Ex Vivo Comparison of Microbicide Efficacies for Preventing HIV-1 Genomic Integration in Intraepithelial Vaginal Cells

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Vaginally applied microbicides hold promise as a strategy to prevent sexual HIV transmission. Several nonspecific microbicides, including the polyanion cellulose sulfate, have been evaluated in large-scale clinical trials but have failed to show significant efficacy. These findings have prompted a renewed search for preclinical testing systems that can predict negative outcomes of microbicide trials. Moreover, the pipeline of potential topical microbicides has been expanded to include antiretroviral agents, such as reverse transcriptase, fusion, and integrase inhibitors. Using a novel ex vivo model of vaginal HIV-1 infection, we compared the prophylactic potentials of two forms of the fusion inhibitor T-20, the CCR5 antagonist TAK-778, the integrase inhibitor 118-D-24, and cellulose sulfate (Ushercell). The T-20 peptide with free N- and C-terminal amino acids was the most efficacious compound, causing significantly greater inhibition of viral genomic integration in intraepithelial vaginal leukocytes, measured by an optimized real-time PCR assay, than the more water-soluble N-acetylated T-20 peptide (Fuzeon) (50% inhibitory concentration [IC50], 0.153 μM versus 51.2 μM [0.687 ng/ml versus 230 ng/ml]; P < 0.0001). In contrast, no significant difference in IC50 was noted in peripheral blood cells (IC50, 13.58 μM versus 7.57 μM [61 ng/ml versus 34 ng/ml]; P = 0.0614). Cellulose sulfate was the least effective of all the compounds tested (IC50, 1.8 μg/ml). These results highlight the merit of our model for screening the mucosal efficacies of novel microbicides and their formulations and potentially rank ordering candidates for clinical evaluation.

The lower genital tract of women constitutes a major site for HIV invasion. Therefore, prevention of vaginal infection would be a major milestone in curbing the global AIDS epidemic. While male condoms are very effective at preventing vaginal human immunodeficiency virus (HIV) transmission, women are frequently not empowered to negotiate their use by their sexual partners or may object to their use due to socio-cultural norms or the desire to conceive. The most effective long-term method of HIV prevention is a vaccine, because it would confer immunological protection, but a successful long-term method of HIV prevention is a vaccine, because it would confer immunological protection, but a successful HIV-1 vaccine is unlikely to emerge in the near future. Thus, alternative strategies are urgently needed to slow the spread of HIV.

Systemic antiviral preexposure prophylaxis and vaginally or rectally delivered topical microbicides are receiving increased attention as preventive tools. To date, only detergent, pH-buffering, and polyanion topical microbicides have completed testing in large-scale clinical trials. With one recently reported potential exception (6), none of these nonspecific microbicides has demonstrated a protective effect against vaginal HIV transmission (23, 24, 45, 47). An increased risk of HIV transmission was indeed documented for the detergent nonoxynol-9 (46). These disappointing findings have had two major effects on the microbicide field. First, efforts have intensified to develop and standardize preclinical and animal testing models with high predictive power for clinical microbicide efficacy. The application of these models in appropriate testing algorithms should have the capacity to screen out compounds such as cellulose sulfate before they enter phase II and III clinical trials (21). Second, the focus has shifted to compounds with specific antiretroviral activity. For example, the reverse transcriptase inhibitors (RTIs) tenofovir, which is already used to treat HIV infection, and dapivirine are currently entering testing as prophylactic vaginal-gel formulations in phase Ib and phase III efficacy trials (10). There are concerns, however, that the use of RTIs as microbicides might increase the spread of HIV-1 resistance (21, 35). Therefore, other classes of antiretroviral drugs that attack HIV-1 at different points in the viral replication cycle would be valuable additions to the microbicide development pipeline. They include more HIV-specific fusion and entry inhibitors—some of which have already demonstrated protection of macaques from vaginal transmission of simian-human immunodeficiency virus (SHIV) (31, 49)—as well as integrase inhibitors (23a).

Recently, improved animal models using macaques and humanized mice have been developed that could become part of a standardized go/no-go decision algorithm for candidate microbicides under development (3, 8, 12, 20). However, these...
animal models have drawbacks. Apart from simian immunodeficiency virus (SIV) or SHIV not being fully representative of HIV-1 (42), study designs using macaques that are informative require large sample sizes and are expensive. Likewise, the two humanized mouse models have limited throughput because human fetal tissues are required to be transplanted into each individual mouse (3, 12). Consequently, human explant organ cultures of the genital or rectal mucosa are being explored as higher-throughput and less expensive preclinical testing models (9, 18). Ex vivo microbiode screening in explant organ cultures could be used to narrow down the number of agents that are subjected to further evaluation in animals. Conceivably, an optimal explant model of HIV infection may even obviate the use of animal models for efficacy testing.

An effective preclinical testing model should simulate mucosal HIV transmission in vivo as closely as possible. We have demonstrated that CD4+ T lymphocytes and Langerhans cells (LC) residing in the outer epithelial layer of the human vagina are the initial targets infected by HIV-1 (26). A successful topical microbicide must block or abort infection of these first-line intraepithelial leukocytes. Thus, we believe that the gold standard for a microbicide efficacy readout in a preclinical model is the quantitative and sensitive measurement of productive infection of these intraepithelial leukocytes. Here, we present an in vivo vaginal HIV infection model that uniquely combines these necessary features.

We have utilized our model to compare the efficacy of the polyanion microbicide cellulose sulfate with those of three classes of antiretrovirals, the fusion inhibitor T-20 (29a), the CCR5 antagonist TAK-779 (2, 15), and the viral integrase inhibitor 118-D-24, a diketo-acid derivative (43, 53). Furthermore, an advantage of the ex vivo organ culture over the in vitro cell line culture is the ability to evaluate tissue bioavailability, including chemical modifications of the same agent and the effects of drug delivery vehicles. Local tissue bioavailability is a crucial factor for microbicide efficacy. Thus, we compared the FDA-approved T-20 peptide (Fuzone) with the T-20 peptide lacking N-acetylation, a chemical modification that increases T-20 lipid solubility (52).

