coupling palmitic acid or other lipids directly to the N-terminus of Aβ as described for hepatitis B antigen vaccination (Livingston, *J. Immunol.* 159, 1383-1392 (1997)). However, such coupling should not substantially change the conformation of Aβ so as to affect the nature of the immune response thereto. Adjuvants can be administered as a component of a therapeutic composition with an active agent or can be administered separately, before, concurrently with, or after administration of the therapeutic agent.

[0211] A preferred class of adjuvants is aluminum salts (alum), such as aluminum hydroxide, aluminum phosphate, aluminum sulfate. Such adjuvants can be used with or without other specific immunostimulating agents such as MPL or 3-DMP, QS21, polymeric or monomeric amino acids such as polyglutamic acid or polylysine. Another class of adjuvants is oil-in-water emulsion formulations. Such adjuvants can be used with or without other specific immunostimulating agents such as muramyl peptides (e.g., N-acetylmuramyl-L-threonyl-D-isoglutamine (thr-MDP), N-acetyl-normuramyl-L-alanyl-D-isoglutamine (nor-MDP), N-acetylmuramyl-L-alanyl-D-isoglutaminyl-L-alanine-2-(1'-2'dipalmitoyl-sn-glycero-3-hydroxyphosphoryloxy)-ethylamine (MTP-PE), N-acetylglucsaminyl-N-acetylmuramyl-L-Al-D-isoglu-L-Ala-dipalmitoxy propylamide (DTP-DPP) theramide™), or other bacterial cell wall components. Oil-in-water emulsions include (a) MF59 (WO 90/14837), containing 5%

Squalene, 0.5% Tween 80, and 0.5% Span 85 (optionally containing various amounts of MTP-PE) formulated into submicron particles using a microfluidizer such as Model 110Y microfluidizer (Microfluidics, Newton MA), (b) SAF, containing 10% Squalane, 0.4% Tween 80, 5% pluronic-blocked polymer L121, and thr-MDP, either microfluidized into a submicron emulsion or vortexed to generate a larger particle size emulsion, and (c) Ribi™ adjuvant system (RAS), (Ribi Immunochem, Hamilton, MT) containing 2% squalene, 0.2% Tween 80, and one or more bacterial cell wall components from the group consisting of monophosphorylipid A (MPL), trehalose dimycolate (TDM), and cell wall skeleton (CWS), preferably MPL + CWS (Detox™). Another class of preferred adjuvants is saponin adjuvants, such as Stimulon™ (QS21, Aquila, Worcester, MA) or particles generated therefrom such as ISCOMs (immunostimulating complexes) and ISCOMATRIX. Other adjuvants include Complete Freund's Adjuvant (CFA) and Incomplete Freund's Adjuvant (IFA). Other adjuvants include cytokines, such as interleukins (IL-1,IL-2, and IL-12), macrophage colony stimulating factor (M-CSF), tumor necrosis factor (TNF).

**[0212]** An adjuvant can be administered with the recombinant virus of the invention as a single composition, or can be administered before, concurrent with or after administration of the recombinant virus of the invention. Immunogen and adjuvant can be packaged and supplied in the same vial or can be packaged in separate vials and mixed before use. Immunogen and adjuvant are typically packaged with a label indicating the intended therapeutic application. If immunogen and adjuvant are packaged separately, the packaging typically includes instructions for mixing before use. The choice of an adjuvant and/or carrier depends on the stability of the vaccine containing the adjuvant, the route of administration, the dosing schedule, the efficacy of the adjuvant for the species being vaccinated, and, in humans, a pharmaceutically acceptable adjuvant is one that has been approved or is approvable for human administration by pertinent regulatory bodies. For example, Complete Freund's adjuvant is not suitable for human administration. Alum, MPL and QS21 are preferred. Optionally, two or more different adjuvants can be used simultaneously. Preferred combinations include alum with MPL, alum with QS21, MPL with QS21, and alum, QS21 and MPL together. Also, Incomplete Freund's ajuvant can be

used (Chang et al., *Advanced Drug Delivery Reviews* 32, 173-186 (1998)), optionally in combination with any of alum, QS21, and MPL and all combinations thereof.

Pharmaceutical compositions and kits

[0213] Also contemplated herein are pharmaceutical compositions and kits containing a recombinant virus provided herein and one or more components. Pharmaceutical compositions can include a recombinant virus provided herein and a pharmaceutical carrier. Kits can include the pharmaceutical compositions and/or combinations provided herein, and one or more components, such as instructions for use, a device for administering a compound to a subject, and a device for administering a compound to a subject.

[0214] Provided herein are pharmaceutical compositions containing a virus provided herein and a suitable pharmaceutical carrier. Pharmaceutical compositions provided herein can be in various forms, e.g., in solid, liquid, powder, aqueous, or lyophilized form. Examples of suitable pharmaceutical carriers are known in the art. Such carriers and/or additives can be formulated by conventional methods and can be administered to the subject at a suitable dose. Stabilizing agents such as lipids, nuclease inhibitors, polymers, and chelating agents can preserve the compositions from degradation within the body.

[0215] The recombinant viruses provided herein can be packaged as kits. Kits can optionally include one or more components such as instructions for use, devices, and additional reagents, and components, such as tubes, containers and syringes for practice of the methods. Exemplary kits can include the viruses provided herein, and can optionally include instructions for use, a device for detecting a virus in a subject, a device for administering the virus to a subject, and a device for administering a compound to a subject.

[0216] Kits comprising polynucleotides encoding a gene of interest (typically an antigen) are also contemplated herein. In some embodiments, the kit includes at least one plasmid encoding virus packaging components and vector encoding a targeting molecule that is engineered to bind dendritic cells, preferably with specificity. In some embodiments, the kit includes at least one plasmid encoding virus packaging components, a vector encoding a targeting molecule that is engineered to bind dendritic cells and a vector encoding at least one DC maturation factor.

[0217] Kits comprising a viral vector encoding a gene of interest (typically an antigen) and optionally, a polynucleotide sequence encoding a DC maturation factor are also contemplated herein. In some embodiments, the kit includes at least one plasmid encoding virus packaging components and vector encoding a targeting molecule that is engineered to bind dendritic cells.

[0218] In one example, a kit can contain instructions. Instructions typically include a tangible expression describing the virus and, optionally, other components included in the kit, and methods for administration, including methods for determining the proper state of the subject, the proper dosage amount, and the proper administration method, for administering the virus. Instructions can also include guidance for monitoring the subject over the duration of the treatment time.

[0219] Kits provided herein also can include a device for administering a virus to a subject. Any of a variety of devices known in the art for administering medications or vaccines can be included in the kits provided herein. Exemplary devices include, but are not limited to, a hypodermic needle, an intravenous needle, a catheter, a needle-less injection device, an inhaler, and a liquid dispenser, such as an eyedropper. Typically, the device for administering a virus of the kit will be compatible with the virus of the kit; for example, a needle-less injection device such as a high pressure injection device can be included in kits with viruses not damaged by high pressure injection, but is typically not included in kits with viruses damaged by high pressure injection.

[0220] Kits provided herein also can include a device for administering a compound, such as a DC activator or stimulator, to a subject. Any of a variety of devices known in the art for administering medications to a subject can be included in the kits provided herein. Exemplary devices include a hypodermic needle, an intravenous needle, a catheter, a needle-less injection, but are not limited to, a hypodermic needle, an intravenous needle, a catheter, a needle-less injection device, an inhaler, and a liquid dispenser such as an eyedropper. Typically the device for administering the compound of the kit will be compatible with the desired method of administration of the compound.

[0221] The following examples are offered for illustrative purposes only, and are not intended to limit the scope of the present invention in any way. Indeed, various

modifications of the invention in addition to those shown and described herein will become apparent to those skilled in the art from the foregoing description and fall within the scope of the appended claims.

[0222] All patent and literature references cited in the present specification are hereby incorporated by reference in their entirety.

## EXAMPLE 1

## ENGINEERING OF A DC-SPECIFIC TARGETING MOLECULE

[0223] Lentiviral vectors can be rationally engineered to make them capable of transducing DCs in a cell-specific manner. Certain subsets of DCs bear on their surface the DC-SIGN protein (Geijtenbeek, T.B., et al. 2000; Geijtenbeek, T.B., et al. 2000, *supra*), a C-type lectin-like receptor capable of rapid binding and endocytosis of materials (Geijtenbeek, T.B., et al. 2004, *supra*.), which can be used as a targeting receptor on DCs. Sindbis virus (SV)—a member of the *Alphavirus* genus and the *Togaviridae* family—is able to infect DCs through DC-SIGN (Klimstra, W.B., et al. 2003. *J. Virol.* 77: 12022-12032, which is incorporated herein by reference in its entirety). However, the canonical viral receptor for the laboratory strain of SV is cell-surface heparan sulfate (HS), which is expressed by many cell types (Strauss, J.H., et al. 1994. *Arch. Virol.* 9: 473-484; Byrnes, A.P., and D.E. Griffin. 1998. *J. Virol.* 72: 7349-7356, each of which is incorporated herein by reference in its entirety). Taking advantage of the physical separation of the two receptor-binding sites on the SV envelope glycoprotein (hereafter designated as SVG), the receptor was engineered to be blind to its canonical binding target HS and to leave intact its ability to interact with DC-SIGN (Figure 1). Once it is incorporated onto a viral surface, this mutant glycoprotein is able to mediate infection of DCs but not other cells.

