**In vivo Anti-HIV Activity of the Heparin-Activated Serine Protease Inhibitor Antithrombin III Encapsulated in Lymph-Targeting Immunoliposomes**

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**Abstract**

Endogenous serine protease inhibitors (serpins) are anti-inflammatory mediators with multiple biologic functions. Several serpins have been reported to modulate HIV pathogenesis, or exhibit potent anti-HIV activity in vitro, but the efficacy of serpins as therapeutic agents for HIV in vivo has not yet been demonstrated. In the present study, we show that heparin-activated antithrombin III (hep-ATIII), a member of the serpin family, significantly inhibits lentiviral replication in a non-human primate model. We further demonstrate greater than one log10 reduction in plasma viremia in the nonhuman primate system by loading of hep-ATIII into anti-HLA-DR immunoliposomes, which target tissue reservoirs of viral replication. We also demonstrate the utility of hep-ATIII as a potential salvage agent for HIV strains resistant to standard anti-retroviral treatment. Finally, we applied gene-expression arrays to analyze hep-ATIII-induced host cell interacomes and found that downstream of hep-ATIII, two independent gene networks were modulated by host factors prostat glandin synthetizease-2, ERK1/2 and NFκB. Ultimately, understanding how serpins, such as hep-ATIII, regulate host responses during HIV infection may reveal new avenues for therapeutic intervention.


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**Introduction**

Current HIV therapies employ combinations of small molecule inhibitors that target viral proteins at different steps in the HIV replication cycle in order to prevent the emergence of HIV resistance to therapy [1,2,3,4]. Despite this strategy, resistance to one or more drug classes can emerge, resulting in a population of patients requiring salvage therapy [5]. The development of new anti-HIV therapeutics that target host proteins important for the virus life cycle could circumvent the problem of viral resistance. Host cell proteins that influence viral replication are less mutable than viral proteins, possibly offering an increased genetic barrier to the development of drug resistance. An analogous therapeutic concept has already proven efficacious in the treatment of HCV: stimulation of the host innate immune response using interferon-based therapy effectively blocks viral replication without induction of viral resistance [6].

Endogenous serine protease inhibitors (serpins) are part of the early innate immune response to viral infection that includes mannose binding lectins, soluble CD14, defensins and antimicrobial peptides [7]. The main biologic function of serpins is the blockage of protease activity involved in blood clotting and complement activation. Serpins belong to a superfamily of proteins that also regulate other inflammatory processes [8].

Serine protease inhibitors have a broad spectrum of anti-viral activity against HIV, HCV, HSV and the influenza virus [9,10]. A number of clinical observations suggest a role for the serpins in controlling HIV infection and disease progression in the mucosa and the peripheral blood. For example, (1) there is a barrier to HIV transmission via the oral mucosa; this may be due to the anti-viral activity of Secretory Leukocyte Inhibitor (SLPI) in saliva [11]. (2) α1-anti-trypsin, the most abundant serpin in blood, prevents HIV replication in vitro at physiological concentrations; in addition, HIV replicates at a much higher rate in the blood of α1-anti-trypsin-deficient individuals, suggesting α1-anti-trypsin might reduce viral replication in vivo [12]. (3) The anti-HIV activity of α1-anti-trypsin is believed to be responsible for the relatively low transmission rates of HIV through contaminated needles, compared to that of HCV and HBV. (4) Furthermore, presence of the α1-anti-trypsin allelic variants M2 and A332A is associated with enhanced HIV-1 acquisition [13].

Antithrombin III (ATIII), a serpin with a role in the coagulation cascade, exhibits potent anti-HIV activity. ATIII exists in three different forms under physiological conditions. In its inactive latent (L) form, ATIII circulates with its reactive COOH-terminal loop not fully exposed, thereby preventing its binding to thrombin. Upon binding to heparin, ATIII undergoes a conformational change to an activated, or stressed (S) form [here also termed hep-
ATIII) allowing the reactive COOH-terminal loop thus increasing the binding of thrombin by 100-fold. The resultant ATIII-thrombin complex eventually dissociates with the release of thrombin and an ATIII with a cleaved reactive loop, inducing a conformational change of ATIII to a relaxed (R) form. A proteolytically cleaved form of ATIII was originally discovered to be a CD8 + T cell anti-HIV factor (CAF) - a non-cytolytic innate immune response in HIV-1 long-term non-progressors [14, 15]. The S form of ATIII has greater antiviral activity against HIV and the simian immunodeficiency virus (SIV) than the R form; the L form has no anti-viral activity [14]. Hep-ATIII is up to 10-fold more potent in inhibiting HIV than the non-activated form of ATIII [16]. When compared to other serpins with anti-HIV activity, α1-antitrypsin and SLPI, heparin-activated antithrombin III (hep-ATIII) displays up to 106 fold higher anti-HIV activity in vitro [11,12,14,16,17,18]. The anti-viral activity of hep-ATIII and ATIII is mediated at least in part by host cell factors prostaglandin synthetase 2 (PTGS2) and transcription factor NFκB [9]. Two hundred-fold less hep-ATIII was required as compared to non-activated ATIII to elicit equivalent changes in gene transcription of these host cell factors [9].