**MATERIALS AND METHODS**

**Vaginal epithelial sheets.** Using a protocol that was approved by the Institutional Review Board (IRB) of the Fred Hutchinson Cancer Research Center in Seattle, WA, we harvested routinely discarded tissues from vaginal-repair surgeries performed in adult women at three medical centers in Seattle. No personal identities or demographic information was collected from the patients. For this reason, a waiver of consent was granted by the IRB. Tissues were placed in ice-cooled phosphate-buffered saline (PBS) and transported to the laboratory within 1 h of removal from the donor. The deep submucosa was removed with surgical scissors, and the remaining mucosa was treated with EDTA to separate the epithelial layer from the underlying stroma. EDTA interferes with the divalent-cation-mediated epithelial-stromal union at the basal membrane (40). We achieved the most consistent results by cutting the vaginal mucosa in 3-mm-wide strips and incubating the strips with agitation in a 5 mM EDTA solution overnight at 4°C. After this treatment, the intact epithelium could be dissected from the vaginal stroma under magnification using a Zeiss KL1500 stereoscope and two surgical microscopes. Cells within the epithelial sheets, including resident intraepithelial leukocytes, remained viable after this procedure; isolated sheets stained with the live-cell marker calcin AM showed almost 100% staining, while virtually no staining was observed in sheets treated with the dead-cell marker ethidium homodimer 1 (26). Higher EDTA concentrations and higher incubation temperatures yielded faster epithelial-stromal separation, but at the expense of decreased cell viability. The isolated intact epithelial sheets were placed in Hank's buffered salt solution containing 5 mM calcium chloride for 1 h on ice, washed in PBS, and placed in culture medium (HEPES-buffered RPMI containing 10% fetal calf serum, 2 mM l-glutamine, 100 U/mL penicillin, and 100 μg/mL streptomycin). A small amount of the stromal tissue was retained for CCR5 genotyping. **Viruses.** Molecular clones of HIV-1JRCSF Env (CCR5 tropic) and HIV-1ΔEnv were produced by calcium phosphate transfection of 293T cells with the proviral constructs plAI-JR (HIV-1JRCSF Env in the plAI backbone) and plAI-ΔEnv (plAI backbone lacking an envelope gene), respectively, as previously described (26, 51). To label virions with green fluorescent protein (GFP), 293T cells were cotransfected with the proviral construct and the pcGFPC3 plasmid (Clontech, Mountain View, CA). The pcGFPC3 plasmid contains the entire Vpr coding region fused to the COOH terminus of enhanced GFP (GFP-Vpr) (36). Cells were washed 18 h posttransfection, the culture medium was replaced 40 h posttransfection, and supernatants containing labeled virus were collected two or three times at 2- to 4-h intervals thereafter. The harvested viruses were concentrated 10- to 100-fold with Centricron Plus-80 100K centrifugal filter units (Millipore, Billerica, MA) and stored at −70°C. A primary mucosal HIV-1 isolate (HIV-1ΔM1) was isolated from mucosal mononuclear cells derived from the ectocervix of an HIV-1-infected woman, expanded in phytohemagglutinin (PHA)-activated lymphoblasts, and stored at −70°C. The peripheral blood mononuclear cells (PBMC) used for the generation of PHA-activated lymphoblasts were obtained from volunteers attending the research clinic of the HIV Vaccine Trials Network (HVTN) in Seattle (WA) and Los Angeles (CA), as previously described (26). PBMCs were thawed and stimulated 18 h posttransfection, and supernatants containing labeled virus were collected two or three times at 2- to 4-h intervals thereafter. The harvested viruses were concentrated 10- to 100-fold with Centricron Plus-80 100K centrifugal filter units (Millipore, Billerica, MA) and stored at −70°C. A primary mucosal HIV-1 isolate (HIV-1ΔM1) was isolated from mucosal mononuclear cells derived from the ectocervix of an HIV-1-infected woman, expanded in phytohemagglutinin (PHA)-activated lymphoblasts, and stored at −70°C. All virus preparations were assayed for infectivity in MAGI cells (50) or PHA-activated lymphoblasts, and the Gag p24 concentrations of the viral stocks were determined by an enzyme-linked immunosorbent assay (HIV-1 p24 Antigen Capture Assay Kit; NCI-Frederick, Frederick, MD).

**Viruses inoculations and preexposure treatments with candidate microbicides.** For confocal fluorescence microscopy, epithelial sheets were cut into ~1.5- by 1.5-mm pieces and placed into round-bottom 96-well plates containing 50 μl of culture medium per well. The epithelial sheets were spinoculated with viruses (200 ng/ml Gag p24 of GFP-tagged HIV-1JRCSF or HIV-1ΔEnv) at room temperature for 2 h at 1,200 × g (38), washed in staining buffer (SB) (PBS containing 1% bovine serum albumin and 0.05% sodium azide), immunostained, and examined by confocal microscopy.

To detect protective infection in LC and T cells emigrating from HIV-1-exposed vaginal epithelium, we placed several strips of epithelial sheets in 6-well plates containing 2 ml of culture medium per well. Prior to viral challenge, we treated some sheets with the fusion inhibitor T-20 (enfuvirtide) or its N-acetylated T-20 derivative Fuzone (manufactured by Roche), the CCR5 antagonist TAK-779, the integrase inhibitor 118-D-24, a diketo-acid derivative (all obtained from the NIH AIDS Research and Reference Reagent Program, Germantown, MD), or cellulose sulfate (Ushercell; kindly provided by George Usher, Polydex Pharmaceuticals, Toronto, Canada) for 1 h at room temperature. The sheets were spinoculated with 100 ng/ml Gag p24 of HIV-1JRCSF or HIV-1ΔM1 for 2 h at 1,200 × g (38), washed at least six times with PBS, and cultured in culture medium for 2 to 3 days at 37°C and 5% CO₂. For HIV-1 Gag p24/p55 detection, all cells that had emigrated from the epithelium into the culture medium after 2 to 3 days were harvested and immunostained for flow cytometric analysis. To detect HIV-1 DNA integration by PCR, emigrated cells and epithelial sheets were harvested 2 to 3 days after viral infection and combined for DNA isolation.