[0224] The cDNA for wild-type SVG was obtained from the laboratory of Dr. J.H. Strauss laboratory at the California Institute of Technology and cloned into the pcDNA3 vector (Invitrogen) by PCR to generate plasmid pSVG. A ten-residue tag (MYPYDVPDYA) sequence was inserted into E2 protein between amino acids 71 and 74 by PCR mutagenesis to disrupt the HS binding site (Karavans, G., et al. 1998. *Crit Rev Oncol Hemat* 28: 7-30; Lavillete, D., et al. 2001. *Curr Opin Biotech* 12: 461-466; Russell, S.J. and F.L. Cosset. 1999. *J Gene Med* 1: 300-311; Sandrin, V., et al. 2003. *Curr Top Microbiol* 281: 137-178;

Verhoeyen, E. and F.L. Cosset. 2004. *J Gene Med* 6: S83-S94, each of which is incorporated herein by reference in its entirety). An available antibody against the inserted tag sequence provided the ability to monitor the expression of the modified SVG. In order to further decrease the HS-specific infection, several critical residues were identified as being involved in binding to HS molecules (Coffin, J. M., et al. 1997. *Retroviruses*. New York: Cold Spring Harbor Laboratory Press; Battini, J.L., et al. 1998. *J Virol* 72:428-435; Valsesiawittmann, S., et al. 1994. *J Virol* 68:4609-4619; Wu, B.W., et al. 2000. *Virology* 269: 7-17; Cosset, F.L., et al. 1995. *J Virol* 69:6314-6322; Kayman, S.C., et al. 1999. *J. Virol* 73: 1802-1808; Lorimar, I.A.J. and S.J. Lavictoire. 2000. *J Immunol Methods* 237:147-157; Barnett, A.L., et al. 2001. *Proc Nat Acad Sci USA* 98: 4113-4118; Benedict, C.A., et al. 2002. *Hum Gene Ther* 10:545-557; Gollan, T.J. and M.R. Green. 2002. *J Virol* 76:3558-3563, each of which is incorporated herein by reference in its entirety). Two such residues were mutated into alanines (157KE158 to 157AA158).

**[0225]** An additional deletion was introduced to the E3 glycoprotein of SVG to remove amino acids 61-64. This modified SVG was designated as SVGmu (SEQ ID NO: 11). The cDNA for SVGmu was cloned downstream of the CMV promoter in the pcDNA3 vector (designated as pSVGmu, SEQ ID NO: 3).

## EXAMPLE 2

## PREPARATION OF RECOMBINANT VIRUS CONTAINING THE DC-SPECIFIC TARGETING MOLECULE

**[0226]** Preparation of the recombinant SVGmu-pseudotyped lentivirus was conducted by standard calcium phosphate-mediated transient transfection of 293T cells with the lentiviral vector FUGW (SEQ ID NO:1) or its derivatives, the packaging constructs encoding *gag*, *pol* and *rev* genes, and pSVGmu (Example 1). FUGW is a self-inactivating lentiviral vector carrying the human ubiquitin-C promoter to drive the expression of a GFP reporter gene (Lois, C., et al. 2002. *Science* 295: 868-872, which is incorporated herein by reference in its entirety). The lentiviral transfer vectors (FUGW and its derivatives) used in these studies are third generation HIV-based lentiviral vectors, in which most of the U3 region of the 3' LTR is deleted, resulting in a self-inactivating 3'-LTR (SIN).

[0227] For the transient transfection of 293T cells, 293T cells cultured in 6-cm tissue culture dishes (Corning or BD Biosciences) were transfected with the appropriate lentiviral transfer vector plasmid (5 μg), along with 2.5 μg each of the envelope plasmid (SVG, SVGmu, Eco, or VSVG) and the packaging plasmids (pMDLg/pRRE and pRSV-Rev). The viral supernatants were harvested 48 and 72 hours post-transfection and filtered through a 0.45-μm filter (Corning). To prepare concentrated viral vectors for *in vivo* study, the viral supernatants were ultracentrifugated (Optima L-80 K preparative ultracentrifuge, Beckman Coulter) at 50,000 x g for 90 min. The pellets were then resuspended in an appropriate volume of cold PBS.

[0228] The resultant viruses pseudotyped with SVGmu are hereafter referred to as FUGW/SVGmu. Control viruses enveloped with the wild-type SVG glycoprotein are hereafter referred to as FUGW/SVG.

## EXAMPLE 3

## CONFOCAL IMAGING OF PACKAGED RECOMBINANT VIRUS

[0229] GFP-vpr-labeled lentivectors were produced as described in Example 2, except with use of FUW lentivector (which does not contain the GFP reporter gene) and with a separate plasmid encoding GFP-vpr (2.5 μg). Fresh viral supernatant was overlaid on polylysine-coated coverslips in a 6-well culture dish and centrifuged at 3,700 x g at 4°C for 2 hours using a Sorvall Legend RT centrifuge. The coverslips were rinsed with cold PBS twice and immunostained by anti-HA-biotin antibody (Miltenyi Biotec) and Cy5-streptavidin (Invitrogen). Fluorescent images were taken by a Zeiss LSM 510 laser scanning confocal microscope equipped with filter sets for fluorescein and Cy5. A plan-apochromat oil immersion objective (63x/1.4) was used for imaging.

[0230] Figure 2 shows the results of the confocal imaging of the recombinant virus produced by the protocol. (The scale bar represents 2 μm.) Particles in the "GFP" slide are stained green, particles in the "SVGmu" slide are stained red, and particles in the "Merged" slide are stained green where only GFP is expressed, red where only SVGmu is expressed, and yellow/yellow-orange where GFP and SVGmu are both expressed. Over 90% of the GFP-labeled particles contained SVGmu. Thus, the production of lentiviral particles displaying SVGmu was confirmed through confocal imaging.

## EXAMPLE 4

## PREPARATION OF DC-SIGN CELL LINES

[0231] To facilitate the study of targeted transduction, DC-SIGN cell lines expressing human DC-SIGN (hereafter referred to as 293T.hDCSIGN) and murine DC-SIGN (hereafter referred to as 293T.mDCSIGN) were constructed. The 293T.hDCSIGN and 293T.mDCSIGN cell lines were generated by stable transduction of parental 293T cells with a VSVG-pseudotyped lentivector. The cDNAs for human DC-SIGN and murine DC-SIGN were amplified from plasmids pUNO-hDCSIGN1Aa and pUNO-mDCSIGN (InvivoGene) and cloned downstream of the human ubiquitin-C promoter in the lentiviral plasmid FUW to generate FUW-hDCSIGN (SEQ ID NO: 5) and FUW-mDCSIGN (SEQ ID NO: 6), respectively. The lentivectors were then pseudotyped with VSVG and used to transduce 293T cells. The resulting cells were subjected to antibody staining (anti-human DC-SIGN antibody from BD Biosciences and anti-murine DC-SIGN from eBioscience) and cell sorting to yield a uniform population of DC-SIGN$^+$ 293T.hDCSIGN and mDC-SIGN$^+$ 293T.mDCSIGN cell lines

[0232] Flow cytometry showed that DC-SIGN was expressed in virtually all of the 293T.hDCSIGN and 293T.mDCSIGN cells of the cell lines (Figure 3A). In each diagram, the solid lines (unfilled area) represents expression of DC-SIGN in the 293T DC-SIGN cell lines, and the shaded area represents the background staining of non-transduced 293T cells.

## EXAMPLE 5

## EVALUATION OF THE DC-SIGN SPECIFIC RECOMBINANT VIRUS BY TRANSDUCTION OF DC-SIGN CELL LINES

[0233] To assess the transduction efficiency and specificity of FUGW/SVG or FUGW/SVGmu (Example 2), the viruses were used to transduce the 293T.hDCSIGN and 293T.mDCSIGN cell lines (Example 4). Transduction efficiency was measured by GFP expression within the cell lines.

[0234] Target cells (293T.hDCSIGN, 293T.mDCSIGN, or 293T cells; $0.2x10^6$ per well) were seeded in a 24-well culture dish (Corning or BD Biosciences) and spin-infected with viral supernatants (1 ml per well) at 2,500 rpm and 30°C for 90 min by using a

Sorvall Legend centrifuge. Subsequently, the supernatants were replaced with fresh culture medium and incubated for 3 days at 37°C with 5% of $CO_2$. The percentage of $GFP^+$ cells was measured by flow cytometry. The transduction titer was determined by the dilution ranges that exhibited a linear response

[0235] Flow cytometry showed that FUGW/SVG (containing the wild-type SVG envelope glycoprotein) had similar transduction efficiency (11~16% transduction) towards the three target cell lines (293T, 293T.hDCSIGN, and 293T.mDCSIGN) (Figure 3B). This indicates that that SVG has broad specificity and the presence of DC-SIGN on the cell surface does not markedly alter the transduction ability of a SVG-pseudotyped lentiviral vector. In contrast, the FUGW/SVGmu vector (containing the mutant SVG envelope glycoprotein) could specifically transduce 293T.hDCSIGN and 293T.mDCSIGN cells with a 42% and 34% transduction efficiency, respectively, but not the 293T cells (Figure 3B). These results demonstrate that a pseudotyped lentiviral vector displaying SVGmu can specifically transduce cells expressing either human or murine DC-SIGN. Furthermore, the mutant SVG gave more efficient transduction of DC-SIGN-expressing cells than of wild type SVG.