In the present study, we sought to validate hep-ATIII as an HIV therapeutic using in vitro, humanized mouse and preclinical primate models of HIV infection. In order to evaluate the potential utility of ATIII as a salvage agent in patients with multidrug resistant HIV, we assessed the ability of hep-ATIII to inhibit a range of drug-resistant HIV-1 isolates in vitro, and in humanized mice infected with highly drug resistant HIV-1. In addition, we studied the effects of ATIII treatment in rhesus macaques chronically infected with SIV. In a novel therapeutic approach, we used anti-HLA-DR antibodies engrafted into immunoliposomes to encapsulate hep-ATIII (termed ET-ATIII): it has been shown that these immunoliposomes specifically target HLA-DR positive cells in lymph nodes including monocytes, macrophages and activated CD4 + T lymphocytes, allowing concentration of therapeutic ATIII in the main cellular reservoirs of HIV and SIV [19]. Finally, we sought to understand the mechanism by which hep-ATIII exerts its antiviral activity. We studied the gene expression profiles of peripheral blood mononuclear cells (PBMC) from SIV-infected macaques treated with hep-ATIII, and identified the transcriptional networks activated or repressed by hep-ATIII treatment. By elaborating the biologic networks associated with HIV inhibition by the innate immune system, we hoped to identify potential biomarkers of drug efficacy, as well as potential future drug targets.

Materials and Methods

Ethics Statement

All animal experimental protocols were approved by the Harvard Institutional Animal Care and Use Committee (IACUC) [20]. Human blood sampling was reviewed and approved by the Human Research Ethics Committee of the Beth Israel Deaconess Medical Center (BIDMC) and Harvard Medical School (IRB 2006-P-000004). Written consent for human blood collection was waived since no personal data were collected. Harvard Medical School follows NIH guidelines for animal handling and has Animal Welfare Assurance A3153-01 on file with the Office for Protection of Research Risks. The institutions involved in the studies maintain full accreditation from Association for Assessment and Accreditation of Laboratory Animal Care. Adult rhesus macaques (Macaca mulatta) were housed at the New England Primate Research Center and Harvard Medical School, a primate animal facility that is accredited by the Association for the Assessment and Accreditation of Laboratory Animal Care International. Research was conducted in compliance with the Animal Welfare Act and other US federal statutes and regulations relating to animals and experiments involving animals, and adhered to principles stated in the Guide for the Care and Use of Laboratory Animals, National Research Council, 1996. All steps were taken to ameliorate the welfare and to avoid the suffering of the animals in accordance with the “Weatherall report for the use of non-human primates” recommendations. Animals were housed either socially or in adjoining individual primate cages allowing social interactions, under controlled conditions of humidity, temperature and light (12-hour light/12-hour dark cycles). Food and water were available ad libitum. Animals were fed commercial monkey chow and treats by trained personnel. Environmental enrichment consisted of commercial toys. Blood draws were conducted under sedation by trained personnel under the supervision of veterinarians.

Mice

NOD/scid/scid-beta-2 microglobulin (b2m) knockout mice (Nod/Scid/b2m<sup>−/−</sup> mice) (6–8 weeks) and C57BL/6 mice were from the Jackson Laboratory (Bar Harbor, ME).

Source and Activation of ATIII

Recombinant human ATIII was produced in transgenic goats by GTC Biotherapeutics (Framingham, MA). These transgenic animals express human ATIII in their mammary glands and secrete it into their milk. ATIII was purified from goat milk through clarification through a 500-kDa tangential flow membrane filtration unit, captured and then eluted through a heparin affinity chromatography column. It was further purified by anion-exchange chromatography and hydrophobic interaction chromatography as described earlier [21]. The product had a biological activity of 6 U/mg. It was more than 99% pure, as determined by sodium dodecyl sulfate-polyacrylamide gel electrophoresis (SDS-PAGE) and by silver-staining, or by C4 high-pressure liquid chromatography (HPLC).

Anti-viral ATIII activity was activated by incubation with heparin as previously described and subsequently referred to as hep-ATIII. Briefly, ATIII was incubated with equal amounts (w/w) of heparin sodium (Polysciences, Warrington, PA, cat. no. 01491, 40–3 kDa fraction) overnight at 37°C to form a non-covalent ATIII-heparin complex. Unbound heparin was then removed by Sephacel 100 AKTA FPLC (GE Health Care Life Sciences, Piscataway, NJ) at 1 ml/min. Protein preparations resulted in less than 5% (w/w) free heparin measured by FPLC with refractive index detection and a formula described earlier [16]. Protein purity was determined by sodium dodecyl sulfate-polyacrylamide gel electrophoresis (SDS-PAGE) and silver staining using a Bio-Rad kit (Bio-Rad Life Science, Hercules, CA) with a 15% slab gel. Molecular weight was compared to a low-range protein molecular weight marker (Bio-Rad).

Encapsulation of Hep-ATIII

To produce 10 ml sterically stabilized anti-HLA-DR unimamellar immunoliposomes a two step protocol was used: The first step included the derivatization of the anti-HLA-DR antibody: 0.6 ml of 0.1 M of octyl glucoside (OG) was added to 6 ml of MES/NaCl buffer. Then 3.3 mg of N-glutaryl-dioleoylphosphatidylethanolamine (NGPE) lipid (Sigma-Aldrich) was dissolved in 2 ml of chloroform and added to a 50 ml round bottom flask. Chloroform was evaporated in a rotary evaporator. OG in MES/NaCl buffer was added to the dried film. Then 1.1 ml of 0.25 M 1-ethyl-3-(3’-(dimethylamino)propyl)carbodiimide (EDC) (Sigma-Aldrich) and

In vivo Inhibition of ATIII

Adult rhesus macaques (Macaca mulatta) were housed at the New England Primate Research Center and Harvard Medical School, a primate animal facility that is accredited by the Association for
1.1 ml of 0.1 M N-hydroxysulfosuccinimide (NHS) was added and incubated at room temperature for 10 min, then adjusted to pH 7.5. Anti-HLA-DR antibody (30 mg, clone 2.06, IgG1, American Type Culture Collection (ATCC)) was dialyzed against sodium borate buffer and added. This solution was incubated for 12 h at 4°C and afterwards dialyzed against PBS buffer. The NGPE conjugated antibody was concentrated in a vacuum concentrator.