**In vitro HIV-1 infection of single-cell suspension cells, we obtained PBMC from two blood donors and activated the cells for 2 days with 0.4 μg/ml PHA (Remel, KS) in cell culture medium. The activated lymphoblasts (100,000 per well) were then distributed into a 96-well plate; treated in duplicate with various concentrations of the T-20 peptide with free N- and C-terminal amino acids, its N-acetylated T-20 derivative Fuzone, or cellulose sulfate for 1 h at room temperature, incubated infected with 200 ng/ml Gag p24 of HIV-1JRCSF, treated with the fusion inhibitor T-20, incubated infected with 200 ng/ml Gag p24 of HIV-1JRCSF, and then cultured at 4°C overnight in 4% buffered paraformaldehyde. Nuclei were counterstained with Topro3 (1 μM; Molecular Probes), and the sheets were embedded in Mowiol 40-88 containing 2.5% (wt/vol) Dabco (Sigma-Aldrich, Milwaukee, WI). Cellular staining was visualized with a Leica TCS SP spectral confocal microscope.
equipped with argon 488, krypton 568, and helium/neon 633 lasers. We analyzed the acquired image stacks using Imaris software (Bitplane AG, Zurich, Switzerland).

Flow cytometry. We used flow cytometry to detect HIV-1 Gag p24/p55 expression in T lymphocytes that had emigrated from virus-exposed sheets. The emigrated cells harvested from virus-exposed sheets were incubated in SB for 30 min on ice with 10 μg/ml phycoerythrin (PE)-conjugated anti-CD3 MAb (UCHT1). For the detection of nonviable cells, we used a previously described method that employed 7-aminoactinomycin D (7-AAD) (Sigma-Aldrich) to stain dead cells before subsequent fixation (41). Next, the cells were fixed, permeabilized, and incubated with fluorescein isothiocyanate (FITC)-conjugated anti-HIV-1 Gag p55/p24 monoclonal antibody (MAb) (KC57; Coulter, Fullerton, CA) according to the manufacturer's protocol. Finally, the cells were again fixed in 2% paraformaldehyde for at least 12 h, acquired on a Calibur flow cytometer (BD Biosciences), and analyzed using CellQuest 3.3 (BD Biosciences) with gates set to isolate single CD3+/HLA-DRlow T cells and to exclude 7-AAD+ dead cells.

PCR assays for HIV-1 proviral and integrated genomic DNAs. We isolated DNA from emigrated cells using the QiaAmp Blood Mini Kit (Qiagen, Valencia, CA) and performed an Alu-long-terminal-repeat (LTR)-based nested-PCR assay, which amplifies viral DNA that has been integrated into the host cell genome; unintegrated viral DNA is not amplified. We introduced the following modifications to the previously published method (5). Platinum Taq SuperMix (Invitrogen) was used for the first-round amplification in an ABI 7900HT thermal cycler (Applied Biosystems), starting with a denaturation step of 2 min at 96°C and then 12 cycles of amplification (96°C for 15 s, 55°C for 60 s, and 70°C for 60 s). One-tenth the volume of first-round amplicons was then amplified in a second round in 1× Absolute Blue QPCR ROX Mix (ABgene USA, Rochester, NY), starting with a denaturation step of 15 min at 96°C and then 40 cycles of amplification (96°C for 15 s and 60°C for 60 s). A 6-FAM (6-carboxyfluorescein)-labeled LTR hybridization probe was used to detect the product in the second round. Reactions were carried out in an ABI 7900HT thermal cycler (Applied Biosystems, Foster City, CA). We generated a standard curve using DNA isolated from serially diluted ACH-2 cells. Alu-LTR copy number and PLAV (NIH AIDS Research and Reference Reagent Program). Alu-LTR copy numbers were calculated in reference to this standard curve.

In the singleplex PCR assay, each sample was tested in parallel wells with a human β-actin primer/probe set (TaqMan β-actin Detection Reagent; Applied Biosystems). For multiplexing the detection of the Alu-LTR and β-actin sequences in the same wells, we used the forward and reverse β-actin primers (82 mM) from the kit as outer primers during the first PCR round. For the second PCR round, 305 nM inner β-actin primers (Hu β-actin Forward, 5′-AC CCACACTGTGCCCATCTACGA-3′, and Hu β-actin Reverse, 5′-CGGAACC GCTACCTGGCAATG-3′) were used. The β-actin hybridization probe that was added to the second round of PCR was the same oligonucleotide provided in the β-actin kit, but labeled with JOE (2′,7′-dimethoxy-4′,5′-dichloro-6-carboxyfluorescein; 200 nM) instead of 6-FAM. A standard curve for β-actin amplification (96°C for 15 s and 60°C for 60 s) was used. A 6-FAM (6-carboxyfluorescein)-labeled LTR hybridization probe was used to detect the product in the second round. Reactions were carried out in an ABI 7900HT thermal cycler (Applied Biosystems, Foster City, CA). We generated a standard curve using DNA isolated from serially diluted ACH-2 cells that were latently infected with HIV-1LV (NIH AIDS Research and Reference Reagent Program). Alu-LTR copy numbers were calculated in reference to this standard curve.