[0236] The stable integration of the FUGW lentiviral vector in the transduced cells was confirmed by PCR analysis of the genomic integration of the GFP reporter gene. To demonstrate that the specific transduction was mediated by DC-SIGN, the addition of soluble anti-human DC-SIGN antibody to the FUGW/SVGmu viral supernatant before its exposure to 293T.hDCSIGN cells reduced the transduction efficiency (data not shown). The specific titer of FUGW/SVGmu for 293T.mDCSIGN was estimated to be $1x10^6$ TU (Transduction Units)/ml. The titer of FUGW/SVGmu for 293T.hDCSIGN was estimated to be $1\text{-}2x10^6$ TU/ml.

## EXAMPLE 6

## EVALUATION OF THE RECOMBINANT VIRUS *in vitro*

[0237] To investigate the specificity of the engineered lentivector for transduction of dendritic cells (DCs) expressing DC-SIGN, total bone marrow (BM) cells were isolated from mice and transduced directly with the FUGW/SVGmu viral vector (Example 2). A protocol to generate mouse DCs from progenitors grown in BM cultures was adapted for use

in the experiment (Buchholz, C.J., et al. 1998. *Nat Biotech* 16:951-954, which is incorporated herein by reference in its entirety).

[0238] Total bone marrow cells were harvested from B6 female mouse (Charles River Breeding Laboratories), and BMDCs were generated as described elsewhere (Yang, L. and D. Baltimore. 2005. *Proc. Natl. Acad. Sci. USA* 102: 4518-4523, which is incorporated herein by reference in its entirety). Either total BM cells or BMDCs were plated in a 24-well culture dish ($2x10^6$ cells per well), and spin-infected with viral supernatant (1 ml per well) at 2,500rpm and 30°C for 90min using a Sorvall RT7 centrifuge. After the spin, the supernatant was removed and replaced with fresh RPMI medium containing 10% FBS and GM-CSF (1:20 J558L conditioned medium). The cells were cultured for 3 days and were analyzed for GFP expression using flow cytometry.

[0239] The BM cells isolated from mice were transduced directly with either FUGW/SVGmu viral vector or with a control vector. For the control, an ecotropic murine leukemia virus glycoprotein (Eco)-enveloped lentivector (FUGW/Eco) was used; vector enveloped with Eco can infect rodent cells with a broad specificity. Three days post-infection, the transduction efficiency was analyzed by flow cytometry (Figure 4A). Approximately 9% of the cells in the mixed BM cultures were DCs (as indicated by the expression of CD11c), of which most (approximately 80%) were DC-SIGN high (data not shown). It was observed that 12% of the total BM cells were GFP positive ($GFP^+$) upon FUGW/SVGmu transduction (Figure 4A). When gated on $GFP^+$ cells, it was observed that up to 95% of the transduced cells were DC-SIGN and CD11c double-positive ($DC\text{-}SIGN^+CD11c^+$), indicating that FUGW/SVGmu specifically transduces DCs expressing DC-SIGN and not other cell types in the bone marrow. In contrast, although 68% of total BM cells were GFP-positive after exposure to FUGW/Eco, only 9% of the transduced cells were DCs, within which 6.5% were $DC\text{-}SIGN^+$.

[0240] The stable transduction of FUGW/SVGmu was verified by Alu PCR analysis (Butler, S.L., et al. 2001. *Nat. Med.* 7: 631-634, which is incorporated herein by reference in its entirety) of the genomic integration of the LTR of the lentivector backbone. In addition, we used FUGW/SVGmu to transduce primary T and B cells harvested from

mouse spleen and virtually no transduction was detected (Figure 4B), indicating remarkable transduction specificity.

[0241] The efficiency of the lentivector bearing SVGmu to transduce *in vitro*-cultured, bone marrow (BM)-derived DCs (BMDCs) was also tested. Bone marrow (BM)-derived DCs (BMDCs) were generated as described above by culturing in the presence of granulocyte-macrophage colony-stimulating factor (GM-CSF) for 6 days. The cells were then exposed to either the FUGW/SVGmu or FUGW/Eco lentivector. Flow cytometry of the BMDCs on day 3 post-transduction showed that FUGW/Eco transduced both $CD11c^+$ DCs (33%) and $CD11c^-$ cells (7.6%) (Figure 5), which is consistent with the wide tropism of Eco. On the contrary, FUGW/SGVmu only transduced $CD11c^+$ DCs (32.7%), and no $GFP^+$ cells were detected among the $CD11c^-$ cells (Figure 5), indicating that FUGW/SVGmu can specifically modify BMDCs.

[0242] These results thus collectively demonstrate that the engineered recombinant lentivectors bearing SVGmu can specifically transduce DCs *in vitro* and that the targeted transduction is correlated with the expression of DC-SIGN on the surface of DCs.

## EXAMPLE 7

## EFFECT OF RECOMBINANT VIRUS ON ACTIVATION OF DENDRITIC CELLS *in vitro*

[0243] The recombinant lentivirus was further examined to determine whether it could specifically target, transduce and activate DCs into mature DCs. The surface up-regulation of the co-stimulatory molecule B7.2 (CD86) and the MHC class II molecule $I\text{-}A^b$, which are considered to be signatures of DC activation (Steinman, R.M., et al. 2003. *Annu. Rev. Immunol.* 21: 685-711, which is incorporated herein by reference in its entirety), was measured in DCs exposed to recombinant virus. BMDCs were generated and infected with FUGW/SVGmu as described in Example 6. LPS at a concentration of 1 μg/ml was also added overnight for further activation of transduced BMDCs.

[0244] Flow cytometry of BMDCs 3 days post-transduction showed that treatment with FUGW/SVGmu elevated the expression of DC activation markers, CD86 and $I\text{-}A^b$, on GFP positive DCs, as compared to GFP negative DCs (Figure 6, top panel). The shaded area indicates GFP negative (untransduced) cells, and the solid line (unfilled area) indicates GFP positive (transduced) cells. It was observed that the targeted transduction of

BMDCs synergized with lipopolysaccharide (LPS) treatment to further mature DCs (Figure 6, bottom panel). This indicates that the targeted transduction can either work alone or in combination with other DC maturation factors to induce DC activation.

## EXAMPLE 8

## TARGETING OF DENDRITIC CELLS *in vivo* BY RECOMBINANT VIRUS

**[0245]** The proof of whether this methodology can be used for vaccination can be examined by *in vivo* experimentation. To test whether engineered lentivectors bearing SVGmu could target DCs *in vivo*, the recombinant and concentrated lentivector FUGW/SVGmu ($50x10^6$ TU resuspended in 200 µl PBS) was injected subcutaneously into the left flank of the C57BL/6 female mice (B6, Charles River Breeding Laboratories) close to an inguinal lymph node (within 1 cm range). The left inguinal lymph node and the equivalent lymph node at the opposite site were isolated for size examination on day 3 post-injection. The cells were harvested from these nodes and their total numbers were counted. The percentage of $GFP^+$ DCs was analyzed by flow cytometry on cells stained with anti-CD11c antibody (BD Biosciences).

**[0246]** On day 3, a significant enlargement of the left inguinal lymph node close to the injection site was observed (Figure 7A, left image), and the cell number in this lymph node increased more than 10-fold, compared with the equivalent lymph node at the opposite side or lymph nodes from a naïve mouse (Figure 7B). This indicates that vector administration can enhance trafficking and proliferation of lymphocytes in a nearby lymph node.

**[0247]** Flow cytometry indicated that approximately 3.8% of the total $CD11c^+$ cells in the left inguinal lymph node cells were $GFP^+$ DCs (Figure 7C), which appear to have migrated from the injection site. This is considered a remarkably large effect from one subcutaneous injection of vector and demonstrates that the recombinant virus is effectively infecting DCs *in vivo*.

## EXAMPLE 9

## EVALUATION OF THE SPECIFICITY OF RECOMBINANT VIRUS BY *in vivo* TRANSDUCTION

[0248] To examine the *in vivo* specificity of the DC-targeted lentivector, a lentiviral vector encoding a firefly luciferase was constructed. The cDNA of firefly luciferase was amplified from pGL4.2LucP (Promega) and cloned into FUGW (Lois, C. et al. 2002. *supra.*) to replace GFP, yielding the construct Fluc (SEQ ID NO: 4) (Figure 22A). The luciferase reporter gene was then used to visualize the *in vivo* transduction of the tissue cells using standard protocols of bioluminescence imaging (BLI).