The second step included the encapsulation of hep-ATIII and binding of the antibody to the liposome: 40 mg of dioleoylphosphatidic acid (DOPA) (Sigma-Aldrich) and 164 mg of dioleoylphosphatidylethanolamine (DOPE) (Sigma-Aldrich) was dissolved in 100 ml of chloroform in a round bottom flask connected to a rotary evaporator. The chloroform was evaporated by vacuum until a thin lipid film was formed. The liposomes were sized to 100 nm by 20 times extrusion through a 5-micron diameter pore polycarbonate membrane filter using a Lipex extruder (Northern Lipids, Burnaby, BC, Canada). The liposomes were dialyzed against 10 L of PBS buffer for 36 h. Efficiency of protein encapsulation was determined by measurement of retained protein in the supernatant after centrifugation of immunoliposomes by a bicinchoninic acid assay (BCA) (Pierce, Rockford, Ill.). The phospholipids concentration was measured using visible derivative spectroscopy.

The total amount of the lipids was 20 mg/ml. The total amount of encapsulated protein was 0.05 mg/ml and the total amount of the liposome was 2.4×10^4 mol/ml.

Conventional multilamellar liposomes were prepared as follows: Phosphatidylcholine (PC) and cholesterol (both purchased from Avanti Polar Lipids, Alabaster, AL) were dissolved in chloroform (total concentration of lipids in chloroform was around 2 mg/ml) and added to a 250 ml capacity round bottom flask. The chloroform was evaporated from the flask using a rotary evaporator for at least 4 h. A thin lipid film was formed on the wall of the round bottom flask. Hep-ATIII protein was purged with Argon gas for 10 min and added to the thin lipid film. The lipid film was hydrated for 4 h at 4°C. The liposomes were formed after the hydration. Liposomes were extruded 20 times through a 5 μm polycarbonate membrane filter using a Lipex extruder (Northern Lipids, Burnaby, BC, Canada). The liposomes were centrifuged at 100,000 g for 30 min at 4°C.

HIV-1 Env Pseudovirus Production and Titration

We used Env plasmids for HIV-1 pseudovirus production representing the standard panel of clade B viruses (PVO4, QH0692) and clade C clades (Du123.6, Du151.2) from NIH AIDS Research and Reference Reagent Program (ARRRP). Stocks of single-round infectious HIV-1 Env pseudoviruses were produced by co-transfecting 293T/17 cells (1.7×10^6 cells per T75 flask) with 2 μg of an HIV-1 rev/env expression plasmid and 12 μg of an env-deficient HIV-1 backbone plasmid (pSG3ΔEnv) using Lipofectamine transfection reagent (Invitrogen, Grand Island, NY). Pseudovirus-containing supernatant was harvested 24 h following transfection and clarified by centrifugation and 0.45-μm filtration. Single-use aliquots (1.0 ml) were stored at −80°C. The 50% tissue culture infectious dose (TCID50) for each pseudovirus preparation was determined by infection of TZM.bl cells as previously described [22]. A T-cell-line-adapted (TCLA) strain of HIV-1 MN was obtained from the NIH ARRRP as contributed by R. Gallo [23,24], and cell-free stocks were generated using H9 cells as previously described [25].

HIV-1 Pseudovirus Inhibition Assay

Virus inhibition was measured using a luciferase-based assay in TZM.bl cells as previously described [26]. This assay measures the reduction in luciferase reporter gene expression in TZM.bl cells following a single round of virus infection. Briefly, TZM.bl cells were added (1×10^4/well in a 100-μl volume) in 10% D-MEM growth medium containing DEAE-dextran (Sigma-Aldrich) at a final concentration of 11 μg/ml. Three-fold serial dilutions of 250 μg/ml non-activated ATIII, 50 μg/ml heparin, 15 μg/ml hep-ATIII and 15 μg/ml 135 kDa ATIII complex stock solution were performed in triplicate (96-well flat bottom plate) in 10% D-MEM growth medium (100 μl/well) and added to the cells. An amount of 200 TCID50 of virus was then immediately added to each well in a volume of 50 μl, and the plates were incubated for 48 h at 37°C. Assay controls included replicate wells of TZM.bl cells alone (cell control) and TZM.bl cells with virus (virus control). Following incubation period, 150 μl of assay medium was removed from each well and 100 μl of Bright-Glo luciferase reagent (Promega, Madison, WI) was added. The cells were allowed to lyse for 2 min, and then 150 μl of the cell lysate was transferred to a 96-well black solid plate, and luminescence was measured using a Victor 3 luminometer (Perkin Elmer, Hopkinton, MA). The 50% inhibitory concentration (IC50) titer was calculated as the serum dilution that caused a 50% reduction in relative luminescence units (RLU) compared to the level in the virus control wells after subtraction of cell control RLU.

In vitro Acute HIV Infection Assay Using Primary Isolates

For in vitro assays, human peripheral blood mononuclear cells (hPBMC) from HIV-1-seronegative donors were obtained by Ficoll-Hypaque gradient centrifugation of heparinized whole blood. After 3 days of mitogen stimulation (6.25 μg/ml concanavalin A), hPBMC were re-suspended at a concentration of 1×10^6 cells/ml in RPMI 1640 culture medium (Sigma-Aldrich) supplemented with 10% fetal cell serum (Sigma-Aldrich), penicillin (50 U/ml), streptomycin (50 μg/ml), L-glutamine (2 mM), HEPES buffer (10 mM), and 50 μM interleukin-2 in 24-well tissue culture plates (Becton Dickinson, San Jose, CA). An HIV-1 inoculum of 1,000 50% tissue culture infective doses (TCID50) of virus control wells after subtraction of cell lysate RLU.

