Three-Dimensional Structural Characterization of HIV-1 Tethered to Human Cells

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ABSTRACT
Tetherin (BST2, CD317, or HM1.24) is a host cellular restriction factor that prevents the release of enveloped viruses by mechanically linking virions to the plasma membrane. The precise arrangement of tetherin molecules at the plasma membrane site of HIV-1 assembly, budding, and restriction is not well understood. To gain insight into the biophysical mechanism underlying tetherin-mediated restriction of HIV-1, we used cryo-electron tomography (cryo-ET) to directly visualize HIV-1 virus-like particles (VLPs) and virions tethered to human cells in three dimensions (3D). Rod-like densities that we refer to as tethers were seen connecting HIV-1 virions to each other and to the plasma membrane. Native immunogold labeling showed tetherin molecules located on HIV-1 VLPs and virions in positions similar to those of the densities observed by cryo-ET. The location of the tethers with respect to the ordered immature Gag lattice or mature conical core was random. However, tethers were not uniformly distributed on the viral membrane but rather formed clusters at sites of contact with the cell or other virions. Chains of tethered HIV-1 virions often were arranged in a linear fashion, primarily as single chains and, to a lesser degree, as branched chains. Distance measurements support the extended tetherin model, in which the coiled-coil ectodomains are oriented perpendicular with respect to the viral and plasma membranes.

IMPORTANT
Tetherin is a cellular factor that restricts HIV-1 release by directly cross-linking the virus to the host cell plasma membrane. We used cryo-electron tomography to visualize HIV-1 tethered to human cells in 3D. We determined that tetherin-restricted HIV-1 virions were physically connected to each other or to the plasma membrane by filamentous tethers that resembled rods ~15 nm in length, which is consistent with the extended tetherin model. In addition, we found the position of the tethers to be arbitrary relative to the ordered immature Gag lattice or the mature conical cores. However, when present as multiple copies, the tethers clustered at the interface between virions. Tethered HIV-1 virions were arranged in a linear fashion, with the majority as single chains. This study advances our understanding of tetherin-mediated HIV-1 restriction by defining the spatial arrangement and orientation of tetherin molecules at sites of HIV-1 restriction.

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mammalian tetherin ectodomain dimer has been solved by X-ray crystallography under oxidized and reduced buffer conditions. Each monomer consists of a continuous alpha helix arranged in parallel orientation, forming a coiled-coil dimer 14.5 to 16.5 nm in length (27–30). Based on X-ray structures of the mammalian ectodomains, researchers have proposed two main models to predict how tetherin cross-links HIV-1 to the plasma membrane (22, 31), with evidence to support both (see Fig. S1 in the supplemental material). In the extended or axial model, the TM and GPI are in trans-configuration, with the coiled-coil ectodomain oriented perpendicular with respect to viral and plasma membranes (29, 32). For the parallel or equatorial model, the TM and GPI are in cis configuration with the coiled-coil ectodomain situated in parallel register between the viral membrane and the plasma membrane. Based on high-resolution structures of the human tetherin ectodomain, one would predict the distance separating the viral membrane from the host cell’s plasma membrane to be 16.5 nm for the extended model and 2.5 nm for the parallel model (30). Studies have demonstrated biochemically that the extended tetherin homodimer physically restricts HIV-1 release (23, 33, 34). However, structural information on tetherin-restricted HIV-1 confirming the extended tetherin model is lacking.

Ultrastructural analysis of HIV-1 tethered to human cells has been limited chiefly to examinations of chemically fixed and heavy-metal-stained samples by either thin-section transmission electron microscopy (TEM) (1, 9, 23, 32, 35–38) or scanning electron microscopy (SEM) (2, 23, 39). In previous studies, clusters of HIV-1 virions retained on the surface of infected or transfected cells expressing tetherin were consistently observed. In a few selected studies, researchers occasionally observed electron-dense material resembling stalks between virions (1, 9, 38). However, the molecular composition of these densities and their dimensions and orientation were not clearly defined. Immunoelectron microscopy studies have shown tetherin staining on viral membranes and on the host cell plasma membrane near sites of HIV-1 budding (23, 32, 37, 38). Electron-dense fibrous material linking HIV-1 to the host cell membrane (37) and to virus-containing compartments in macrophages was observed (36). However, the length of these tethers (between 50 and 100 nm), which was inferred from TEM two-dimensional (2D) projection images and not 3D volumes, exceeded the length predicted by either tetherin model by an order of 3- to 6-fold.