[0249] The recombinant lentivector (hereafter referred to as Fluc/SVGmu) was injected subcutaneously at the left flank of the mouse. In another mouse, a lentivector pseudotyped with vesicular stomatitis viral glycoprotein (hereafter referred to as Fluc/VSVG) was injected as a non-specific vector control. Vector-treated mice were then imaged non-invasively using BLI. Fluc/VSVG-treated mice had a strong and permanent signal at the injection site, indicating that non-specific tissues were transduced to express luciferase (Figure 22B). This is consistent with the fact that VSVG-enveloped virus has broad specificity. In contrast, no significant signal was detected at the injection site of Fluc/SVGmu-treated mice (Figure 22B), indicating that the lentivector bearing SVGmu had a relatively stringent target specificity. At no time was luminescence signal able to be detected in the targeted mice, likely due to the rare and sparse distribution of the DCs, which is beyond the sensitivity of the current BLI method.

[0250] After one month, the mice injected with Fluc/SVGmu were subjected to biodistribution analysis by quantitative RT-PCR and no detectable copy of the lentivector was observed in all isolated organs (heart, liver, spleen, kidney, gonad, lung, skin, lymph node), verifying the lack of non-specific infection in the animals and thus the specificity of the targeted vector for DCs.

## EXAMPLE 10

## *In vitro* ANTIGEN DELIVERY BY RECOMBINANT VIRUS

[0251] To determine whether the targeted transduction of DCs by a recombinant lentivector could be used to effectively deliver antigen genes to DCs for stimulation of antigen-specific $CD8^+$ and $CD4^+$ T cell responses, a lentivector expressing the model antigen, chicken ovalbumin (OVA), was constructed. In C57BL/6J (B6) mice, OVA is a well-characterized target antigen for the $CD8^+$ T-cell receptor OT1, which specifically binds

$OVA_{257-269}$ (designated as OVAp), and for the $CD4^+$ T-cell receptor OT2, which specifically binds $OVA_{323-339}$ (designated as OVAp*) (Yang, L. and D. Baltimore. 2005. *Proc. Natl. Acad. Sci. USA* 102: 4518-4523, which is incorporated by reference in its entirety). The lentivector expressing OVA (FOVA (SEQ ID NO:2), Figure 8, top) was constructed from FUGW (Figure 8, bottom) by replacing the GFP with the cDNA of chicken ovalbumin.

[0252] The BMDCs (Example 6) were transduced on day 6 of culture with either recombinant lentivirus FOVA/SVGmu or control recombinant lentivirus FUGW/SVGmu (encoding a non-relevant reporter gene GFP). The day 6 BMDCs were spin-infected with viral supernatant, and cultured for an additional 3 days. On day 9, the non-adherent cells were collected and re-cultured in RPMI medium containing 10% FBS, GM-CSF (1:20 J558L conditional medium), and 1μg/ml LPS (Sigma). On day 10, the cells were collected and used for T cell stimulation. The modified BMDCs were designated as DC/FOVA and DC/FUGW, depending on the lentivector used for transduction. In parallel, non-adherent cells were collected from non-transduced day 9 BMDC culture, and were re-cultured in the same medium (RPMI containing 10% FBS, GM-CSF and LPS). On day 10, the cells were collected and loaded with either OVAp ($OVA_{257-269}$, specifically bound by OT1 T-cell receptors, hereafter referred to as DC/OVAp) or OVAp* ($OVA_{323-339}$, specifically bound by OT2 T-cell receptors, hereafter referred to as DC/OVAp*), and used as positive controls for T cell stimulation. To examine the ability of vector-transduced BMDCs to process and present the transgenic OVA antigen, spleen cells were collected from the OT1and OT2 transgenic mice and cultured with the lentivector-transduced BMDCs, or BMDCs loaded with either OVAp or OVAp*, at the indicated ratio. Three days later, the supernatant was collected and assayed for IFN-γ production using ELISA and the cells were collected and analyzed for their surface activation markers using flow cytometry. T cell proliferation was assayed using [$^3$H] thymidine incorporation.

[0253] After a three-day coculture with varying ratios of DC/FOVA to transgenic T cells, OT1 T cells responded vigorously as measured by the release of IFN-γ (Figure 10A) and T cell proliferation (Figure 10B). As expected, no obvious OVA response was detected using DG/FUGW (Figures 10A and 10B). It was also observed that the transgenic expression of OVA was even more efficient than peptide-loading for stimulation of an OT1 T cell

response, which is consistent with the notion that MHC class I favors the presentation of endogenously produced peptides. Flow cytometry showed that the activated OT1 T cells exhibited the typical effector cytotoxic T cell phenotype ($CD25^+CD69^+CD62L^{low}CD44^{high}$) after stimulation by either DC/FOVA or DC/OVAp (Figure 9).

**[0254]** When the DCs were co-cultured with OT2 $CD4^+$ T cells, T cell activation was also observed, as indicated by changes in the surface markers (Figure 11) and the production of IFN-γ (Figure 12). However, stimulation of $CD4^+$ cells was not as pronounced as that of $CD8^+$ cells, presumably due to the less efficient presentation of endogenous antigen peptides to the MHC class II molecules. By modifying the cellular localization of OVA antigen to direct it to MHC class II presentation pathway, an enhancement of CD4 stimulation was achieved that was even better than that of peptide-pulsed DCs (data not shown).

**[0255]** These results show that the method of DC targeting through lentivector infection can effectively deliver antigens to DCs and stimulate both $CD8^+$ and $CD4^+$ T cell responses.

## EXAMPLE 11

## *In vivo* ANTIGEN DELIVERY BY RECOMBINANT VIRUS

**[0256]** To determine if DCs targeted with lentivectors could activate antigen-specific T cells *in vivo*, a method of T-cell receptor (TCR) gene transfer into murine hematopoietic stem cells (HSCs) was used to generate antigen-specific and TCR-engineered T cells in mice, as described elsewhere (Yang, L. and D. Baltimore, D. 2005. *supra.*). A tricistronic retroviral vector MIG-OT1 co-expressing OT1 TCRα and TCRβ, along with the GFP marker (Figure 13A) was constructed.

**[0257]** Briefly, B6 female mice (Charles River Breedling Laboratories) were treated with 250μg of 5-flurouracil (Sigma). Five days later, bone marrow (BM) cells enriched with HSCs were harvested from the tibia and femur and cultured in a 24-well culture plate ($2x10^6$ cells per well) in BM culture medium (RPMI containing 10% FBS, 20ng/ml rmIL-3, 50ng/ml rmIL-6 and 50ng/ml rmSCF (PeproTech)). On day 1 and day 2 of the culture, the cells were spin-infected with the MIG-OT1 retroviral vector pseudotyped with Eco (2 ml viral supernatant per well) at 2,500rpm and 30°C for 90min. After each spin,

the supernatant was removed and replaced with fresh BM culture medium. On day 3, the transduced BM cells were collected and transferred into B6 recipient mice receiving 1,200 rads of total body irradiation. Eight weeks post-transfer, the mice were used for the *in vivo* immunization study. Each mouse received one dose of subcutaneous injection of $10x10^6$ TU of targeting lentivector. Seven days later, spleen and lymph node cells were harvested and analyzed for the presence of OT1 T cells and their surface activation markers using flow cytometry.

**[0258]** Eight weeks post-transfer, analysis of the peripheral T cells of the reconstituted mice showed that approximately 5% of the $CD8^+$ T cells were $GFP^+OT1^+$ (Figure 13B). Some of the reconstituted mice were immunized via subcutaneous injection of the same dose ($10x10^6$ TU) of either FOVA/SVGmu (Example 10) or FUGW/SVGmu (Example 2). Analysis of $GFP^+OT1^+$ T cells harvested from peripheral lymphoid organs 7 days later showed that the targeted DC immunization by FOVA/SVGmu doubled the number of OT1 T cells as compared to the control mice, which were either not immunized or immunized with FUGW/SVGmu (Figure 14B). The $GFP^+OT1^+$ T cells derived from FOVA/SVGmu-immunized mice exhibited an effector memory phenotype ($CD69^{low}CD62^{high}CD44^{high}$), indicating these cells have gone through a productive immune response (Figure 14A).

**[0259]** These results demonstrate that a recombinant lentivector bearing surface SVGmu can target DCs *in vivo* to efficiently stimulate antigen-specific T cells and induce a strong immune response.

## EXAMPLE 12

## INDUCTION OF *in vivo* CTL AND ANTIBODY RESPONSES BY DIRECT ADMINISTRATION OF RECOMBINANT VIRUS

**[0260]** Studies were conducted on the efficacy of the *in vivo* DC targeting for inducing an antigen-specific $CD8^+$ cytotoxic T lymphocyte (CTL) response and antibody response through the administration of the targeting lentivector to naïve, wild-type mice.

**[0261]** Wild-type B6 mice (Charles River Breeding Laboratories) were given a single injection of targeting lentivector ($50x10^6$ TU of FUGW/SVG or FOVA/SVGmu) subcutaneously on the right flank at the indicated dose. On day 7 and day 14 post-

immunization, blood was collected from the immunized mice through tail bleeding, and the serum anti-OVA IgG was measured using ELISA. On day 14, spleen and lymph node cells were harvested and analyzed for the presence of OVA-specific T cells and their surface activation markers using flow cytometry.