RESULTS

A simplified ex vivo model of intraepithelial HIV-1 infection in the human vagina. To enable larger-scale screening of candidate microbicides for their antiviral efficacies in the vaginal mucosa, we simplified and optimized our previous explant model designed to investigate the initial events of vaginal HIV transmission (26). In this earlier model, epithelial sheets were isolated from the underlying vaginal stroma by suction blistering. This method was not efficient, yielding epithelial sheets from only ∼20% of each vaginal tissue sample. For the present study, therefore, we optimized the treatment with the calcium and magnesium chelator EDTA as an alternative to suction blistering or using proteolytic enzymes, which have the undesirable effect of cleaving off HIV-1 surface receptors (1, 19). HIV-1 coreceptor expression remained intact after EDTA treatment. We previously reported high frequencies of CCR5 expression on resident CD3+ T cells and CD1a+ LC in EDTA-separated viable sheets (26). This allowed us to isolate and utilize 100% of the epithelium from each tissue sample for our experiments.

Next, we determined the optimal conditions for HIV-1 infection in the EDTA-separated sheets. We first confirmed that GFP-tagged HIV-1 virions localized to intraepithelial leukocytes (Fig. 1A and B) in distributions similar to those in previous localization experiments with suction blister sheets (26). By confocal microscopy, we observed that HIV-1 virions bound to intraepithelial lymphocytes in a characteristic circular pattern while also localizing to a subset of CD1a+ LC (Fig. 1A and B). Because a previous study had demonstrated that EDTA treatment interferes with HIV-1 envelope-mediated fusion after CD4 binding (14), we determined if calcium replenishment following EDTA treatment increased the level of productive infection in our model. After 1 h of incubation in Hanks buffered salt solution with or without 5 mM calcium chloride, EDTA-isolated vaginal epithelial sheets were exposed to HIV-1JR-CSF. Intracellular HIV-1 Gag expression, as determined by flow cytometry, was used to detect the productive infection of T cells that had migrated over 48 h from the epithelium into the culture supernatant. One representative sample is depicted in Fig. 1C, showing that calcium replenishment of the epithelial sheets after EDTA treatment increased the percentage of infected CD3+ T cells. Without calcium treatment, 1.5% of the emigrant CD3+ T cells were infected with HIV-1JR-CSF infections without preexposure prophylaxis, there were between 0.129 and 1.675 copies per cell. However, the method does not employ precisely quantified Alu-LTR and β-actin DNA standards and does not allow reliable determination of absolute copy numbers. Thus, the magnitude of viral integration under the various experimental conditions is reported relative to the virus infection performed without preexposure prophylaxis as the calibrator. Quadruplicate PCRs were run for each experimental setup. Using ACH-2 cells, the lower detection limit of integrated HIV-1 DNA was ∼50 copies for the singleplex PCR assay and ∼5 copies for the multiplex PCR assay (not shown).

CCR5 genotyping. PCR and DNA restriction fragment length polymorphism analyses were performed with DNA isolated from vaginal tissues, as previously described (25).

Statistics. Differences in the levels of relative viral integration between different experimental conditions were determined by two-sided paired (see Fig. 2) or unpaired (see Fig. 3A and B) t tests. The standard deviations calculated from the raw cycle threshold values of quadruplicate PCRs were compared between singleplex and multiplex assays by a two-sided unpaired t test. Dose-response curves for drug titrations were fitted by nonlinear regression (see Fig. 3C and D), and 50% inhibitory concentrations (IC50s) were compared between different compounds by an F test using Prism 4.0 (GraphPad, San Diego, CA).
tissue donors; treated the sheets for 1 h with the fusion inhibitor T-20 (the peptide version with free N- and C-terminal amino acids), the CCR5 antagonist TAK-779, or the integrase inhibitor 118-D-24; and then exposed the sheets to CCR5-tropic HIV-1JR-CSF. To detect infection, we harvested the epithelial sheets and the supernatants containing the emigrated cells after a 48-h culture period and measured HIV-1 genomic DNA integration by a sensitive nested real-time PCR assay (5). This method requires less cellular material than flow cytometric methods and is specific for postentry events that signify the initiation of a productive viral life cycle.

In initial experiments, epithelial sheets from two donors were exposed for 2 h to HIV-1JR-CSF at a relatively low virus concentration (10 ng/ml Gag p24). No viral integration was detected with this infection protocol. However, increasing the viral dosage to 100 ng/ml Gag p24 and including a spinoculation step (38), as used in our previous study (26), permitted HIV-1JR-CSF infection of intraepithelial vaginal cells in five of six donor tissues. The one donor tissue lacking detectable integrated HIV-1 provirus tested heterozygous for the CCR5-Δ32 mutation (CCR5 wild type [wt]/CCR5Δ32), consistent with this tissue’s reduced susceptibility to a CCR5-dependent HIV-1 infection (32). In the five CCR5 wt/wt donor tissues, all three compounds (T-20, TAK-779, and 118-D-24) strongly suppressed genomic integration of HIV-1JR-CSF (Fig. 2A). To avoid potential operator bias, we repeated the PCR assays four times, with three experimental replicates conducted by three different operators who were blinded to the sample treatment. Using these assays, we found that T-20 (0.223 μM) decreased viral integration to 8% (mean; range, 0.01 to 15.5%; P < 0.0001) of the level detected when infection was performed without preexposure prophylaxis. Similarly, TAK-779 (30 μM) decreased viral integration to 10% (mean; range, 1.8 to 17.9%; P < 0.0001) and 118-D-24 (1 μM) decreased integration to