Despite progress made over the past few years, several fundamental questions regarding the ultrastructure of tethered HIV-1 remain unanswered, mainly: (i) how are tetherin molecules and domains oriented, (ii) what is the distance separating tethered virions from the cell and between tethered virions, and (iii) how are tethered HIV-1 virions arranged in 3D at the plasma membrane. In this study, we directly visualized HIV-1 virions tethered to human cells by cryo-electron tomography (cryo-ET). HIV-1 virions were linked by tethers in a linear, unbranched fashion and less often as branched chains. Rod-like densities or tethers connecting virions to each other and to the plasma membrane were seen; measurements of these tethers support the extended tetherin model. These findings provide strong support for tetherin’s role as a proteinaceous link between virions and the plasma membrane and provide additional insight into the formation of tetherin-linked chains.

**MATERIALS AND METHODS**

**Cell culture and plasmids.** HT1080 and HeLa cell lines were obtained from the American Type Culture Collection (ATCC) and maintained in high-glucose pyruvate-Dulbecco modified Eagle medium (DMEM) (GIBCO, Grand Island, NY) supplemented with 10% fetal bovine serum (FBS), 5 mM l-glutamine, and 5 mM penicillin-streptomycin. Subconfluent cultures (40 to 70%) were grown directly on gold Quantifoil R2/1 or R2/2 TEM grids (Quantifoil Micro Tools GmbH, Jena, Germany) and on glass-bottom MatTek dishes (MatTek Corporation, Ashland, MA). HIV-1080 cells were grown on MatTek dishes and on TEM grids coated with collagen (0.2 mg/ml in 0.2% acetic acid). HeLa cells were grown on MatTek dishes coated with poly-γ-lysine or on TEM grids that were incubated overnight in DMEM supplemented with 10% FBS, 5 mM l-glutamine, and 5 mM penicillin-streptomycin. TEM grids were inspected under a light microscope to ensure the integrity of the holey carbon film, which subsequently was reinforced by evaporating a 4- to 5-nm layer of carbon on top of it using a Denton Benchtop Turbo apparatus (Denton Vacuum, Moorestown, NJ). Prior to collagen coating or overnight incubation in media, the TEM grids were sterilized by plasma cleaning followed by immersion in 70% ethanol.

HIV-1 VLPs were generated by cotransfecting cells with a 3:1 ratio of pVRC-3900 (a plasmid encoding coamino-optimized HIV-1 PR55True) and GagOpt-mCherry. GagOpt-mCherry was constructed by swapping the mCherry gene into Gag-yellow fluorescent protein (YFP) using BamHI and NotI sites (40). The plasmid pEGFP-tetherin (encoding an N-terminal enhanced green fluorescent protein [EGFP]-linked tetherin) was made by cloning tetherin in-frame from pFLAG-Tetherin into Sall and BamHI sites of pEGFP-C1 (Clontech Laboratories Inc.). The plasmids pNLenvΔU (encoding an HIV-1 env- and vpu-deficient provirus) and pEGFP-C3A-tetherin were kindly provided by Klaus Strehbel (NIADDK, Bethesda, MD) (41, 42). Cells were allowed to grow on TEM grids for 24 h prior to transfection using jetPRIME (Polyplus-Transfection Inc., New York, NY) according to the manufacturer’s instructions. HT1080 cells were transfected overnight with an 8:1 ratio of pNLenvΔU to pEGFP-tetherin or pEGFP-C3A-tetherin. HeLa cells were transfected overnight with 500 ng of pNLenvΔU.

**Viral release assay.** HT1080 cells were transfected with pEGFP-tetherin or pEGFP-C3A-tetherin titration (10, 25, 75, and 125 ng) and 1 μg pNLenvΔU. Transfected HT1080 cell supernatants were harvested, clarified by low-speed centrifugation, and subsequently concentrated by ultracentrifugation through a 20% sucrose cushion (100,000 × g for 2 h at 4°C). Viral pellets were lysed in 1× radioimmunoprecipitation assay (RIPA) buffer supplemented with protease inhibitors (RIPA-PI). HT1080 cells were washed with phosphate-buffered saline (PBS) prior to detachment using prewarmed EDTA (0.2 g/liter EDTA-Na2 in PBS; Invitrogen). Cells were pelleted by low-speed centrifugation, washed with PBS, and lysed with 1× RIPA-PI for 30 min at 4°C. Lysates were clarified by centrifugation at 15,000 × g for 30 min at 4°C. Analysis of cell lysates and concentrated supernatants was performed by Western blotting using anti-p24 hybridoma 183-H12-5C (obtained from Bruce Chesboro and Hardy Chen through the National Institutes of Health [NIH] AIDS Research and Reference Reagent Program) supernatants (1:1,000) and rabbit anti-tetherin antisera (1:2,000) (37).