**[0262]** The presence of OVA-specific T cells was measured by measuring cytokine secretion and tetramer staining. At day 14 post-injection, T cells harvested from peripheral lymphoid organs were analyzed. Lentivector targeting to native DCs was able to elicit OVA-responsive $CD8^+$ T cells in both the lymph node (data not shown) and spleen (Figure 23). Administration of a single dose of recombinant FOVA/SVGmu was sufficient to generate $CD8^+$ T cells, which could be primed to secrete IFN-γ upon OVAp restimulation (Figure 23). Administration of the control vector FUGW/SVGmu failed to generate any OVAp-specific responses (Figure 23). To further evaluate the magnitude of responses, the OVAp-specific $CD8^+$ T cells was measured by MHC class I tetramer staining. A high frequency of OVAp-specific T cells (>6%) was obtained following a single dose injection (Figure 15); no tetramer-positive cells were detected in the mice treated with FUGW/SVGmu (Figure 15). The data generated by tetramer quantitation correlated well with the analysis of $CD8^+$ effector cells assayed by intracellular IFN-γ staining (Figure 23). Phenotype analysis of these OVAp-positive T cells showed that these cells displayed the surface characteristics of effector memory T cells ($CD25^{low}CD69^{low}CD62L^{high}CD44^{high}$) (Figure 17A).

**[0263]** To investigate the dose response of lentivector administration, doses of FOVA/SVGmu ranging from $100x10^6$ TU to $3x10^6$ TU were injected subcutaneously and OVAp-specific T cells in the spleen were measured at day 14 post-injection. An exceptionally high frequency (12%) of OVAp-specific $CD8^+$ T cells was detected at the dose of $100x10^6$ TU (Figure 16A). The percentage of OVAp-specific cells correlated proportionately with the amount of recombinant vector administered (Figure 16B). A plateau in the dose response was not achieved with the doses that were tested, indicating that further enhancement can be achieved by increasing the amount of vector injected and/or the frequency of injection.

**[0264]** Further, the serum IgG levels specific for OVA in mice were examined on the 7th and 14th days after immunization with FOVA/SVGmu ($50x10^6$ TU). The IgG serum

titer was 1:10,000 on day 7 and 1:30,000 on day 14 (Figure 17B). This is a rather impressive antibody response for a single dose injection without additional adjuvant or other stimuli, indicating that targeted lentivector immunization can also elicit significant B cell secretion of antigen-specific antibodies.

[0265] These results show that *in vivo* administration of a DC-targeting lentivector can induce both cellular and humoral immune responses against the delivered antigen.

## EXAMPLE 13

## GENERATION OF ANTI-TUMOR IMMUNITY: PREVENTIVE PROTECTION

[0266] The anti-tumor immunity generated after an *in vivo* administration of DC-targeted lentivector was evaluated. An E.G7 tumor model (Wang, L. and D. Baltimore. 2005. *supra.*) was used in which OVA serves as the tumor antigen.

[0267] The tumor cell lines EL4 (C57BL/6J, H-$2^b$, thymoma) and E.G7 (EL4 cells stably expressing one copy of chicken OVA cDNA) were used for the tumor challenge of mice. For the tumor protection experiment, B6 mice (Charles River Breeding Laboratories) received a single injection of $50x10^6$ TU of the targeting lentivector (FOVA/SVGmu or FUGW/SVGmu) on the right flank. Two weeks later, $5x10^6$ EL4 or E.G7 cells were injected subcutaneously into the left flank of the mice. Tumor size was measured every other day using fine calipers and was shown as the product of the two largest perpendicular diameters $a$ x $b$ ($mm^2$). The mice were killed when the tumors reached $400mm^2$.

[0268] Vaccination with $50x10^6$ TU FOVA/SVGmu completely protected the mice from the E.G7 tumor challenge (Figure 18, left), while tumors grew rapidly in mice receiving a mock vaccination with a lentivector lacking the OVA transgene (Figure 18, left). This protection was OVA-specific because the vaccinated mice grew control EL4 tumors that lack expression of OVA (Figure 18, right), regardless of the lentivector used for immunization.

## EXAMPLE 14

## GENERATION OF ANTI-TUMOR IMMUNITY: TUMOR TREATMENT

[0269] The anti-tumor immunity generated after an *in vivo* administration of DC-targeted lentivector was evaluated where tumor cells were introduced prior to administration of the lentivector. The steps of tumor injection and lentivector administration were reversed relative to that in Example 13 to test whether an established tumor could be eliminated, in a test of "therapeutic vaccination". To this end, E.G7 tumor cells expressing the firefly luciferase gene (E.G7.luc) were used to challenge mice, allowing close monitoring of tumor growth kinetics in live animals using BLI. To facilitate imaging, an albino strain of B6 mice (The Jackson Laboratory) was used. These mice lack pigmentation and therefore have low background absorption of the luminescence signal. Injection of these mice with $100x10^6$ TU of FOVA/SVGmu (Example 10) showed a similar response to that observed in canonical B6 mice (Figure 21). E.G7.luc tumor cells ($5x10^6$) were implanted subcutaneously in the albino B6 mice. The mice were immunized by FOVA/SVGmu ($50x10^6$ TU per mice per time) twice on days 3 and 10 post-tumor challenge via subcutaneous injection. The experiment was repeated three times with a representative experiment shown in Figures 19 and 20.

[0270] The mice receiving the DC-targeting lentivector immunization showed a decline of tumor growth starting at day 9, followed by tumor regression and a reduction of luminescence below the detection level on day 11 (Figures 19 and 20). Although minimal tumor recurrence was observed from day 12 to day 16, mice treated with FOVA/SVGmu were free of disease at the end of day 18 and thereafter; no tumor relapse was observed for as long as the experiment ran (>60 days). In contrast, tumors grew progressively in the mice receiving no treatment and the mice had to be removed from the experiment after day 16 due to the large size of the tumors. It was a interesting to note that tumor regression was observed starting at 7 days after the lentivector immunization. The timing of tumor regression correlates well with the kinetics of an antigen-specific immune response induced by vaccination.

## EXAMPLE 15

## *In vitro* DELIVERY OF ANTIGEN AND MATURATION FACTORS BY A RECOMBINANT VIRUS

[0271] The success of DC vaccination can depend on the maturation state of DCs (Banchereau, J. and A.K. Palucka. 2005. *Nat Rev Immunol* 5:296-306; Schuler, G., et al.

2003. *Curr Opin Immunol* 15: 138-147; Figdor, C.G., et al. 2004. *Nat Med* 10: 475-480, each of which is incorporated herein by reference in its entirety). Therefore, genes can be included in the lentiviral vectors that encode the stimulatory molecules to trigger the desired DC-maturation. Cytokines that can be used include, but are not limited to, GM-CSF, IL-4, TNFα, IL-6, and the like. In some embodiments, the maturation agent that is used is the CD40 ligand (CD40L), which is typically expressed on CD4 T cells and serves as a ligand for the CD40 receptor on DCs (Matano, T., et al. 1995. *J Gen Virol* 76: 3165-3169; Nguyen, T.H., et al. 1998. *Hum Gene Ther* 9: 2469-2479, each of which is incorporated herein by reference in its entirety). To further manipulate DCs to be a potent vaccine for therapy, a drug-inducible CD40 receptor (iCD40) is adapted into the gene delivery system in some embodiments. As described elsewhere, iCD40 was designed and consists of a cytoplasmic domain of CD40 fused to ligand-binding domains and a membrane-targeting sequence (Hanks, B.A., et al. 2005. *Nat Med* 11: 130-137, which is herein incorporated by reference in its entirety). When iCD40 is expressed, maturation and activation of DCs is regulated with a lipid-permeable, dimerizing drug.

[0272] To examine the effect of including DC maturation factors, the cDNAs for ovalbumin (OVA, as described in Example 10), GM-CSF, IL-4, TNFα, IL-6 and CD40L are obtained. The iCD40 is constructed as described elsewhere (Hanks, B. A., et al. 2005. *supra*). Using IRES and 2A-like sequences, multicistronic lentiviral vectors capable of efficiently translating up to four proteins are constructed. This system is adapted to construct lentiviral vectors co-expressing the following genes: OVA and a maturation factor molecule (GM-CSF, IL-4, TNFa, IL-6, CD40L or iCD40) (Figure 24a, labeled as "FUOIM"). An exemplary vector sequence is provided by SEQ ID NO: 7. SVGmu-enveloped lentiviruses are prepared (as described in Example 2), and the lentiviruses are transduced *in vitro* into cultured mouse BMDCs (generated as described in Example 6) to specifically deliver these genes into the cells. Maturation of BMDCs is measured by FACS analysis for up-regulation of several key molecules that have essential roles in the process of T cell stimulation. Typical representative markers are ICAM-1 (CD54), B7.1 (CD80), MHC class I, MHC class II and endogenous CD40. BMDCs transduced with lentiviruses encoding only OVA and GFP genes serve as controls for the experiment. It is observed that up-regulation of

maturation markers is achieved when iCD40-modified DCs are exposed to an effective amount of dimeric drug AP20187.