FIG. 1. HIV-1 infection of leukocytes residing in vaginal epithelial sheets obtained by EDTA treatment. (A and B) Confocal microscopy of HIV-1 binding to intraepithelial lymphocytes and Langerhans cells. Epithelial sheets were separated from the underlying vaginal stroma by overnight incubation in 5 mM EDTA at 4°C, placed in Hanks buffered salt solution containing 5 mM calcium chloride for 1 h on ice, washed in PBS, and spinoculated for 2 h with either GFP-Vpr-tagged HIV-1JR-CSF or HIV-1ΔEnv at room temperature. Subsequently, the sheets were stained with anti-CD1a antibody and analyzed by confocal microscopy. Virus is shown in green, and the round staining pattern is typical for virus that is bound to intraepithelial T lymphocytes (arrows) (26). The arrowheads point to virus that localized to CD1a+ Langerhans cells. The overlap between green-fluorescence-labeled virus and red-fluorescent CD1a staining is in yellow. The blue staining shows the TOPRO-3 nuclear counterstain. The images depict tissues from two different individuals. Exposure to HIV-1ΔEnv exhibited no specific binding (not shown). (C) Calcium replenishment after EDTA treatment of vaginal epithelial sheets improves HIV-1 infectivity. EDTA-separated vaginal epithelial sheets were incubated with or without the addition of 5 mM calcium chloride for 1 h, spinoculated with HIV-1JR-CSF for 2 h, and cultured for 48 h. Cells that had emigrated from the epithelium into the culture supernatant were harvested, stained for HIV-1 Gag and CD3 using anti-HIV-1 Gag p55/p24 and anti-CD3 antibodies, and analyzed by flow cytometry. The gating in CellQuest was set to exclude 7-AAD+ dead cells, and HIV-1 Gag p24/p55 expression is plotted on the x axis versus CD3 on the y axis. The percentages of Gag-positive CD3+ T cells are given in the right upper quadrants. One tissue donor out of two donors examined is shown.
8.4% (mean; range, 0.24 to 19%; \( P < 0.0001 \)) relative to the samples with no preexposure prophylaxis. The CXCR4 antagonist AMD-3100 (1 \( \mu \text{M} \)), which does not inhibit infection by HIV-1 variants using the coreceptor CCR5, was used as a positive control treatment and exhibited a tendency to increase viral integration to 177% (mean; range, 113.7 to 265.2%; \( P = 0.066 \)) relative to samples with no preexposure treatment. These data show that the HIV-1-inhibitory activities of three tested microbicides can be measured by viral integration in our ex vivo model, indicating the potential of the model for preclinical microbicide screening.

Advantages of measuring viral integration with a multiplexed PCR assay. The comparative screening of microbicides requires a highly reliable assay readout. Therefore, we analyzed our PCR results for consistency between operators and PCR replicates. The three operators in our study consistently produced real-time PCR amplifications with raw cycle threshold values for positive samples between 15 and 25 cycles and only rare outliers (see Fig. S1 in the supplemental material). The quadruplicate cycle threshold values for each sample were generally tight, with small standard deviations (see Fig. S1 in the supplemental material; note the error bars). However, the variability in raw cycle threshold values between different operators was still of concern, in particular with the singleplex assay, in which the Alu-LTR and \( \beta \)-actin PCR amplifications are performed in separate wells (singleplex PCR assay). Each PCR assay was performed independently, either by four operators for the singleplex assay (A) or by two operators for the multiplex assay (B and C). Individual PCRs were performed in quadruplicate and averaged. The values depicted represent means, and the error bars depict the standard deviations across individual operators. The concentrations of the compounds used to treat the tissues were based on previously published in vitro studies (11, 13, 15, 43) and were as follows: CXCR4 antagonist AMD-3100, 0.794 \( \mu \text{g/ml} \) (1 \( \mu \text{M} \)); fusion inhibitor T-20 (manufactured by the Division of AIDS, NIAID), 1 \( \mu \text{g/ml} \) (0.223 \( \mu \text{M} \)); CCR5 antagonist TAK-779, 0.531 \( \mu \text{g/ml} \) (1 \( \mu \text{M} \)); and integrase inhibitor 118-D-24, 7.416 \( \mu \text{g/ml} \) (30 \( \mu \text{M} \)). The viral inoculum contained negligible amounts of Alu-LTR DNA.

FIG. 2. Ex vivo preexposure prophylaxis inhibits HIV-1 genomic integration in vaginal intraepithelial cells. Vaginal epithelial sheets from six tissue donors were incubated with the indicated compounds for 1 h at 37°C, spinoculated with 100 ng/ml HIV-1 Gag p24 of the CCR5-tropic laboratory clone HIV-1JRCSF (A and B) or the primary mucosal isolate HIV-1M1 (C) for 2 h, washed extensively, and cultured for 2 days. Total DNA was isolated from the sheets and emigrated cells, and the amount of integrated HIV-1 DNA in tissues treated with microbicides before infection was determined relative to the amount of integrated HIV-1 DNA in tissue not treated with microbicides before infection (= 100%).

(A) In initial experiments, the PCR for the housekeeping gene \( \beta \)-actin, which was used to normalize variability in DNA input, was performed in separate wells (singleplex PCR assay). (B and C) Subsequently, conditions were optimized to run the Alu-LTR and \( \beta \)-actin PCR in the same wells (multiplex PCR assay). Each PCR assay was performed independently, either by four operators for the singleplex assay (A) or by two operators for the multiplex assay (B and C). Individual PCRs were performed in quadruplicate and averaged. The values depicted represent means, and the error bars depict the standard deviations across individual operators. The concentrations of the compounds used to treat the tissues were based on previously published in vitro studies (11, 13, 15, 43) and were as follows: CXCR4 antagonist AMD-3100, 0.794 \( \mu \text{g/ml} \) (1 \( \mu \text{M} \)); fusion inhibitor T-20 (manufactured by the Division of AIDS, NIAID), 1 \( \mu \text{g/ml} \) (0.223 \( \mu \text{M} \)); CCR5 antagonist TAK-779, 0.531 \( \mu \text{g/ml} \) (1 \( \mu \text{M} \)); and integrase inhibitor 118-D-24, 7.416 \( \mu \text{g/ml} \) (30 \( \mu \text{M} \)). The viral inoculum contained negligible amounts of Alu-LTR DNA.
ependent multiplex assays confirmed the biological results of the singleplex assay. In the multiplex assay, T-20 decreased viral integration to 6% (mean; range, 1.8 to 18.7%; \( P < 0.0001 \)), TAK-779 to 8.6% (mean; range, 0.1 to 19.4%; \( P < 0.0001 \)), and 118-D-24 to 6.5% (mean; range, 0.5 to 20.3%; \( P < 0.0001 \)) of the level detected when infection was performed without preexposure prophylaxis. Less enhancement of viral integration after treatment with AMD-3100 was noted with the multiplex assay (mean, 121%; range, 94.6 to 172.2%; \( P = 0.195 \)) than with the singleplex assay (mean, 177%).