**Immunofluorescence microscopy.** HT1080 cells were seeded on collagen-coated MatTek dishes at a density of 1.2 × 105 cells per dish. HT1080 cells were transfected with an 8:1 ratio of pNLenvΔU to either pEGFP-tetherin or pEGFP-C3A-tetherin. HeLa cells were transfected overnight with 500 ng pNLenvΔU. Cells were washed with PBS and subsequently fixed in 4% paraformaldehyde (Electron Microscopy Sciences, Hatfield, PA) for 10 min at room temperature. Following fixation, cells were extensively washed with PBS and permeabilized for 10 min with 0.2% Triton X-100. Cells were blocked for 30 min with Dako protein block (Dako, Carpenteria, CA) followed by primary and secondary antibody staining at the appropriate concentrations in Dako antibody diluent. Cells were stained with primary antibody for 1.5 h, followed by secondary
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antibody for 1 h at room temperature. Finally, 4′,6-diamidino-2-phenylindole (DAPI) was used to stain chromatin of labeled cell samples. Immunofluorescence microscopy (IFM) was performed using the DeltaVision imaging station (Applied Precision/GE Healthcare, Marlborough, MA).

**Correlative light electron microscopy (CLEM).** Transfected HT1080 cells grown on gold London Finder Quantifoil R2/2 TEM grids maintained in uncoated MatTek dishes were imaged in real time with a DeltaVision imaging station equipped with a 20× objective lens (Olympus). Images were analyzed with Velocity 6.3 (PerkinElmer, Waltham, MA) software. After acquiring transmitted and fluorescence images (15 to 30 min), the TEM grids were cryo-immobilized. The letters and numbers of the London Finder grid were used to track areas of the grid imaged by light microscopy and then by cryo-EM/ET. Fluorescence light micrographs (mCherry-Gag) were superimposed on selected regions of the cryo-EM montages (100× nominal magnification) after scanning and rotating images in Adobe Photoshop CS6.

**Immuo-TEM.** Live cells grown on gold TEM grids were immunolabeled with rabbit anti-tetherin antiserum (37) and 6-nm colloidal gold conjugated to goat anti-human IgG or protein G (Aurion) as described by previously (35).

**Cryo-ET.** Whole cells were cryo-immobilized by rapid immersion in liquid ethane using a Cryoplunge 3 system (Gatan, Pleasanton, CA). TEM grids were gently dipped in warm PBS, and a 4-μl aliquot of bovine serum albumin (BSA) conjugated to 10- or 20-nm gold nanoparticles (Sigma-Aldrich, St. Louis, MO) was applied to the surface of the TEM grid for 30 min. The grids were cryo-immobilized by rapid immersion in liquid ethane using a Cryoplunge 3 system (Gatan, Pleasanton, CA). TEM grids were gently dipped in warm PBS, and a 4-μl aliquot of bovine serum albumin (BSA) conjugated to 10- or 20-nm gold nanoparticles (Sigma-Aldrich, St. Louis, MO) was applied to the surface of the TEM grid for 30 min. The grids were cryo-immobilized by rapid immersion in liquid ethane using a Cryoplunge 3 system (Gatan, Pleasanton, CA). TEM grids were gently dipped in warm PBS, and a 4-μl aliquot of bovine serum albumin (BSA) conjugated to 10- or 20-nm gold nanoparticles (Sigma-Aldrich, St. Louis, MO) was applied to the surface of the TEM grid for 30 min. The TEM grids were cryo-immobilized. The letters and numbers of the London Finder grid were used to track areas of the grid imaged by light microscopy and then by cryo-EM/ET. Fluorescence light micrographs (mCherry-Gag) were superimposed on selected regions of the cryo-EM montages (100× nominal magnification) after scanning and rotating images in Adobe Photoshop CS6.

**RESULTS**

**CLEM and cryo-ET of HIV-1 VLPs tethered to human cells.** For this study, we set out to characterize the ultrastructure of HIV-1 virions tethered to human cells by cryo-ET. HT1080 cells were used as a model system to study the structural basis of tetherin-mediated restriction, as these cells contain long extensions, such as lamella, lamellipodia, and microspikes, that are sufficiently thin for cryo-ET (50). Furthermore, this cell line can produce HIV-1 and does not constitutively express tetherin. Several groups have utilized this cell line to study the molecular basis of tetherin-mediated restriction of HIV-1 (1, 23, 51, 52). Viral release assays confirmed transfection with pEGFP-tetherin inhibited the release of HIV-1 in a concentration-dependent manner (see Fig. S2A in the supplemental material). Transfection with pEGFP-C3A-tetherin, a previously characterized tetherin mutant that does not form the disulfide bonds between monomers that contribute to dimer stability (26, 53), failed to prevent HIV-1 release (see Fig. S2A). The examination of transfected HT1080 cells by IFM revealed puncta of EGFP-tetherin, EGFP-C3A-tetherin, and the HIV-1 Gag capsid protein p24 on the plasma membrane, including thin cellular protrusions (see Fig. S2B). HeLa cells transfected with pNLenvΔU exhibited the enrichment of HIV-1 p24 and tetherin in plasma membrane puncta consistent with the presence of tethered virion clustering (see Fig. S2B). Relative cellular tetherin expression levels of pEGFP-tetherin-transfected HT1080 cells were 2.4 times greater than endogenous tetherin expression in HeLa cells (see Fig. S2C). HT1080 cells transfected with pEGFP-tetherin exhibited a 2.6-fold increase in tetherin cell surface levels compared to endogenous tetherin expression in HeLa cells (see Fig. S2C).