[0273] In addition, two characteristic features of matured DCs are the reduced capacity for endocytosis and the improved potential for T cell activation. The uptake of FITC-tagged dextran is used to quantify the endocytosis of transduced DCs. The mature DCs are also used to stimulate T cells expressing OT1 T cell receptors (TCRs) (as described in Example 10), in order to evaluate their capacity to mount an immune response. It is observed that when iCD40-modified DCs are exposed to an effective amount of dimeric drug AP20187, the uptake of FITC-tagged dextran is reduced relative to that of non-iCD40-modified DCs. Furthermore, it is observed that after coculture with varying ratios of iCD40-modified DCs (treated with the dimeric drug) to transgenic T cells, OT1 T cells respond more vigorously as measured by the release of IFN-$\gamma$ and T cell proliferation than do those co-cultured with non-iCD40-modified DCs.

[0274] Longevity of DCs is another parameter that determines T-cell-dependent immunity. The effects of stimulator molecules on DC survival using an *in vitro* serum-starvation assay will be compared using the method as described in Hanks et al. (Hanks, B.A., et al. 2005. *supra).*

[0275] If necessary, two maturation factor molecules can be delivered by lentiviral vector to targeted DCs, as the vector configuration has the capacity to express four proteins.

## EXAMPLE 16

## *In vivo* DELIVERY OF ANTIGEN AND MATURATION FACTORS BY A RECOMBINANT VIRUS

[0276] Recombinant viruses packaged with FUOIM lentiviral vector (SEQ ID NO: 7) are prepared as described in Example 15. The viruses are administered to naive B6 mice to deliver OVA antigen and maturation factor molecules to DCs, and induction of immunity to graded doses of viruses is evaluated as described in Example 11.

[0277] It is observed that the targeted DC immunization by iCD40-containing lentiviruses increases the number of OVA responsive T cells as compared to the control mice, which are either not immunized, immunized with a non-OVA containing lentivirus

(e.g. FUGW/SVGmu), or immunized with non-iCD40 containing lentivirus (e.g. FOVA/SVGmu).

[0278] In addition, the resistance of the animals to a tumor challenge is assessed with the iCD40-containing lentivectors, as described in Example 13. The mice are injected with the following lentivectors in the tumor challenge experiment: FUOIM/SVGmu, FOVA/SVGmu, or FUGW/SVGmu. The following cell lines are used for tumor challenge: EL4 (C57BL/6J, H-$2^b$, thymoma) and E.G7 ((EL4 cells stably expressing one copy of chicken OVA cDNA). It is observed that the mice receiving immunization by the DC-targeting lentivectors FUOIM/SVGmu and FOVA/SVGmu are protected from the tumor challenge. In contrast, it is observed that tumors grow rapidly in mice receiving a mock vaccination with a lentivector lacking the OVA transgene (FUGW/SVGmu). This protection is OVA-specific because the vaccinated mice grow control EL4 tumors that lack expression of OVA, regardless of the lentivector used for immunization.

[0279] Finally, the potential of this method to eradicate an established tumor is assessed with the iCD40-containing lentivectors, as described in Example 14. The following lentivectors are used for immunization in the experiment: FUOIM/SVGmu and FOVA/SVGmu. The following cell lines are used for tumor treatment: EL4 and E.G7. It is observed that the tumor cell-injected mice receiving immunization by the DC-targeting lentivectors (FUOIM/SVGmu and FOVA/SVGmu) show a decline of tumor growth, followed by tumor regression and a reduction of luminescence below the detection level. Further, no tumor relapse is observed for as long as the experiment runs (>60 days). In contrast, tumors grow progressively in the mice receiving no treatment.

## EXAMPLE 17

## HIV/AIDS ANTIGEN PRESENTATION BY RECOMBINANT VIRUS *in vitro*

[0280] To treat HIV/AIDS, "dual-functional" DCs are generated based on the described gene delivery strategy. The "dual functional" DCs are efficacious at both eliciting neutralizing antibodies (Nabs) and inducing T cell immunity (Figure 25). To efficiently elicit NAbs, a gene encoding chimeric membrane-bound gp120 (gp120m) is delivered to DCs. Gp120 is an envelope glycoprotein for HIV and is considered to be the most potent

immunogen (Klimstra, W.B., et al. 2003. *J Virol* 77:12022-12032; Bernard, K.A., et al. 2000. *Virology* 276:93-103; Byrnes, A.P., et al. 1998. *J Virol* 72: 7349-7356, each of which is incorporated herein by reference in its entirety). As described elsewhere, gp120 fused with the transmembrane domain of the vesicular stomatitis virus glycoprotein can be expressed on the cell surface in a trimeric form, mimicking the mature trimer on the HIV virion surface (Klimstra, W.B., et al. 1998. *J Virol* 72: 7357-7366, which is incorporated herein by reference in its entirety). This form of immunogen will be displayed on the DC's surface. In addition to surface expression, the DCs can also present epitope peptides derived from gp120 in MHC restricted fashion to T cells.

**[0281]** Since HIV infection can significantly impair DC function through the depletion of CD4 T cells, it is desirable to engineer DCs that function independently of T cells. Expression of CD40L or iCD40 can result in maturation and activation of DCs in the absence of CD4 T cells. Thus, the engineered CD40L or iCD40, as described in Example 16, which functions as a maturation and stimulatory molecule, is incorporated into the DC-targeting virus.

**[0282]** The lentiviral construct for genetically modifying DCs is illustrated in Figure 24b and is labeled as FUGmID (SEQ ID NO: 8). Codon-optimized cDNAs for gp120 from NIH AIDS Research & Reference Reagent Program are obtained. The codon-optimized sequence can achieve exceptionally high levels of gene expression outside of the context of the HIV-1 genome. The construct is prepared by fusion of gp120 with the transmembrane domain of the vesicular stomatitis virus glycoprotein.

**[0283]** *In vitro* assays are conducted to assess the efficacy of gene-modified DCs to elicit NAbs. $CD19^+$ B cells are isolated from the spleens of naive B6 mice using anti-CD19 microbeads (MiHenyi Biotech, Auburn, CA) and co-cultured with modified DCs in the presence of IL-4 and IL-6. The lentiviral vector FUmGID is co-transfected with SVGmu in cell lines to prepare the FUmGID/SVGmu virus, as described in Example 2. The resultant viruses are transduced into bone marrow-derived DCs (BMDCs). The transduced DCs are be irradiated (3,000 rad) and used as antigen presenting cells (APCs) in co-culture with B cells. The time course of the proliferation of B cells in response to transduced BMDCs is measured.

It is observed that B cells proliferate to a greater extent in co-culture with transduced BMDCs than those that are co-cultured with mock-transduced BMDCs.

[0284] To investigate the effect of genetically modified DCs on the differentiation of B cells into specific immunoglobulin-secreting cells, the co-culture method as previously described is employed with the exception that the DCs are not irradiated. After 14 days, the titer of various isotypes of HIV-specific antibody in culture supernatants is determined by ELISA using recombinant gp120 (available from NIB: AIDS Research & Reference Reagent Program) as the antigen. Expression of the various isotypes of HIV-specific antibody are greater in B-cells co-cultured with transduced BMDCs than in those cocultured with mock-transduced BMDCs.

[0285] To assess the efficacy of the genetically modified DCs to activate T cells *in vitro*, $CD3^+$ T cells are isolated from naive B6 mice and co-cultured with lentivirus-infected and irradiated DCs. The time course of T cell proliferation is measured. T cell proliferation is found to be greater in T cell cultures co-cultured with transduced and irradiated DCs than in those co-cultured with mock-transduced DCs.

[0286] The results are expected to collectively demonstrate that BMDCs transduced with the FUmGID/SVGmu lentivector is effective in both stimulation of B-cells to produce neutralizing antibodies (Nabs) and in inducing T cell immunity against HIV/AIDS.

## EXAMPLE 18

## HIV/AIDS ANTIGEN PRESENTATION BY RECOMBINANT VIRUS *in vivo*

[0287] To evaluate the activation of B cells *in vivo*, B6 mice are immunized by subcutaneous injection with the recombinant lentiviruses prepared as described in Example 17. Controls include mice injected with lentiviruses encoding antigens alone, lentiviruses encoding maturation molecules alone, and naive mice without any treatment. Two weeks after virus injection, serum antibodies against HIV are measured by ELISA. The antibody titer is found to be higher in those mice injected with the FUmGID/SVGmu virus as well as in those injected with lentivirus encoding antigens alone. In contrast, The antibody titer is relatively low in those mice immunized with lentivirus encoding maturation molecules alone and in naïve mice.

[0288] For *in vivo* activation of T cells, the recombinant viruses described are injected into B6 mice. Seven days later, T cells are isolated, and their proliferation and cytokine secretion, after *in vitro* restimulation with genetically modified DCs, is measured as described in Example 12. The durability of the effector T cell responses is also monitored. Lentivector targeting to native DCs is able to elicit HIV-responsive T cells in both the lymph node and spleen. Administration of recombinant FUmGID/SVGmu is sufficient to generate T cells which secrete IFN-γ. In contrast, administration of a mock control vector (e.g. FUGW/SVGmu) fails to elicit an HIV-specific response.