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In vivo Inhibition of ATIII

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ing diketo acid derivates, was used as a control of an anti-HIV drug with a known IC50 between 2 and 10 μM [28].

Treatment of Rhesus Macaques with Different Forms of ATIII

For the non-human primate studies, Indian-origin rhesus macaques were intravenously infected with a 50-fold 50% monkey infectious dose (MID_{50}) of SIVmac231, and followed for more than 450 days after infection. Animals then received 0.8 μmol/kg, non-activated ATIII by the intravenous route daily for 4 days and then every 3 days for another 9 days. Hep-ATIII was administered daily for the first 4 days at 0.6 μmol/kg. Immunoliposome preparations were injected as 1.5 ml subcutaneous administrations at day 1 and 2 with 0.3 nmol/kg hep-ATIII.

Measurements of HIV-1 Infection

Protection from HIV induced cytotoxicity in hPBMC was measured in an acute HIV-1 infection model with 6 to 8-week old female Nod/Scid/b2mnull mice from The Jackson Laboratory (Bar Harbor, ME). These mice were chosen because of their primary blood CD4+ T lymphocyte counts were calculated by multiplying the total lymphocyte count by the percentage of CD3+CD4+ T cells determined by mAb staining and flow cytometric analysis [32].

Complete Blood Count and Peripheral Blood CD4+ T Lymphocyte Count for Rhesus Macaques and C57BL/6 Mice

Complete Blood Count (CBC) testing white blood cell count (WBC), red blood cells (RBC), hemoglobin (HGB), hematocrit (HCT), mean red cell volume (MCV), mean cell hemoglobin (MCH), platelet count (PLT) and mean platelet volume (MPV) was performed using the ADVIA Hematology System (Bayer, Leverkusen, Germany) according manufacturers protocol. Peripher-}

Data Analysis

The statistical significance of differences between groups was determined using the program GraphPad Prism 4.0 (GraphPad Software, La Jolla, CA). A P value of <0.05 was considered statistically significant. Statistical analysis was performed by use of
the Mann-Whitney test, paired T-test and the ΔΔCt method. Error bars represent standard error of the mean (S. E.).

**Results**

**Anti-viral Activation of ATIII**

Anti-viral capacity of ATIII was activated by overnight incubation with heparin at 37°C. This resulted in a mixture containing three compounds, which we subsequently separated by Sephacyl S100 FPLC. We found 1–3% w/w of a 135 kDa ATIII polymer with a retention volume of 7–8 ml. Ninety-five to ninety-nine % (w/w) of the mixture was 66–68 kDa hep-ATIII, in which heparin was bound to ATIII, at a retention volume of 10–14 ml. At approximately 35 kDa a protein-free fraction comprised of unbound heparin polymer was contained (15–19 ml retention volume) (Fig. 1A). The amount of this free heparin was calculated to be routinely below 5% (w/w) of the total mixture. We used fractionated hep-ATIII for our experiments.

We confirmed the purity of our fractionated hep-ATIII (66–68 kDa) preparations by SDS-PAGE and silver staining. We found that these hep-ATIII fractions were routinely more than 99% pure (Fig. 1B).

**Anti-viral Activity of Activated and Non-activated ATIII in a Single-round HIV Pseudovirus Inhibition Assay**

We used the single-round HIV inhibition assay to measure the anti-viral activity of activated ATIII, hep-ATIII, and compared that with unmodified ATIII, the 135 kDa ATIII complex and a heparin control. This system allowed the measurement of inhibition effects on all phases in a virus’ life-cycle during one round of replication. To investigate the susceptibility of different HIV-1 envelopes to hep-ATIII inhibition we used pseudoviruses with clade B (PVO.4, QH0692.42) and clade C (Du123.6, Du151.2) envelopes. We found that the 66–68 kDa fraction, containing heparin-activated ATIII, exhibited anti-viral activity. The IC50 of hep-ATIII was between 20–100 nM, and independent of envelope usage (Fig. 2). Unmodified ATIII had no inhibitory activity (Fig. 2) as well as the 135 kDa ATIII polymer (data not shown). Both demonstrated no inhibition as defined as inhibition below 25% in the pseudovirus inhibition assay. We also observed that heparin had an IC50 of 8 μM (Fig. 2), comparable to what has been previously reported.

**Anti-viral Activity of Activated and Non-activated ATIII in PBMC Acutely Infected with Drug-resistant HIV-1**

Anti-HIV-1 therapy that targets viral proteins must contend with the virus’ ability to rapidly evolve leading to the emergence of
drug resistant isolates. Antiviral therapy that targets host proteins while stimulating host innate immunity may be able to circumvent antiviral resistance. We have previously shown that non-activated ATIII exerts limited anti-HIV-1 activity and has only limited effects on host cell gene expression. The anti-HIV-1 activity of ATIII can be augmented through overnight incubation with heparin [16], which results in non-covalent attachment of heparin to ATIII, creating activated hep-ATIII. We sought to determine if hep-ATIII could overcome current limitations in drug treatment options for multidrug resistant HIV.