Fluorescently labeled HIV-1 VLPs tethered to human cells were imaged by CLEM. Briefly, cells were grown on collagen-coated gold London Finder TEM grids, imaged in real time, and then cryo-immobilized by rapid immersion in liquid ethane. Cotransfected cells bore puncta of mCherry-Gag and EGFP-tetherin along thin cellular extensions (Fig. 1A and B). Areas of the TEM grid imaged by live-cell microscopy then were imaged by cryo-EM, making use of the finder grid letters to collect montages for identifying large clusters of HIV-1 VLPs attached to the cells (Fig. 1C and D). Clusters of VLPs were imaged by cryo-ET, thus providing nanometer-scale resolution in 3D (Fig. 1E and F; also see Movie S1 in the supplemental material). Spherical VLPs ranging from 81 to 173 nm in diameter contained ordered immature Gag lattice, with the gross morphology being similar to that of previous reports (54). As reported in previous cryo-ET studies (55, 56), we observed sheets of Gag polyprotein below the plasma membrane in F-actin-rich cell extensions, indicating that assembly, budding, and retention to the plasma membrane occurred along the thin cellular extensions (Fig. 2C and D; also see Movie S1). Upon close inspection of tomographic slices, rod-like densities, which are referred to as tethers, were seen connecting HIV-1 VLPs to each other and to the cell plasma membrane. Tethers connecting HIV-1 VLPs to each other and to the plasma membrane were observed consistently in cryo-specimens prepared and imaged on separate dates (Fig. 2A to H).
Cryo-ET of HIV-1 tethered to human cells. HT1080 cells cotransfected with pEGFP-tetherin and pNLenv1ΔU (deficient in env and vpu) were examined by cryo-ET (Fig. 3A to D; also see Movie S2 in the supplemental material). As with VLPs, HIV-1 virions attached to thin cellular extensions were observed. Regions of Gag polyprotein situated below the plasma membrane, which have been reported in previous cryo-ET studies (55, 56), were visualized at the point of tethering (Fig. 3C, white triangle). This suggests that assembly, budding, and tethering of HIV-1 to the plasma membrane occur at the same location. Spherical virions with diameters ranging from 64 to 150 nm were observed, with gross morphology similar to that seen in previous reports (57, 58). Although most particles visualized were mature, immature virions and some with the irregular cores of maturation intermediates also were apparent (56, 59–63).

Tethers connecting HIV-1 virions to each other and to the plasma membrane were seen in cryosamples (Fig. 2I to P and 3; also see Movie S2 in the supplemental material). These tethers were similar to those identified on HIV-1 VLPs. Cells transfected with pEGFP-C3A-tetherin and pNLenv1ΔU did not have large clusters of HIV-1 (Fig. 3E to G). Released virions also were imaged by cryo-ET, revealing densities on the viral membranes but generally lacking visible tethers between viral particles (Fig. 3E to G; also see Movie S3). In contrast, the majority of virions produced by cells transfected with HIV-1 pEGFP-tetherin and pNLenv1ΔU were connected, by a tether, to either a viral or cellular membrane.

To visualize endogenous tethers we used HeLa cells, which constitutively express tetherin (1). HeLa cells were transfected with pNLenv1ΔU and imaged by cryo-ET. HIV-1 virions connected to one another and to the plasma membrane by filamentous tethers were observed (Fig. 2Q to X and 4). The endogenous tethers observed in tomograms of HeLa cells resembled the tethers seen in tomograms of HT1080 cells transfected with pEGFP-tetherin. The length of the endogenous tethers was identical to that of recombinant tethers (Table 1). Extended layers of the Gag polyprotein were situated underneath the plasma membrane, and budding HIV-1 particles were observed near sites of HIV-1 restriction (Fig. 2S and 4B). As best illustrated in segmented tomograms, HIV-1 virions connected to the cell and to other virions by endogenous tethers were ar-
ranged in a linear fashion, which resemble beads on a string (see Fig. 6C).