The overall variability between the quadruplicate PCR amplifications of each DNA sample was lower for the multiplex than for the singleplex assay. The individual standard deviations calculated from the raw cycle threshold values of each of the quadruplicate PCRs averaged 0.99 for the singleplex and 0.46 for the multiplex Alu-LTR amplifications (\( P < 0.0001 \)). For the \( \beta \)-actin amplifications, these averages were 0.23 and 0.78 for the singleplex and multiplex reactions, respectively (\( P < 0.00001 \)). In summary, the multiplex assay yielded the same biological results as the singleplex assay and displayed lower variability between identical replicates. Moreover, the multiplex assay required only half the DNA material. Thus, we adopted the multiplex protocol for our subsequent studies.

**Prophylaxis of vaginal chromosomal integration of a mucosal HIV-1 isolate.** Effective microbicides need to prevent infection with HIV-1 wild-type strains that are adapted to the mucosal environment. We were therefore interested to determine if the candidate microbicides could inhibit intra-epithelial cell integration of a CCR5-tropic HIV-1 isolate (HIV-1M1) derived from the ectocervical mucosa of an HIV-1-infected woman. We obtained vaginal epithelial sheets from two additional donors and preincubated the tissues with T-20 (0.223 μM), TAK-779 (1 μM), or AMD-3100 (1 μM) before infecting them with HIV-1M1. After a 48-h culture period, we detected chromosomal integration of HIV-1M1 using the multiplex PCR assay. Both T-20 and TAK-779 strongly suppressed genomic integration of HIV-1M1 to less than 2% of the level detected when infection was performed without preexposure prophylaxis (Fig. 2C). The control CXCR4-antagonist, AMD-3100, increased viral integration of HIV-1M1 in the two tissue donors to 296% and 117%, respectively (Fig. 2C). These data lend support to the idea that our ex vivo vaginal-infection model is suitable to test the antiviral efficacies of candidate microbicides against wild-type HIV-1 variants adapted to the mucosal environment.

**N-acetylated T-20 is less effective than free T-20 in preventing vaginal HIV-1 infection.** We further validated the feasibility of our vaginal-infection model for antiviral drug screening by performing a dose dependency analysis with titrations of the three inhibitory compounds, T-20, TAK-778, and 118-D-24. In addition, we wanted to determine if the model discriminated between pharmacological versions of the same drug that differed in water and lipid solubilities. For this purpose, we included two distinct peptides of T-20 in the titration: (i) the N-acetylated peptide, which is present in Fuzeon (produced and distributed by Trimeris/Roche), and (ii) a peptide with free N- and C-terminal amino acids (produced by the Division of AIDS [DAIDS], National Institute of Allergy and Infectious Diseases [NIAID]). Both T-20 versions exhibited a clear dose-dependent inhibitory effect on viral integration (Fig. 3A and C). The concentration at which the more lipid-soluble T-20 peptide from DAIDS induced a 50% inhibition of HIV-1JRCSF genomic integration in leukocytes residing within the vaginal epithelium (IC_{50}) was 0.153 μM (0.687 ng/ml; 95% confidence interval, 0.563 to 0.84 ng/ml; \( n = 7 \) independent experiments with 4 donor tissues). In contrast, the more water-soluble Fuzeon product exhibited an IC_{50} of 51.2 μM (230 ng/ml; 95% confidence interval, 198 to 267 ng/ml; \( n = 8 \) independent experiments with 4 donor tissues) and was thus markedly less effective than the T-20 peptide from DAIDS (\( P < 0.0001 \)) (Fig. 3A and C). Of note, this marked difference in efficacy between the two chemical forms of T-20 was not observed for inhibition of HIV-1 integration in PHA-activated peripheral blood lymphocytes infected with HIV-1JRCSF in single-cell suspension (Fig. 3D). The IC_{50}s for inhibiting HIV-1 integration with T-20 from DAIDS and T-20 from Roche in PHA-activated lymphocytes were 7.57 and 13.58 μM (34 and 61 ng/ml), respectively, and were not significantly different from each other (\( P = 0.0614 \)).

Dose-dependent inhibition of HIV-1JRCSF integration in the vaginal epithelium was also observed for 118-D-24 and TAK-778 (see Fig. S2 in the supplemental material). The IC_{50}s of 118-D-24 and TAK-779 were 190.13 μM (47 ng/ml; \( n = 3 \) donor tissues) and 5.84 μM (3.1 ng/ml; \( n = 2 \) donor tissues), respectively. In the seven donor tissues used in the titration studies, pretreatment with the control CXCR4 antagonist, AMD-3100, increased viral integration to an average of 126% relative to samples with no preexposure treatment (range, 97 to 180%; see Fig. S3 in the supplemental material).

In summary, we observed a clear dose-dependent inhibitory effect on viral integration in intraepithelial vaginal leukocytes by all four tested compounds. In multiple titrations of the two T-20 peptides, we found that the titration curves were highly reproducible between independently performed experiments, both within the same and across different donor tissues (Fig. 3A and C). Moreover, the distinct properties of lipid solubility and water solubility between the two T-20 peptides had a strong impact on the efficacy of T-20 in inhibiting HIV-1 infection of leukocytes residing within the vaginal epithelium but not on its efficacy in inhibiting infection of peripheral blood leukocytes in single-cell suspension.