We tested the anti-HIV activity of hep-ATIII against an array of primary isolates from different clades, with T-cell tropism (X4), macrophage tropism (R5) or dual-tropism (X4R5), and differing in drug resistance profiles. After infection of hPBMC with the various HIV isolates, we then added hep-ATIII at the indicated concentrations (at day 1 and 4 of infection), and followed the infection by p24-antigen ELISA for 7 days. We then used the resulting dose-response curves for day 7 to calculate IC50 values. Our experiments demonstrated that hep-ATIII exhibited potent anti-HIV activity that was independent of prior drug exposure, clade or co-receptor usage (Table 1). Importantly, we found that the anti-viral activity of hep-ATIII was observed at therapeutically favorable levels with IC50 values ranging from 16–240 nM (Table 1), which was similar to those observed in the pseudovirus inhibition assays (Fig. 2).

Effect of Hep-ATIII on HIV-induced Cytotoxicity in Engrafted hPBMC in Nod/Scid/b2mnull Mice

We hypothesized that the immunomodulatory effects of hep-ATIII might not only inhibit HIV replication in target cells, but may also protect infected cells and uninfected bystander cells from HIV-related cytotoxic effects. We utilized the hPBMC engrailed, HIV-infected Nod/Scid/b2mnull mice to test this hypothesis. These mice lack murine lymphoid tissue and NK cell function, enabling superior engraftment of hPBMC compared to other Nod/Scid mice [30]. To simulate therapy of the challenging multidrug resistant HIV patient, we engrafted mice with hPBMC that were infected in vitro with a highly resistant HIV-1 isolate. We assessed whether daily treatment with low doses of hep-ATIII (25 nmol/kg) might reduce virus-induced hPBMC cytotoxicity. We used 5 Nod/Scid/b2mnull mice per non-engrafted group, non-
Activity of Heparin-activated and Non-activated ATIII in Rhesus Macaques

Although there are numerous reports describing the *in vitro* anti-viral activity of the serpins α1-anti-trypsin [12,33] and SLPI [11,17,18], there are no reports demonstrating their *in vivo* anti-viral efficacy. One obstacle to the *in vivo* assessment of the therapeutic potential of serpins may be that of generating and delivering an optimally activated form of the protease inhibitors. We utilized the rhesus macaque model of simian immunodeficiency virus (SIV) infection to assess whether variably activated forms of the serpin ATIII could inhibit viral replication. We have previously demonstrated that SIV strains are inhibited to a similar degree by ATIII as HIV-1 isolates [14].

Indian-origin rhesus macaques (*Macaca mulatta*) were infected by the intravenous (i.v.) route with 50-fold MID90 of SIVmac251 and were followed clinically for more than 450 days post infection. Viral loads of animals at the time of drug administration were stable with not more than 0.25 log10 variation between measurements in any given animal, and with viral loads routinely between 10^4–10^6 copies per ml for each of the different animals. Peripheral blood CD4^+ T lymphocyte counts were between 10^4 and 10^5 cells per ml.

We first tested non-activated ATIII in 3 rhesus macaques. We based our dosing regimen for non-activated ATIII on a baboon model of sepsis, in which ATIII administration prompted us to further test hep-ATIII in a more sophisticated non-human primate model of chronic lentiviral infection.

![Figure 3. Effect of heparin-activated ATIII on HIV-induced cytotoxicity in NOD/Scid/b2mnull mice.](image)

To measure HIV-induced cytotoxicity, splenocytes from NOD/Scid/b2mnull mice engrafted with HIV-infected hPBMC were quantified after 14-day incubation. We utilized a strain of HIV-1 that produced more than 90% virus-associated cell death of infected hPBMC in mice. We found that there was a 100% increase in spleocyte number after 14 days of treatment with hep-ATIII (*P* = 0.008, Mann-Whitney test) compared to untreated HIV-infected hPBMC engrafted control mice, suggesting protection of hPBMC from HIV cytoxicity.

This demonstration of *in vivo* efficacy of hep-ATIII against HIV in the humanized mouse model prompted us to further test hep-ATIII in a more sophisticated non-human primate model of chronic lentiviral infection.

In *In vivo* Inhibition of ATIII

In addition to proper biochemical activation, another obstacle to the successful therapeutic use of serpins may be in their pleiotropic activity, and potential for negative off-target side effects. We hypothesized that by targeting hep-ATIII specifically to tissues in which HIV replication is most robust, we could simultaneously increase therapeutic efficacy and reduce off-target drug exposure. We thus sought to determine if the therapeutic...
potential of hep-ATIII may be enhanced by encapsulation of hep-ATIII into immunoliposomes. As serpins lack the ability to specifically traffic to the lymph nodes, the primary tissue of viral replication, we sought to facilitate delivery of hep-ATIII to the lymph nodes by encapsulation into sterically stabilized anti-HLA-DR immunoliposomes (termed ET-ATIII) [40]. These liposomes enable dissemination of drugs directly to the lymphatic system, and also primarily home in on HIV-1 infected cells expressing the HLA-DR receptor [40].

We assessed the viral inhibitory activity of unencapsulated hep-ATIII, hep-ATIII encapsulated into conventional liposomes lacking anti-HLA-DR, and ET-ATIII against the dual-tropic (X4R5) HIV 89.6, and the macrophage-tropic (R5) SF162 in cell culture. These two HIV-1 isolates are derived from two different viral reservoirs: 89.6 was isolated from PBMC, and SF162 from the cerebrospinal fluid. 89.6 is a prototype for syncytium-forming, highly cytopathic HIV-1 viruses that replicate to high titers in cells bearing either CXCR4 or CCR5 receptors, reflective of isolates that may be found in individuals with AIDS [41]. In contrast, SF162 has more restricted co-receptor usage, is less cytopathic and more typical of primary, transmitted HIV isolates [42].