We utilized native immunogold labeling to confirm the localization of tetherin molecules on transfected cells and on virions (43). This method involves labeling live cells with antibodies prior to cryo-immobilization or chemical fixation, which preserved the integrity of the epitope of interest and the arrangement of macromolecules on the surface of cells and viruses (64). For these experiments we utilized a previously characterized antitetherin antiserum generated against tetherin’s extracellular coiled-coil ectodomain (corresponding to amino acids 43 to 179) (37). Cryo-ET of native immunogold-labeled spec-
imens showed tetherin located on HIV-1 VLPs, HIV-1 virions, and the plasma membrane (Fig. 5). Tetherin staining was not uniformly distributed over the cell but was very punctate, as seen by fluorescence microscopy (see Fig. S2B in the supplemental material). Patches of immunogold were visualized on thin cellular extensions devoid of HIV-1 virions (Fig. 5G and H). Bundles of F-actin were oriented parallel to the plasma membrane near patches of immunolabeled tetherin (Fig. 5). Immunogold labeling also was seen on vesicles tethered to HIV-1 VLPs and virions (data not shown). These results confirm the presence of tetherin on HIV-1 VLPs, virions, and transfected cells. Previous immunolabeling studies of chemically fixed, embedded, or cryosectioned material have reported similar distributions of tetherin on transfected or HIV-1-infected cells (23, 32, 37, 38).

Spatial distribution of tethers on mature and immature HIV-1 virions. To gain insight into the biophysical basis of tetherin-mediated restriction of HIV, we characterized the spatial distribution of tethers on HIV-1. Tomograms of HIV-1 tethered to thin cellular extensions were manually segmented with the Amira software package (49). In the analysis, mature virions (106 virions) possessed 1 to 8 tethers, with an average of 2 tethers per virion. The position of the tether relative to the conical core’s 2-fold axis of symmetry varied from virion to virion and from tether to tether (Fig. 6). When present as multiple copies, tethers...

FIG 3 Tetherin homodimers are required for formation of filamentous tethers. (A to D) HT1080 cells cotransfected with pNLenvΔU and pEGFP-tetherin possess HIV-1 virions connected to the cell by filamentous tethers. (A and B) Cryo-EM montage of HIV-1 virions attached to a long cellular extension emanating from the cell (as indicated by the term “Cell” and by the white dashed line). The dashed black boxes in panels A and B indicate the positions at which the tilt series were collected. (C) Tomographic slice (7.64 nm) of HIV-1 virions tethered to a thin cellular extension. HIV-1 budding from the cell was observed, as indicated by a white triangle pointing to the Gag polyprotein situated underneath the plasma membrane. (D) Enlargement of the tomographic slice, corresponding to the black dashed box in panel C. Tethers are seen connecting HIV-1 virions to each other and to the plasma membrane (as indicated by the black triangle). (E to G) Released HIV-1 virions produced from HT1080 cells cotransfected with pEGFP-C3A-tetherin and pNLenvΔU were imaged by cryo-ET. (E and F) Cryo-EM montage of an HT1080 cell, as indicated by the term “Cell” and by the dashed white line drawn around the periphery of the cell, and released HIV-1. Dashed black boxes are positioned over the areas where the tilt series were collected. (G) Tomographic slice (7.64 nm) of released HIV-1 virions. Filamentous rods were rarely seen between these HIV-1 virions. Immature and mature HIV-1 virions as well as maturation intermediates were observed. Scale bars are 2 μm (A and E), 1 μm (B), 500 nm (F), 100 nm (C and G), and 50 nm (D).
were not uniformly distributed over the viral membrane but rather formed clusters at sites of contact between other HIV-1 virions or the cell plasma membrane (Fig. 6).

The distribution of tethers attached to 43 immature HIV-1 virions was characterized in segmented tomograms. Tethers were seen making contact with the viral membrane adjacent to the Gag polyprotein or in areas that were devoid of Gag (Fig. 7). The number of tethers adjacent to Gag (54%) was close to that of the tethers not adjacent to Gag (46%) (Table 2). The results of this analysis indicate EGFP tethers are present on the immature viral membrane without respect to the Gag polyprotein or to areas of the viral membrane lacking an underlying Gag polyprotein.

Distance measurements of tethers cross-linking HIV-1 virions to each other and to the cell. To determine whether tetherin restricts HIV-1 release by adopting the extended conformation, the length of segmented tethers (recombinant tethers [15.3 ± 5.93 nm] or endogenous tethers [15.6 ± 4.78 nm]) and distance between tethered virions was measured (Table 1 and Fig. 8). The average distance between HIV-1 virions tethered to an HT1080 cell was 19.9 ± 6.82 nm, which was slightly greater than the distance between two tethered virions, 17.1 ± 6.50 nm. The average length of the segmented tethers and distance between membranes is close to the length of the mammalian ectodomain homodimer (27–30), which is predicted for the extended tetherin model (see Fig. S1 in the supplemental material). The histogram analysis showed a range of distances between HIV-1 tethered to cells of 7 to 35 nm and a range of 6 to 37 nm for virus-to-virus tethers (Fig. 8A and B). We did not observe tethers greater than 37 nm in length, as seen in selected images of chemically fixed samples imaged by conventional TEM (32, 36, 37). The distance between tethered virions was the same for mature (17.8 ± 7.24 nm) and immature virions (17.9 ± 6.31 nm), which suggests that HIV-1 maturation does not influence the length of the tether.