## EXAMPLE 19

## *In situ* HIV/AIDS VACCINATION BY RECOMBINANT VIRUS: PROTECTION AGAINST HIV CHALLENGE

[0289] In order to test *in situ* DC vaccination approach to deal with HIV, a new mouse model of HIV pathogenesis involving human/mouse chimeras is developed. As described elsewhere, the RAG2$^{-/-}\gamma_c^{-/-}$ mouse can be reconstituted with a human adaptive immune system (Strauss, J.H., et al. 1994. *Archives of Virology* 9:473-484, which is incorporated herein by reference in its entirety). The RAG2$^{-/-}\gamma_c^{-/-}$ mice lack B, T, and NK cells (Morizono, K., et al. 2001. *J Virol* 75: 8016-8020, which is incorporated herein by reference in its entirety). Injection of CD34$^+$ human cord blood into the liver of one-day old partially-irradiated mice leads to the generation and maturation of functionally diverse human DCs, B cells, and T cells with human MHC restriction. Additionally, this model directs the development of primary and secondary lymphoid organs, and the production of a functional CD8$^+$ T cell immune response against a viral challenge. Furthermore, the observation of the Ig isotype switching from IgM to IgG indicates the existence of functional CD4$^+$ T cell immunity.

[0290] To determine the effectiveness of preventive protection against HIV by DC-targeted immunization, the human/mouse chimeras are administered recombinant viruses enveloped with SVGmu by injection. The recombinant viruses encode gpl20m antigen (Example 17) in conjunction with a maturation stimulator (for example, CD40L or iCD40 as in Example 15), and they are prepared and concentrated as described in Example 2. The immunized mice are then inoculated with HIV according to methods well known in the art,

such as, for example, via intraperitoneal or intravenous routes. Since the reconstituted mice maintain human CD4 T cells, the animals are challenged with molecularly cloned HIV reporter viruses, NFNSX-r-HSAS (CCR5-tropic), NL-r-HSAS (CXCR4-tropic) and clinical isolates (Baenziger, et al. 2006. *Proc Natl Acad Sci USA* 103:15951-15956, which is incorporated herein by reference in its entirety). The replication-competent reporter viruses also contain the heat-stable antigen (HSA) in the vpr region. Further, to establish a productive infection prior to inoculation, infected syngeneic peripheral blood mononuclear cells (PBMCs) are injected into the peritoneal space of the reconstituted human/mouse chimera.

[0291] Evidence of HIV infection is monitored over time in spleens, lymph nodes, PBMCs, and peripheral blood. FACS for HSA in the HIV reporter viruses is used to test for HIV viral integration and replication. HIV viral load is also measured from plasma using RT-PCR. Through evaluation of HIV infection by these methods, it is observed that productive *in situ* DC vaccination makes the immunized mice more resistant to the HIV challenge than those which are not immunized.

## EXAMPLE 20

## *In situ* HIV/AIDS VACCINATION BY RECOMBINANT VIRUS: CLEARANCE OF HIV INFECTION

[0292] To test the ability of the *in situ* DC vaccination approach to clear an active HIV infection, human/mouse chimeras are first challenged with molecularly cloned HIV reporter virus, NFNSX-r-HSAS (CCR5-tropic), as described in Example 19. Active HIV infection is monitored by FACS analysis of HSA expression in human CD4 T cells. Once successful HIV infection is confirmed, the engineered recombinant viruses (Example 19) are injected into animals via subcutaneous injection or by an optimal route determined by one of skill in the art (for example, s.c., i.d., i.v. or i.p.). The HIV viral load is then monitored by RT-PCR, and peripheral CD4 counts are followed. It is observed that DC vaccination is able to lower HIV viral load and to clear an established HIV infection in immunized mice compared to non-vaccinated controls.

[0293] Highly active antiretroviral therapy (HAART), utilizing a three-drug strategy, has significantly improved AIDS morbidity and mortality. The strategy outlined

above can be adapted to this paradigm by simultaneously transducing DC cells *in vivo* with engineered recombinant viruses. In conjunction with HAART, the above studies are repeated to evaluate the ability to prevent or reduce infection after HIV challenge (Example 19) and to clear an active HIV infection.

## EXAMPLE 21

## TREATMENT OF A MALIGNANT TUMOR IN A HUMAN USING A RECOMBINANT VIRUS

[0294] A human patient is diagnosed with a malignant tumor. The patient is administered a suitable amount of recombinant virus containing a gene that encodes an antigen specific for the tumor and enveloped with a DC-SIGN specific targeting molecule, such as, for example, SVGmu. The virus optionally contains a gene encoding a DC maturation factor, as described in Example 15. The virus is administered by weekly intravenous injection for the duration of treatment. At periodic times during and after the treatment regimen, tumor burden is assessed by magnetic resonance imaging (MRI). Significant reductions in tumor size are found as treatment progresses.

## EXAMPLE 22

## PREVENTION OF TUMOR FORMATION IN A HUMAN USING A RECOMBINANT VIRUS

[0295] A group of human patients is administered a suitable amount of recombinant virus containing at least one gene encoding an antigen that is commonly and specifically associated with tumor cells and optionally containing a gene encoding a DC maturation factor, as described in Example 15. The virus is enveloped with a DC-SIGN specific targeting molecule, such as, for example, SVGmu (Example 2). Patients in the experimental group and in a control group are monitored periodically for tumor growth. It is observed that the incidence of malignant tumor formation is lower in patients to whom the virus is administered than in the control group.

## EXAMPLE 23

## TREATMENT OF AIDS/HIV IN A HUMAN USING A RECOMBINANT VIRUS

[0296] A human patient is diagnosed with HIV/AIDS. The patient is administered a suitable amount of recombinant virus containing a gene that encodes Gp120 (Example 17) and enveloped with a DC-SIGN specific targeting molecule, such as, for example, SVGmu (Example 2). The virus optionally contains a gene encoding a DC maturation factor, as described in Example 15. The virus is administered by weekly intravenous injection for the duration of treatment. At periodic times during and after the treatment regimen, HIV viral load is assessed by measuring antibodies in the patient's blood against HIV using ELISA. The patient's T-cell count is also evaluated. It is observed that a significant reduction in HIV viral load is achieved as treatment progresses. Furthermore, it is observed that the patient's T-cell count stops decreasing as treatment progresses.

## EXAMPLE 24

## PREVENTION OF HIV/AIDS IN A HUMAN USING A RECOMBINANT VIRUS

[0297] A group of human patients considered at risk for HIV infection is administered a suitable amount of recombinant virus containing a gene encoding GP120 (Example 17) and optionally containing a gene encoding a DC maturation factor, as described in Example 15. The virus is enveloped with a DC-SIGN specific targeting molecule, such as, for example, SVGmu (Example 2). Patients in the experimental group and in a control group are tested every 6 months for HIV infection and if positive, monitored for HIV viral load and T-cell counts. In positively infected patients within the vaccinated group, it is observed that HIV viral load stays low and T-cell counts remain high relative to the positively-infected patients of the control group.

[0298] Although the foregoing invention has been described in detail for purposes of clarity of understanding, it will be obvious that certain modifications may be practiced within the scope of the appended claims. All publications and patent documents cited herein are hereby incorporated by reference in their entirety for all purposes to the same extent as if each were so individually denoted.

WHAT IS CLAIMED IS:

1. An *in vitro* method of delivering a lentiviral vector encoding an antigen to a dendritic cell expressing DC-SIGN (Dendritic Cell Specific ICAM-3 (Intracellular Adhesion Molecules 3)-Grabbing Nonintegrin), the method comprising:

   transducing the dendritic cell with a recombinant virus, wherein the recombinant virus comprises said lentiviral vector,
   wherein the recombinant virus comprises an alphavirus glycoprotein that targets said cell expressing DC-SIGN,
   wherein said glycoprotein is an alphavirus E2 glycoprotein mutated at a heparan sulfate binding site to decrease or eliminate its binding to heparan sulfate.

2. The method of claim 1, wherein said glycoprotein is a Sindbis E2 glycoprotein mutated at a heparan sulfate binding site.

3. The method of claim 2, wherein the virus comprises a Sindbis E1 protein and said Sindbis E2 protein and optionally (a) comprises sequences from a murine leukemia virus (MLV) genome or from a human immunodeficiency virus (HIV) genome, and/or (b) encodes a tumor antigen or an HIV antigen.

4. A recombinant virus as defined in any one of claims 1 to 3, or a pharmaceutical composition comprising said recombinant virus.

5. A recombinant virus comprising a lentiviral vector encoding an antigen and an alphavirus glycoprotein that targets cells expressing DC-SIGN wherein said glycoprotein is an alphavirus E2 glycoprotein mutated at a heparan sulfate binding site to decrease or eliminate its binding to heparan sulfate, for use in stimulating an immune response to said antigen in a mammal.

6. The recombinant virus for use according to claim 5 wherein said glycoprotein is a Sindbis E2 glycoprotein mutated at a heparan sulfate binding site.

7. The recombinant virus for use according to claim 5 or 6, wherein the mammal is human.

8. The recombinant virus for use according to claim 5, 6 or 7, wherein the virus comprises a Sindbis E1 protein and said Sindbis E2 protein.

9. The recombinant virus for use according to claim any one of claims 5 to 8, wherein the lentiviral vector comprises sequences from a Murine Leukemia Virus (MLV) genome or from an HIV genome.