**Efficacy of cellulose sulfate in preventing vaginal HIV-1 infection.** In a large clinical trial, cellulose sulfate, a nonspecific HIV entry inhibitor, did not prevent HIV infection and may have increased the risk of HIV acquisition (45). Moreover, a HIV entry inhibitor, did not prevent HIV infection and may have increased the risk of HIV acquisition (45). Moreover, a water-soluble cellulose sulfate, yielding an IC_{50} of 1.116 to 2.92 μg/ml (95% confidence interval, 1.116 to 2.92 μg/ml). However, no enhancement of infection was present at any of the concentrations, except for an increase of viral integration to 132% relative to no preexposure treatment when cellulose sulfate was used at a concentration of 0.1 μg/ml in a single experiment. Likewise, no enhancement of...
infection by cellulose sulfate was observed in two titration experiments performed with PHA-activated peripheral blood lymphocytes from two separate donors (Fig. 3D). In contrast, 1 μM (0.7944 μg/ml) of the control CXCR4 antagonist, AMD-3100, increased viral integration of HIV-1 DNA to an average of 125% relative to samples with no preexposure treatment (range, 94.6 to 180%; P = 0.01) across all 12 tested donor tissues in our study (Fig. 2B; see Fig. S3 in the supplemental material).

Of all the tested compounds, cellulose sulfate was the least effective in inhibiting the infection of vaginal intraepithelial leukocytes with R5-tropic HIV-1. Comparing the tissue IC50 of cellulose sulfate to the tissue IC50 of the two T-20 peptides, cellulose sulfate was ~1 log unit less effective than the Fuzeon product and >3 log units less effective than the T-20 peptide from DAIDS (P < 0.0001 for both IC50 comparisons) (Fig. 3C). At the specific concentration of 0.5 μg/ml, cellulose sulfate decreased viral integration in intraepithelial leukocytes only slightly, to 81.4% (mean; range, 65.8 to 102.9%) of uninhibited infection, compared to a reduction to 30.4% (mean; range, 28.2 to 38.4%) after treatment with 0.5 μg/ml Fuzeon (P < 0.0001) and to 1.92% (mean; range, 0.75 to 4.21%) after treatment with 0.1 μg/ml T-20 from DAIDS (P < 0.0001). Thus, our vaginal model reproducibly identified cellulose sulfate as a compound with relatively weak efficacy for preventing HIV-1 infection of leukocytes residing in the outer vaginal epithelium. On the other hand, cellulose sulfate also did not enhance infection in our model.

DISCUSSION

We consistently detected integrated HIV-1 provirus in intact, stroma-free epithelial sheets from the human vagina within 2 days of HIV-1 exposure, demonstrating that cells residing within the outer vaginal epithelium are highly susceptible to infection by HIV-1. A microbicide that fails to block this initial step of infection is unlikely to be successful in preventing sexual HIV transmission. Thus, prescreening novel microbicides for HIV-1-inhibitory activities using ex vivo vaginal intraepithelial cells can permit rational choices of which candidates may hold promise in larger-scale in vivo preclinical and clinical studies.
To build a feasible platform for systematic microbicide evaluation, we adapted our \textit{ex vivo} vaginal HIV transmission model (26) to quantify alterations in infectivity with preexposure prophylaxis. First, we improved the efficiency of epithelial-stromal separation, allowing us to harvest 100% of the epithelium from each vaginal-tissue sample, thereby decreasing the total number of samples needed for testing. Second, we adopted a readout of productive infection based on real-time PCR amplification of HIV-1 proviral DNA sequences that had integrated into the genome of infected cells. This method of detecting HIV-1 infection of vaginal intraepithelial cells offers three major advantages: high sensitivity, an indication for an advanced step in the productive viral life cycle, and its ability to reliably quantify the relative antiviral efficacies of a given panel of microbicides. The high sensitivity of the PCR assay can detect a newly occurring HIV-1 infection of cells within the vaginal epithelium as early as 2 days following viral challenge. During this short interval, contamination of the \textit{ex vivo} cultures with bacteria or fungi rarely occurs, even if tissue processing is performed under clean, but not sterile, conditions. Previously reported \textit{ex vivo} human explant studies of microbicide efficacy have employed whole mucosal organ cultures (7, 9, 18, 22, 27, 34), which usually require longer culture periods for detection of HIV infection, potentially increasing the risk of tissue degeneration and pathogen contamination. The greater sensitivity of the real-time PCR assay also ensures that a number of different microbicides with wide titration ranges can be tested in pairwise comparisons within the same donor tissues, as each experimental condition requires only a relatively small amount of epithelium.

The real-time format of the PCR assay allows quantification of the integrated viral copies per cell. To create a standard curve for the calculation of integrated HIV-1 copies, we titrated latently infected ACH-2 cells in parallel with each experimental PCR assay. Because the precise number of proviral copies in a given number of ACH-2 cells was not known, we used the ACH-2 cell standard curve to calculate the relative amounts of integrated provirus under different experimental conditions rather than the absolute number of integrated viral copies. For the purpose of our study, which was to determine whether a given microbicidal peptide inhibits viral integration in vaginal cells relative to viral integration in the absence of the microbicidal, relative quantification was sufficient. Our comparative dose-response studies clearly demonstrate the power of relative quantification by our PCR assay to discriminate the efficacies of different microbicides for inhibiting viral integration in vaginal target cells.