Spatial arrangement of HIV-1 virions tethered to the cell and to other virions. Clusters of HIV-1 VLPs and virions attached to the cell have been imaged by conventional TEM (1, 9, 23, 32, 36–38) and SEM (2, 23, 39). However, it is not clear how HIV-1 virions are attached to each other or how the virions are arranged.

### Table 1: Distance between tethered membranes

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<th>Target of measurement</th>
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<tr>
<td></td>
<td>Mean</td>
</tr>
<tr>
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<td></td>
</tr>
<tr>
<td>Segmented tethers</td>
<td>15.3</td>
</tr>
<tr>
<td>Segmented membranes</td>
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</tr>
<tr>
<td>HIV-cell</td>
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<tr>
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<tr>
<td>Mature-cell</td>
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<tr>
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<td>17.9</td>
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<tr>
<td>HeLa cells</td>
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<td>Segmented tethers</td>
<td>15.6</td>
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<tr>
<td>Segmented membranes</td>
<td>18.6</td>
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*For the length of segmented tethers, only the segmented tethers were measured.

*Distance between tethered virions. Measurements were made along the segmented tethers between the viral or cellular membranes.
FIG 5 Cryo-ET of native immunolabeled tetherin associated with HIV-1 VLPs and HIV-1 virions. Protein G conjugated to 6-nm colloidal gold distributed along the plasma membrane, on tethered HIV-1 VLPs, and on HIV-1 virions. (A) Tomographic slices (7.64 nm) of immunolabeled HT1080 cells transfected with plasmids encoding mCherry Gag (1:3 ratio of mCherry Gag and codon-optimized Gag) and pEGFP-tetherin. (B) Enlarged image of the dashed white box in panel A, which was magnified by a factor of 3. Shown is immunogold staining of tethered HIV-1 VLPs attached to the cell, as indicated by black triangles, and between other HIV-1 VLPs, as indicated by white triangles. (C) Enlarged image of the dashed black box in panel A, which was magnified by a factor of 3. (D) Tomographic slice (7.37 nm) of HIV-1 virions attached to the plasma membrane of an HT1080 cell (transfected with pNLenv/ΔU and pEGFP-tetherin). Black triangles point to immunogold staining. (E) Enlarged image of the dashed white box in panel D (magnified by a factor of 3). (F) Enlarged image of the dashed black box in panel D, which was magnified by a factor of 3. (G) Tomographic slice (7.64 nm) of a thin cellular extension devoid of HIV-1 virions but containing tetherin, as indicated by black double triangles. (H) Enlargement of area in panel G, which was magnified by a factor of 2. Scale bars are 100 nm (A, D, and G) and 50 nm (B, C, E, F, and H).
We sought to better understand how tethered virions were organized in relation to the cell and to other virions. For segmented tomograms, groups of tethered virions were classified according to the number of virions tethered together and the number of connections between virions (Fig. 9 and Table 3; also see Table S3 in the supplemental material). Tethered HIV-1 virions possessed between 1 and 3 nodes, or connections, consisting of at least one tether. Based on our analysis, we concluded that tethered HIV-1 virions most frequently are arranged in a linear fashion. Tethered HIV-1 virions were observed primarily as single chains (77%) and less often as branched chains (23%). This suggests that the formation of branch points is relatively rare and implies that particles bud repeatedly from a tetherin-enriched plasma membrane site in a generally linear fashion.

DISCUSSION

The discovery of tetherin as the Vpu-responsive host restriction factor that retains particles on the plasma membrane of cells was made in 2008 by the Bieniasz group (1). Since that time, a number of important aspects of how tetherin functions have been elucidated. Tetherin functions as a proteinaceous link between the plasma membrane and virions, as revealed by biochemical and electron microscopic analysis (23, 37). The ectodomain of tetherin forms a coiled-coil dimer, and dimerization is essential to tetherin’s function in restriction (26–29). Tetherin does not interact with viral proteins in attaching particles to cells and to each other but rather inserts into the lipid envelope of virions. This property somehow is facilitated by the ability of tetherin to compartmentalize to very punctate microdomains where HIV virions bud (51, 65). Intricate biochemical and genetic studies have established that the most likely orientation of the tetherin dimer is oriented in an axial or extended configuration in which either the transmembrane domains or GPI anchors insert into the viral membrane, with some preference for the GPI ends of the dimers to be within the viral membrane versus the cell membrane (23,
Biophysical studies indicate the purified coiled-coil tetherin ectodomain dimer exists as an L-shaped rod of 15 to 18 nm in length and exhibits flexibility in solution (27). In this study, we provide ultrastructural confirmation of this size prediction as well as additional insights into tetherin’s mechanism of restriction of HIV-1 using cryo-ET.