10. The recombinant virus for use according to any one of claims 5 to 9, wherein the antigen is a tumour antigen or an HIV antigen.

11. The recombinant virus for use according to any one of claims 5 to 10, wherein the recombinant virus encodes a second gene of interest, such as a maturation factor selected from the group consisting of GM-CSF, IL-2, IL-4, IL-6, IL-7, IL-15, IL-21, IL-23, TNFα, B7.1, B7.2, 4-1 BB, CD40 ligand (CD40L) and drug-inducible CD40 (iCD40).

12. A dendritic cell transduced with a recombinant virus, wherein the recombinant virus is as defined in any one of claims 1 to 3.

13. The recombinant virus for use according to claim 5 wherein the antigen is a tumor associated antigen, viral antigen, bacterial antigen, fungal antigen, protozoan parasite antigen, helminth parasite antigen, or ectoparasite antigen.

14. The recombinant virus for use according to claim 13,

wherein said tumor associated antigen is selected from the group consisting of Her-2 receptor, MAGE, BAGE, RAGE, and NY-ESO, MART-1/Melan-A, gp100, gp75, mda-7, tyrosinase and tyrosinase-related protein, prostate specific membrane antigen (PSMA), prostate-specific antigen (PSA), mutated ras, bcr/abl rearrangement, Her2/neu, mutated or wild-type p53, cytochrome P450 1B1, N-acetylglucosaminyltransferase-V; human papilloma virus proteins E6 and E7; carcinoembryonic antigen and alpha-fetoprotein;
wherein said viral antigen is selected from the group consisting of adenovirus polypeptides, alphavirus polypeptides, calicivirus polypeptides, calicivirus capsid antigen, coronavirus polypeptides, distemper virus polypeptides, Ebola virus polypeptides, enterovirus polypeptides, flavivirus polypeptides, hepatitis virus (AE) polypeptides, hepatitis B core or surface antigen, herpesvirus polypeptides, herpes simplex virus glycoprotein, varicella zoster virus glycoprotein, immunodeficiency virus polypeptides, human immunodeficiency virus envelope or protease, infectious peritonitis virus polypeptides, influenza virus polypeptides, influenza A hemagglutinin, influenza A neuraminidase, influenza A nucleoprotein, leukemia virus polypeptides, Marburg virus polypeptides, orthomyxovirus polypeptides, papilloma virus polypeptides, parainfluenza virus polypeptides, parainfluenza virus hemagglutinin/neuraminidase, paramyxovirus polypeptides, parvovirus polypeptides, pestivirus polypeptides, picorna virus polypeptides, poliovirus capsid polypeptide, pox virus polypeptides, vaccinia virus polypeptide, rabies virus polypeptides, rabies virus glycoprotein G, reovirus polypeptides, retrovirus polypeptides, and rotavirus polypeptides;
wherein said bacterial antigen is selected from the group consisting of Actinomyces polypeptides, Bacillus polypeptides, Bacteroides polypeptides, Bordetella polypeptides, Bartonella polypeptides, Borrelia polypeptides, B. burgdorferi OspA, Brucella polypeptides, Campylobacter polypeptides, Capnocytophaga polypeptides, Chlamydia polypeptides, Clostridium polypeptides, Corynebacterium polypeptides, Coxiella polypeptides, Dermatophilus polypeptides, Enterococcus polypeptides, Ehrlichia polypeptides, Escherichia polypeptides, Francisella polypeptides, Fusobacterium polypeptides, Haemobartonella polypeptides, Haemophilus polypeptides, H. influenzae type b outer membrane protein, Helicobacter polypeptides, Klebsiella polypeptides, L-form bacteria polypeptides, Leptospira polypeptides, Listeria polypeptides, Mycobacteria polypeptides, Mycoplasma polypeptides, Neisseria polypeptides, Neorickettsia polypeptides, Nocardia polypeptides, Pasteurella polypeptides, Peptococcus polypeptides, Peptostreptococcus polypeptides, Pneumococcus polypeptides, Proteus polypeptides, Pseudomonas polypeptides, Rickettsia polypeptides, Rochalimaea polypeptides, Salmonella polypeptides, Shigella polypeptides, Staphylococcus polypeptides, Streptococcus polypeptides, S. pyogenes M proteins, Treponema polypeptides, andYersinia polypeptides, Y. pestis F1 antigen and Y. pestis V antigen;
wherein said fungal antigen is selected from the group consisting of Absidia polypeptides, Acremonium polypeptides, Alternaria polypeptides, Aspergillus polypeptides, Basidiobolus polypeptides, Bipolaris polypeptides, Blastomyces polypeptides, Candida

polypeptides, Coccidioides polypeptides, Conidiobolus polypeptides, Cryptococcus polypeptides, Curvalaria polypeptides, Epidermophyton polypeptides, Exophiala polypeptides, Geotrichum polypeptides, Histoplasma polypeptides, Madurella polypeptides, Malassezia polypeptides, Microsporum polypeptides, Moniliella polypeptides, Mortierella polypeptides, Mucor polypeptides, Paecilomyces polypeptides, Penicillium polypeptides, Phialemonium polypeptides, Phialophora polypeptides, Prototheca polypeptides, Pseudallescheria polypeptides, Pseudomicrodochium polypeptides, Pythium polypeptides, Rhinosporidium polypeptides, Rhizopus polypeptides, Scolecobasidium polypeptides, Sporothrix polypeptides, Stemphylium polypeptides, Trichophyton polypeptides, Trichosporon polypeptides, and Xylohypha polypeptides;

wherein said protozoan antigen is selected from the group consisting of Babesia polypeptides, Balantidium polypeptides, Besnoitia polypeptides, Cryptosporidium polypeptides, Eimeria polypeptides, Encephalitozoon polypeptides, Entamoeba polypeptides, Giardia polypeptides, Hammondia polypeptides, Hepatozoon polypeptides, Isospora polypeptides, Leishmania polypeptides, Microsporidia polypeptides, Neospora polypeptides, Nosema polypeptides, Pentatrichomonas polypeptides, Plasmodium polypeptides, P. falciparum circumsporozoite (PfCSP), sporozoite surface protein 2 (PfSSP2), carboxyl terminus of liver state antigen 1 (PfLSA1 c-term), exported protein 1 (PfExp-1), Pneumocystis polypeptides, Sarcocystis polypeptides, Schistosoma polypeptides, Theileria polypeptides, Toxoplasma polypeptides, and Trypanosoma polypeptides;

wherein said helminth antigen is selected from the group consisting of Acanthocheilonema polypeptides, Aelurostrongylus polypeptides, Ancylostoma polypeptides, Angiostrongylus polypeptides, Ascaris polypeptides, Brugia polypeptides, Bunostomum polypeptides, Capillaria polypeptides, Chabertia polypeptides, Cooperia polypeptides, Crenosoma polypeptides, Dictyocaulus polypeptides, Dioctophyme polypeptides, Dipetalonema polypeptides, Diphyllobothrium polypeptides, Diplydium polypeptides, Dirofilaria polypeptides, Dracunculus polypeptides, Enterobius polypeptides, Filaroides polypeptides, Haemonchus polypeptides, Lagochilascaris polypeptides, Loa polypeptides, Mansonella polypeptides, Muellerius polypeptides, Nanophyetus polypeptides, Necator polypeptides, Nematodirus polypeptides, Oesophagostomum polypeptides, Onchocerca polypeptides, Opisthorchis polypeptides, Ostertagia polypeptides, Parafilaria polypeptides, Paragonimus polypeptides, Parascaris polypeptides, Physaloptera polypeptides, Protostrongylus polypeptides, Setaria polypeptides, Spirocerca polypeptides Spirometra polypeptides, Stephanofilaria polypeptides, Strongyloides polypeptides, Strongylus polypeptides, Thelazia polypeptides, Toxascaris polypeptides, Toxocara polypeptides, Trichinella polypeptides, Trichostrongylus polypeptides, Trichuris polypeptides, Uncinaria polypeptides, and Wuchereria polypeptides; and wherein said ectoparasite antigen is selected from the group consisting of flea polypeptides; tick polypeptides, hard tick polypeptides, soft tick polypeptides; fly polypeptides, midge polypeptides, mosquito polypeptides, sand fly polypeptides, black fly polypeptides, horse fly polypeptides, horn fly polypeptides, deer fly polypeptides, tsetse fly polypeptides, stable fly polypeptides, myiasis-causing fly polypeptides and biting gnat fly polypeptides; ant fly polypeptides; spider fly polypeptides, lice fly polypeptides; mite fly polypeptides; bed bug fly polypeptides and kissing bug fly polypeptides.

15. The recombinant virus for use according to claim 5 wherein the recombinant virus is administered subcutaneously or intradermally.

# TARGETED GENE DELIVERY FOR DENDRITIC CELL VACCINATION


## Abstract

Methods and compositions are provided for delivery of a polynucleotide encoding a gene of interest, typically an antigen, to a dendritic cell (DC). The virus envelope comprises a DC-SIGN specific targeting molecule. The methods and related compositions can be used to treat patients suffering from a wide range of conditions, including infection, such as HIV/AIDS, and various types of cancers.

(No suitable figure)