We infected hPBMC with SF162 and 89.6, and treated cells with hep-ATIII either unencapsulated or encapsulated into either conventional liposomes or sterically-stabilized anti-HLA-DR immunoliposomes (ET-ATIII) (Table 2). We found that encapsulation into immunoliposomes increased the anti-viral potency of hep-ATIII 107–150–fold, resulting in sub-nanomolar IC50 values of 0.4–0.7 nM. In contrast the use of conventional liposomes had only a limited effect on hep-ATIII potency. The IC90 for immunoliposomes was 3.7 nM for the 89.6 strain and 4.1 nM for the SF162 strain. We also compared the anti-HIV activity of ET-ATIII to that of the integrase inhibitor, 118-D-24. We observed an IC50 for 118-D-24 of 1750 nM, similar to what has been previously reported [28], suggesting a 1000-fold greater activity for ET-ATIII on a molar basis (Table 2). A vehicle liposome control was used for both liposome constructs to confirm that the liposomal vehicle did not have antiviral properties itself, consistent with prior studies [43].

Conventional liposomes and sterically-stabilized immunoliposomes have been used to encapsulate imaging reagents, small molecule drugs and proteins in both pre-clinical experiments and clinical settings, including in HIV patients, to minimize drug side-effects by increasing target tissue specificity [19,40,43,44,45,46,47]. There has been no cell toxicity reported after administration of proteins encapsulated in conventional or sterically stabilized liposomes [43,48,49]. To assess the therapeutic

Figure 4. In vivo anti-viral activity of non-activated and heparin-activated ATIII in rhesus macaques. (A) Viral loads as RNA copies/ml of chronically SIVmac239 infected rhesus macaques treated with 0.8 μmol/kg non-activated ATIII (n = 3) and (B) corresponding log10 reduction of viral load of same treatment group. (C) Viral loads as RNA copies/ml of chronically SIVmac239 infected rhesus macaques treated with 0.6 μmol/kg heparin-activated ATIII (n = 3) and (D) corresponding log10 reduction of viral load of same treatment group. Administration via i. v. inoculation is shown at indicated time points depicted by arrows. Viral load was measured and compared to animals before treatment (day 0). *, P<0.05, paired T-test, compared to pre-treatment (day 0). Data are shown as mean ± S.E. doi:10.1371/journal.pone.0048234.g004
In vivo Anti-viral Activity of hep-ATIII after Encapsulation into Sterically Stabilized Anti-HLA-DR Immunoliposomes

Under normal physiologic conditions, ATIII is not detectable in the lymphatic system [50]. As the lymph nodes are a major compartment for HIV-1 replication, we hypothesized that targeting hep-ATIII directly to the lymphatic system may increase the in vivo activity of hep-ATIII in our chronically SIV-infected macaque model. It has been previously shown that sterically stabilized anti-HLA-DR immunoliposomes accumulate in cervical and brachial lymph nodes, suggesting that they may effectively target HLA-DR positive cells, i.e. monocytes/macrophages and activated CD4+ T lymphocytes that are the primary cellular targets of HIV-1 [19]. Hep-ATIII was encapsulated in immunoliposomes (0.05 mg/mL) of 100 nm diameter with 4×10⁴ mol/mL anti-HLA-DR antibody incorporated. We subcutaneously injected chronically two SIV-infected animals with 0.3 nmol/kg of ET-ATIII. The overall quantity of hep-ATIII inoculated was 2000-fold less than the dose of unencapsulated hep-ATIII (3–30 nM). We found that encapsulated hep-ATIII had a very favorable TI of >100. A TI of >10 is considered feasible for an antiviral drug.

Gene Expression in PBMC from Hep-ATIII Treated Rhesus Macaques

The exact molecular mechanisms by which hep-ATIII exerts its anti-HIV effect in vivo is unknown. We used transcriptional profiling of PBMC taken from SIV-infected, hep-ATIII-treated rhesus macaques to identify host molecular pathways that might contribute to viral suppression in an extension of our prior in vitro investigations [9]. We compared the transcriptional profiles of 47,000 mRNAs at day 7 post-hep-ATIII therapy to the pre-treatment controls, when SIV inhibition was maximal. We also compared transcriptional profiles from day 15 post-therapy, when SIV inhibition had dissipated, to pre-treatment controls. We found that the expression of only a limited number of genes were significantly affected (P<0.01, ΔΔCt, method) by hep-ATIII therapy when compared to pre-treatment (Fig. 6). We grouped genes into three groups dependent on the gene-expression pattern at the treatment time point compared to pre-treatment (Fig. 6A/B/C; abbreviations of gene names are specified in Table S1). (1) We identified 16 genes and 15 gene loci that were over-expressed at both day 7 and day 15 in relation to pretreatment (Fig. 6A). (2) We found 20 genes and 12 loci that were significantly down-regulated at the time of maximal inhibition (day 7) compared to pre-treatment controls, but were up-regulated by day 15 compared to pre-treatment controls, when inhibition had diminished (Fig. 6B). (3) One gene and 2 loci were up-regulated after 7 days but down-regulated at day 15 (Fig. 6C). We also found that six genes and 7 loci were down regulated at both time points after therapy (Fig. 6C).

Network Analysis of Hep-ATIII-induced Interactomes during Lentiviral Replication in vivo

Interactomes describe relationships between genes that may be functionally linked. Certain genes may be central to the interactome, and modulation of these key genes may exert disproportionate effects on the other genes in the interactome. In order to identify genes that were central to the activity of hep-ATIII, we have previously analyzed the expression of 84 key genes of certain pathways in hep-ATIII treated, HIV-infected hPBMC in vitro, and found NFkB and prostaglandin synthetase-2 (PTGS2) to be highly regulated by hep-ATIII [9]. In the present study, we extended our analysis to a whole genome expression profile of PBMC from hep-ATIII-treated, SIV-infected rhesus macaques, evaluating 47,000 transcripts in all.