Previous EM studies of HIV-1 tethered to human cells have relied mainly on imaging chemically fixed, embedded, sectioned, and stained tissue (1, 9, 32, 37, 38, 66). Our group has used immuno-EM techniques to definitively show that tetherin is present between the plasma membrane and tethered particles, as well as within the virus-containing compartment (VCC) of human macrophages (36, 37). We observed some electron-dense structures that could be consistent with tetherin in these studies, including some very extended filamentous connections that would be inconsistent with the length of tetherin dimers. Although useful, standard TEM techniques could not provide high-resolution or 3D information of the tethers restricting HIV-1 release, and we considered that the very long apparent tethers could have been a shrinkage/processing artifact. Cryo-ET offers several advantages over conventional imaging methods, mainly the acquisition of high-resolution 3D spatial information of unstained frozen-hydrated biological specimens (67, 68). Cryo-immobilization by rapid immersion into liquid ethane preserves the ultrastructure of thin eukaryotic cellular appendages and isolated viruses (69–72). This was best illustrated by the application of whole-cell cryo-ET to study HIV-1 assembly events as well as maturation (55, 56, 59).

In this study, the use of whole-cell cryo-ET permitted the direct visualization of tethers composed of tetherin connecting HIV-1 VLPs and virions to each other and to the cell, which would not have been resolvable by light microscopy or conventional EM.

We observed that HIV-1 VLPs and HIV-1 virions were connected to each other and to the plasma membrane by rod-like bodies, referred to as tethers. The tethers were present only on cells transfected with tetherin. As expected, these tethers were rarely seen on released HIV-1 virions produced from cells transfected with C3A-tetherin, a tetherin mutant that does not restrict HIV-1

<table>
<thead>
<tr>
<th>Class</th>
<th>Virions</th>
<th>Tethers</th>
<th>Adjacent</th>
<th>Nonadjacent</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cell-immature</td>
<td>11</td>
<td>19</td>
<td>8</td>
<td>11</td>
</tr>
<tr>
<td>Immature-immature</td>
<td>11</td>
<td>28</td>
<td>16</td>
<td>12</td>
</tr>
<tr>
<td>Immature-mature</td>
<td>26</td>
<td>59</td>
<td>32</td>
<td>26</td>
</tr>
<tr>
<td>Total</td>
<td>48</td>
<td>106</td>
<td>57</td>
<td>49</td>
</tr>
</tbody>
</table>
Immunogold staining was performed in parallel experiments, providing corroborative evidence that the filamentous structures imaged by cryo-ET indeed contain tetherin molecules. This represents the first definitive and high-resolution visualization of the proteinaceous tethers between cells and virions and provided us, for the first time, with 3D data suitable for further analysis.

We observed a range of 1 to 8 filamentous tethers bound to each HIV-1 virion, with an average of 2 tethers per particle. The number of filamentous tethers visualized by cryo-ET is on the
same order of magnitude as the number (on average, 4 to 7) of tetherin homodimers on HIV assembly sites as estimated by superresolution light microscopy (33) but is one order of magnitude less than that estimated by quantitative Western blot analysis (34).

One possibility is that the filamentous tethers observed by cryo-ET consist of multiple closely associated tetherin homodimers. Biophysical and structural studies have shown that the isolated tetherin ectodomain can oligomerize in solution and can form a tetramer consisting of two antiparallel homodimers (28, 30). However, distance measurements of cryo-ET data suggest that the extended tetherin homodimer (and not the tetramer) is responsible for restricting HIV release. In addition, tethers were not evenly distributed over the viral membrane but formed discrete clusters at contact points between membranes. This agrees with observations made by superresolution light microscopy that 80% of the tetherin-positive HIV budding sites on transfected HeLa cells contained a single cluster of mEosFP-tetherin (33).