Of note, the measurement of viral integration is not specific for a particular cell type. Thus, unless mucosal cells are sorted into subpopulations before DNA isolation, the PCR assay does not identify which cells are infected. The specific cell type(s) infected with HIV-1 within the vaginal epithelium could be determined by flow cytometric analysis of isolated cells or by \textit{in situ} microscopy techniques, as we have done previously (26). Compared to real-time PCR, flow cytometry relies on the analysis of a relatively high number of isolated cells in single-cell suspension, and therefore, for enumerating infected cells, it requires a much larger amount of vaginal tissue for each experimental condition. Microscopy techniques, on the other hand, are labor-intensive and harder to accurately quantify than real-time PCR results.

While the PCR assay does not specify the cell type infected with HIV-1, our model ensures that cells within the outer vaginal epithelium, which are the first encountered by HIV during viral penetration \textit{in vivo}, are the sole source of the integrated HIV provirus. The vaginal epithelial sheets were completely stroma free and did not contain any microvasculature, which focused the analysis on T lymphocytes and LCs, the sole two leukocyte subtypes consistently residing within the outer vaginal epithelium (17, 26). Our prior studies had demonstrated that CD4+ T lymphocytes are the main cell type within the vaginal epithelium that is productively infected by HIV-1 (26). Thus, we presume that integrated provirus detected in our present study is derived mostly or entirely from infected intraepithelial CD4+ T cells.

Utilizing our intraepithelial-infection model to compare the HIV-1-inhibitory efficacies of several potential microbicides yielded some relevant findings about the potential activities of microbicides in future studies. The different potencies of these microbicides for preventing HIV-1 integration in intraepithelial target cells, which were consistent in experiments with several donor tissues, demonstrate the potential utility of the model for preclinical microbicide screening. Importantly, we observed a pronounced difference in efficacy between the two different pharmacological versions of the fusion inhibitor T-20 in the tissue model, but not in single target cell suspensions. This underscores two crucial points: (i) Microbicides that show promise after initial testing using PBMC or indicator cell lines require testing in tissue infection models; \textit{in vitro} testing alone is not sufficient. (ii) Drugs that are efficacious systemically may be less so when applied as a topical microbicide. The T-20 peptide with free terminal ends likely exhibits higher lipid solubility than the Roche-manufactured N-acetylated T-20 peptide (52) and thus may penetrate the vaginal epithelium more readily. Compared to our IC$_{50}$ determination for the Roche-manufactured T-20 (230 ng/ml in tissue; 61 ng/ml in PHA-activated T cells) or the IC$_{50}$ ranges that have been previously reported for this agent (0.4 to 480 ng/ml for CCR5-tropic viruses in various \textit{in vitro} systems [30]), the T-20 peptide lacking N-acetylation was highly protective against HIV-1 chromosomal integration in the vaginal epithelium (0.687 ng/ml).

Notably, both T-20 versions inhibited infection of vaginal intraepithelial cells in our model more effectively than cellulose sulfate (Ushercell). Likewise, the CCR5 antagonist TAK-779 and the integrase inhibitor 118-D-24 were markedly more efficacious than cellulose sulfate. Going forward, clear results criteria for comparative efficacy screening in a relevant \textit{ex vivo} model like the one presented here need to be formulated to determine whether a product may proceed to further evaluation \textit{in vivo}. These criteria will have to incorporate toxicity in the form of a therapeutic index that puts efficacy in relationship to the compound’s potential toxicity for the vaginal epithelium. Moreover, screening criteria cannot focus solely on comparing equal dosages of microbicidal agents but will have to consider what concentrations are actually achievable \textit{in vivo} and at what cost. Our findings indicate that the T-20 DAIDS peptide with free N- and C-terminal amino acids may be topically effective in the vagina at a much lower dosage than
Fuzen. At 10 ng/ml, >80% inhibition of viral integration in the mucosa was achieved. Extrapolating the amount of tissue we treated in each titration step to the complete surface of the vaginal cavity (39), we estimate that a total dose of 10 mg T-20 DAIDS could be effective as a vaginal microbicide, costing between $2 and $3. While even less expensive topical microbicides are desirable, this nevertheless indicates that, due to the potent protective efficacy of some fusion inhibitors, as exemplified both in our study for T-20 DIAIDS and in previous work with other compounds (16, 48, 49), fusion inhibitors could potentially be efficacious in humans as topical microbicides at concentrations that are not prohibitively expensive.

Enhancement of HIV infection of peripheral blood mononuclear cells by cellulose sulfate at low concentrations of around 0.3 μg/ml was suggested by a recently published study (44). The authors concluded that this may explain why cellulose sulfate appeared to increase the risk of HIV infection in one of two large clinical trials (45). However, the final statistical analysis comparing the HIV transmission risk between the cellulose sulfate and the placebo groups of the two trials was not significant (23, 45). Indeed, one of the two studies explicitly concluded that a 6% cellulose sulfate vaginal gel was safe (23). These clinical observations are consistent with the monophasic dose-response curve observed for cellulose sulfate in our vaginal-infection model; while cellulose sulfate was less efficacious than the other four compounds tested, it also did not enhance infection at any concentration.

In conclusion, we developed and validated an ex vivo tissue model that uniquely quantifies the sum of the initial events whereby HIV-1 establishes infection of cells embedded in the outer epithelial layer of the human vagina. Mucosal tissues for this model can be easily obtained on a weekly basis from one university medical center as a discarded by-product of vaginal-repair surgeries (4, 29, 33). We demonstrate that our vaginal-infection model can be utilized to screen topical-microbicide candidates for their efficacy in blocking chromosomal integration of HIV-1, measured by a sensitive real-time PCR assay, in intraepithelial vaginal cells. The relative inefficiency of cellulose sulfate in preventing infection of intraepithelial leukocytes, as well as the superior efficacy of a lipid-soluble over a water-soluble version of T-20 in our model, underscores our model’s potential as a screening tool for microbicides in the development pipeline. We propose that this preclinical testing system can be used to narrow down the number of microbicide candidates that progress to human trials.

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The authors declare that they have no competing financial interests.

REFERENCES