Applying Ingenuity-based network analysis to these gene expression profiles we once again identified NFkB in one network and ERK1/2 and PTGS2 in another network central to the two highest scoring regulatory networks modulated by hep-ATIII treatment [Fig. 7, Fig. 8, Fig. S1 contains explanation of network symbols]. Thus, in this comprehensive analysis of transcriptional activation by hep-ATIII, we have confirmed that NFkB and ERK1/2-PTGS2 are the likely major effectors of hep-

### Table 2. IC50 of hep-ATIII in different liposome formulations.

<table>
<thead>
<tr>
<th>Formulation</th>
<th>HIV-1 isolate</th>
<th>IC50 (nM)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Free hep-ATIII control</td>
<td>89.6</td>
<td>60</td>
</tr>
<tr>
<td>SF162</td>
<td>75</td>
<td></td>
</tr>
<tr>
<td>Conventional Liposomes</td>
<td>89.6</td>
<td>24</td>
</tr>
<tr>
<td>SF162</td>
<td>22</td>
<td></td>
</tr>
<tr>
<td>ET-ATIII</td>
<td>89.6</td>
<td>0.4</td>
</tr>
<tr>
<td>SF162</td>
<td>0.7</td>
<td></td>
</tr>
</tbody>
</table>

doi:10.1371/journal.pone.0048234.t002

index (TI) of our liposomes we tested for cytotoxicity over a wide dose range. We calculated TI as the ratio of the 50% cytotoxic dose (CD50) to the IC50. To measure the CD50 we tested the effect of ET-ATIII on cell viability using the Guava ViaCount® Assay. For these assays we used hPBMC from an HIV-1 infected patient as the indicator of cytotoxicity, as these best reflect cell populations that would be targeted by the liposome treatment in vivo. Additionally, we also assessed the toxicity of the liposomes against endothelial cells as ATIII is known to affect this cell type, inducing the release of anti-inflammatory prostacyclin and prostaglandins [7,8]. We found no significant decrease in viability of either cell population in response to an escalating dose of encapsulated hep-ATIII (3–30 nM). We found that encapsulated hep-ATIII had a very favorable TI of >100. A TI of >10 is considered feasible for an antiviral drug.

ET-ATIII up to 30 nmol/kg, 100-fold the effective dose for in vivo SIV inhibition. We measured the complete blood count (CBC) to assess for the hematologic effects of the ET-ATIII formulation. In particular, the hematocrit (HCT) was used as a surrogate marker for internal bleeding, a potential side effect of the use of hep-ATIII. We found no significant change in animal weight, white blood cell count or HCT. All other blood parameters as well as liver function tests were within the expected normal range (data not shown). Thus, no in vivo cytotoxicity could be detected in mice at concentrations significantly in excess of the therapeutically effective anti-viral dose.
Figure 5. \textit{In vivo} anti-viral activity of ET-ATIII in rhesus macaques. Chronically SIV\textsubscript{mac239} infected rhesus macaques (n = 2) were treated with 1.5 ml ET-ATIII (0.3 nmol/kg encapsulated hep-ATIII) at indicated time points depicted by arrows. (A) Viral load of ET-ATIII treated animals as RNA copies/ml. (B) Log\textsubscript{10} reduction of viral load. Vehicle liposomes were used as a control. Viral load was measured and compared to animals before treatment (day 0). Data are shown as mean ± S.E. doi:10.1371/journal.pone.0048234.g005

Figure 6. Changes in gene expression in PBMC induced by hep-ATIII treatment of chronically SIV-infected rhesus macaques. The GeneChip\textsuperscript{R} Rhesus Macaque Genome Array was used to assay genome-wide RNA expression (47,000 transcripts) in rhesus macaque PBMC before and after hep-ATIII treatment (n = 3). Differential gene expression comparison of time points when lentiviral replication was observed (day 7) and after viral replication returned to baseline (day 15) for the three monkeys are shown. Only loci or genes that were significantly (P<0.01, ΔΔ\textit{Ct} method) up-regulated (red) and down-regulated (green) in comparison to pre-treatment controls are shown. A 3-step color contrast for low, medium and high gene expression change was used. (A) Group of genes significantly up-regulated at the day 7 and 15 day time points compared to pre-treatment controls. (B) Genes significantly down-regulated at day 7 time point but significantly up-regulated at the day 15 time point compared to pre-treatment controls. (C) Genes either significantly up-regulated at the 7 day time point and down-regulated at the 15 day time point, or else significantly down-regulated at both time points compared to pretreatment controls. Full names of genes are given in Table S1. doi:10.1371/journal.pone.0048234.g006
ATIII activity as described for an in vitro system with hPBMC before [9].

Discussion

Serpins are induced rapidly following virus infection as part of a complex host innate immune response [7]. Mounting clinical evidence demonstrates an association between increased levels of serpin expression and either reduced HIV acquisition in uninfected individuals or delayed disease progression in chronically infected individuals [12,13,14,51,52,53,54,55]. For example, serpins have been found to be present at high levels in the cervical fluids of uninfected but repeatedly HIV-1 exposed sex workers [56]. ATIII, a serpin with functions in the coagulation cascade, was shown to have antiviral activity in vitro against not only HIV but HCV and HSV as well [9,14,15,16,57]. We are beginning to recognize that the serpins may have broad roles in the innate immune response, which in the case of ATIII includes an anti-inflammatory function in sepsis [58], anti-angiogenesis in tumor growth [59], and chemotaxis for neutrophils, human peripheral blood lymphocytes and monocytes [60,61,62]. The role of serpins as adjuvants of the innate immune system may suggest a potentially novel application for serpins in antiviral therapy.