The arrangement of tethers, relative to the position of the Gag polyprotein in immature HIV-1, was characterized in segmented

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**TABLE 3** Arrangement of tethered HIV-1

<table>
<thead>
<tr>
<th>Class</th>
<th>n</th>
<th>%</th>
</tr>
</thead>
<tbody>
<tr>
<td>Single chain</td>
<td>20</td>
<td>77</td>
</tr>
<tr>
<td>Cell-HIV</td>
<td>8</td>
<td>30</td>
</tr>
<tr>
<td>HIV-HIV</td>
<td>12</td>
<td>46</td>
</tr>
<tr>
<td>Branched chain</td>
<td>6</td>
<td>23</td>
</tr>
<tr>
<td>Cell-HIV</td>
<td>3</td>
<td>12</td>
</tr>
<tr>
<td>HIV-HIV</td>
<td>3</td>
<td>12</td>
</tr>
</tbody>
</table>
tomographic reconstructions. When interpreting the results of this analysis, one can consider the possibility that the EGFP tag could disrupt the Gag lattice or putative protein-protein interaction between tetherin and the Gag protein. In addition, Venkatash and Bieniasz have shown that the GPI anchor of tetherin is inserted preferably (by a factor of 3 to 5) into the viral membrane (34). However, cryo-ET results from the HeLa cells that express endogenous levels of tetherin indicate that the EGFP tag does not disrupt putative protein-protein interactions or ordering of the Gag lattice. We also reasoned that if the tetherin CT tail was interacting strongly with the Gag polyprotein or being excluded by steric hindrance, one would expect that the ratio of adjacent to nonadjacent tethers for HIV-1 tethered to the cell would be different from that of HIV-1 tethered to other virions. This was not the case, as the ratio of adjacent to nonadjacent tethers was similar for the different classes of immature HIV-1, namely, 21:29 for immature HIV-1 tethered to the plasma membrane, 57:43 for immature HIV-1 tethered to immature HIV, and 27:23 for immature HIV-1 tethered to mature HIV-1.

When present in linear chains, the tethers often were present on opposite poles of the viral envelope, suggesting that virion budding had occurred sequentially through a single tetherin-enriched microdomain. The orientation of the tethers relative to the mature conical core (narrow or broad end), on the other hand, was random. Tethers present on immature HIV-1 virions were situated on the viral membrane at areas both adjacent and nonadjacent to the underlying Gag polyprotein, again suggesting that the distribution of tethers on the viral envelope relative to Gag is random. Based on our results, it is likely that tetherin remains attached to the viral membrane without any direct interaction with the immature Gag lattice, remains so during the remodeling of the core that accompanies viral maturation, and has no influence on the resulting orientation of the conical core in the mature virion.

An important aspect of this study is the confirmation of the extended ectodomain dimer model obtained through biochemical and genetic studies (23, 33, 34). The average length of segmented tethers in our study was 15.3 nm, and the distance between tethered HIV-1 virions was slightly longer at 17.9 nm. We observed a range of distances between 7 and 37 nm separating tethered virions from each other and from the cell plasma membrane. One explanation for the presence of shorter tethers is the conformational flexibility of the tetherin molecule. Bending of the coiled-coil ectodomain is thought to enable the tetherin homodimer to remain attached to the HIV-1 virions during assembly and budding (29). However, flexibility of the tetherin coiled-coil ectodomain alone does not explain the presence of the occasional tethers observed that were greater than 18 nm in length. A possible explanation for the longer tethers is that they include a deformation or extension of the lipid bilayer of the virion or plasma membrane in addition to the proteinaceous tether. Altogether, however, these data strongly support the established model of an extended, parallel homodimer of tetherin as the basic unit forming the connections between viral and cellular membranes and between tethered virions in chains.

Another intriguing aspect of tetherin biology that is highlighted by the current study is the extended linear conformation of chains of virions created by tetherin. We were able to characterize these chains in more detail than was previously possible by generating 3D volumes of particle chains by cryo-ET. We found that approximately three-quarters of the chains were unbranched. The unbranched chain predominance and the polar appearance of tethers support a model of budding and restriction in which particles repeatedly bud from a common plasma membrane microdomain in the presence of a concentration of tetherin dimers, producing a beads-on-a-string, linear appearance. Occasionally a branch point in the chain is observed, which must be formed by two adjacent budding virions separately tethered to a particle that has completed the budding process, as depicted in Fig. 9A (also see Fig. S3 in the supplemental material). Based on the number of branched chains observed, we propose that the probability of tethers being incorporated into multiple assembly sites is a relatively uncommon event.

A somewhat unexpected finding was the appearance of multiple separate tethers in some images, such as those depicted in Fig. 6. Although most commonly there were only 1 to 2 tethers observed (Fig. 2), we documented in some cases 4 or more distinct tethers. This suggests that in most cases the tetherin dimers coalesce around 1 to 2 physical connections but can occasionally form multiple distinct proteinaceous links between membranes.

In summary, the current study defined the 3D ultrastructure of HIV-1 tethered to human cells through the use of cryo-ET, native immunolabeling, and CLEM. The ability of tetherin to surround and capture budding HIV-1 virions implies that tetherin dimers undergo dramatic conformational changes during assembly and budding prior to the formation of the final rod-like tether. Future cryo-ET studies may allow individual conformational intermediates of tetherin to be better defined to provide a more complete picture of the restriction of particle release at this unique late stage of the viral life cycle.

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