Although the arsenal of small molecule HIV inhibitors continues to grow, drug resistance remains an important obstacle to long-term HIV therapy. Modulators of the innate immune system are attractive therapeutics because they act indirectly on the virus through multiple host pathways, and so are not as vulnerable to the evolution of viral resistance mutations. Indeed, our results suggest that ATIII may be an effective part of a salvage regimen for patients with highly drug resistant HIV strains. We also found that when appropriately modified and targeted through
liposomal encapsulation, hep-ATIII appears to be very safe, with a favorable TI >100 and no obvious negative effects in murine and nonhuman primate models.

Our experiments suggest that the precise biochemical modification and packaging of ATIII is critical to its therapeutic utility. It is well described that the various biological functions of ATIII are dependent on its tertiary structure [59,63]. This structure-de-
dependent functionality of ATIII holds true for its ability to inhibit HIV as well. Interestingly, in vitro, heparin-activated ATIII and the thrombin-ATIII complex showed the highest level of HIV-1 inhibition, followed by pre-latent ATIII [15,16]. A relaxed form of ATIII has a 50% reduced inhibitory activity, whereas HIV inhibition in vitro is negligible for the L-isomers of ATIII [14]. In vivo as well, ATIII antiviral activity appears to be dependent on biochemical modification: CD8+ T cells of HIV long-term non-progressors (LTNP) exhibit enhanced ability to activate ATIII that may be partially responsible for the reported non-cytolytic inhibition of HIV-1 in this cohort [64]. In vivo, ATIII is predominately in its S-configuration in blood at a physiological concentration of about 2.4 μM. To determine whether modification of ATIII has an effect on in vivo therapeutic HIV activity, we assessed three forms of the protein: non-activated ATIII, heparin-activated ATIII - both given intravenously - and liposomally encapsulated ATIII given subcutaneously. Non-activated ATIII, at a concentration sufficient to reduce inflammation in a baboon model of sepsis [34], and at 10–20-fold normal physiologic concentrations, did not impede viral replication. In vivo experiments had demonstrated that the anti-HIV activity of ATIII could be enhanced through heparin activation [16], and in concordance with this we found that intravenous administration of hep-ATIII resulted in a modest inhibition of viral replication in vivo, confirming the importance of ATIII activation.

However, we observed the most potent inhibition of plasma virus when ATIII was packaged in immunoliposomes and delivered subcutaneously. There are several possible explanations for this observation: (1) It is likely that unencapsulated hep-ATIII is not specifically transported to lymph nodes, a tissue that harbors viral replication [65], while in contrast, anti-HLA-DR immunoliposomes likely transport ET-ATIII to this location [19]. (2) Follicular dendritic cells (FDC) may stimulate viral replication in lymphocytes, and it has been demonstrated that serpins may interfere with this process [66]. (3) HIV disease progression is associated with ATIII deficiency in blood [51,52,67]. Nevertheless, there is likely considerable circulating anti-HIV serpin activity in plasma, such that the serpin anti-HIV activity in plasma may be saturated, and intravenous inoculation of hep-ATIII into the plasma has limited additive effect. In contrast subcutaneous administration of ET-ATIII targeting lymphoid organs may be more effective because baseline serpin activity in lymphoid organs is minimal.

We probed the underlying mechanism of hep-ATIII anti-HIV activity using software-supported interactome analysis, which allowed us to identify key host cell factors that are immediately downstream of drug treatment, and which in turn modulate the expression of overarching gene networks. We previously found that hep-ATIII activated two interactomes in HIV-1 infected PBMC: one interactome dependent on the NFκB transcription factor and a second interactome anchored by ERK1/2. These host factors are known to significantly impact HIV-1 replication. We now have expanded our analysis of transcriptional changes downstream of treatment with hep-ATIII, and studied these changes in the significantly more complex in vivo environment. Once again we found networks regulated by NFκB (Fig. 7) and ERK1/2-PTGS2 (Fig. 8) associated with hep-ATIII treatment confirming earlier in vitro results from PBMC acutely infected with HIV-1 [9]. There is a great need to counter HIV-induced inflammation and its consequences on the central nervous system (CNS) including HIV dementia. In the current studies we found that hep-ATIII treatment down-regulated NFκB after 7 days. This is important since the NFκB dimer consisting of p50 and RelA is considered to be the largest contributor to activation of HIV transcription and inflammation [68].

In conclusion, our data suggest that activated ATIII targeted to lymph nodes may have substantial in vivo activity against HIV-1. Further understanding of the mechanisms by which hep-ATIII interferes with HIV replication in lymphoid tissues might have important implications for the design of therapeutic strategies that harness the innate immune system for both its direct antiretroviral potential and its ability to modulate the adaptive immune response.

Supporting Information

Figure S1 Legend to interactive networks. Explanation of symbols and lines from Figure 7 and Figure 8. (TIFF)

Table S1 Full names of genes significantly altered by hep-ATIII treatment used in Figure 6. (DOCX)

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Author Contributions
Conceived and designed the experiments: MA JBW AC RS RGL.Performed the experiments: MA JBW CL AC RGL. Analyzed the data: MA JBW RS NLL RGL. Contributed reagents/materials/analysis tools: RS. Wrote the paper: MA JBW RGL.

References


