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Accessibility
Preferential Budding of Vesicular Stomatitis Virus from the Basolateral Surface of Polarized Epithelial Cells Is Not Solely Directed by Matrix Protein or Glycoprotein

Eugene Drokhlyansky, a Timothy K. Soh, b Constance L. Cepko a

Department of Genetics and Department of Ophthalmology, Harvard Medical School, Howard Hughes Medical Institute, Boston, Massachusetts, USA a; Department of Microbiology and Immunobiology, Program in Virology, Harvard Medical School, Boston, Massachusetts, USA b

Vesicular stomatitis virus has been shown to bud basolaterally, and the matrix protein, but not glycoprotein, was proposed to mediate this asymmetry. Using polarized T84 monolayers, we demonstrate that no single viral protein is sufficient for polarized budding. Particles are released from the apical and basolateral surfaces and are indistinguishable, indicating that there is no apical assembly defect. We propose that aspects of host cell polarity create a more efficient budding process at the basolateral surface.

Many viruses have distinct entry and budding sites in polarized epithelial cells (1–3). Vesicular stomatitis virus (VSV) is the prototypic nonsegmented negative-strand RNA virus and buds preferentially from the basolateral surface of polarized epithelial cells. This budding preference correlates with the basolateral localization of its glycoprotein (G) (4). However, mislocalization of G did not change this phenotype, and thus it was proposed that the matrix protein (M) dictates preferential VSV budding (5). In this study, we demonstrate that neither G nor M alone can account for this bias.

Recombinant VSV (rVSV) was tested for infection and budding preference from the polarized human epithelial T84 cell line. T84 monolayers were infected after polarization on collagen-coated Transwell supports, with polarity demonstrated by a trans-epithelial resistance (TER) of $\geq 1,000$ Ω and confirmed by proper localization of the apical tight-junction marker ZO-1 (6), Golgi compartment marker GP130 (7, 8), and the nucleus (7) (Fig. 1A). rVSV infected the basolateral surface $62 \pm 14$ ($n = 4$) times more efficiently than the apical surface. Postinfection, rVSV was found to bud preferentially from the basolateral surface (Fig. 1B). Infectious virus appeared initially in the basolateral compartment but was later detected in the apical chamber, with cells maintaining a tight monolayer. Both infection and budding preferences are similar to previous observations with MDCK cells (9). Monolayer integrity was monitored by TER and small-molecule diffusion using medium with or without phenol red in complementary culture compartments. Cells maintained high TER and limited small-molecule diffusion through $12$ h postinfection (hpi). Subsequently, TER gradually dropped, reaching $150$ Ω at $22$ hpi and loss of TER at $24$ hpi, when phenol red diffusion was observed (data not shown). Immunocytochemistry analysis with previously characterized antibodies was used to identify the subcellular localization of VSV proteins (10, 11) (Fig. 1C). The nucleocapsid protein (N), phosphoprotein (P), and large polymerase protein (L) have been reported to localize to inclusion bodies throughout the cytoplasm (12). Likewise, we observed N and P in a nonpolarized distribution (Fig. 1C), demonstrating that replication and transcription were not polarized. Similarly, M was found to be cytosolic and membrane bound throughout the apical and basolateral compartments, indicating its nonpolarized distribution. This observation contrasts with previous findings in which M was basolaterally localized in MDCK cells (13). While this localization may not be universally true, it demonstrates that polarized M localization is dispensable for polarized budding. In contrast, G was predominantly basolateral (Fig. 1C), as previously shown (4, 14).

Since G was the only polarized VSV protein, we tested whether its absence might alter VSV budding. We used an rVSV with the G coding sequence deleted and enhanced green fluorescent protein (eGFP) in the first position (rVSV eGFP ΔG). This virus was grown in BSR T7/5 cells with G supplied by transfection (Fig. 2A). To assay budding in T84 monolayers, newly synthesized rVSV eGFP ΔG virions from the apical and basolateral chambers were radiolabeled (Fig. 2B) and analyzed via low-bis SDS-PAGE and autoradiography (Fig. 2C) with the N protein band quantified by ImageQuant TL v7 (GE Healthcare, Piscataway, NJ). This assay revealed that rVSV and rVSV eGFP ΔG preferentially bud basolaterally. To determine if this bias was due to the relative basolateral and apical surface areas, these were measured with ultrathin-section transmission electron microscopy (TEM) of cells (15) and ImageJ (U.S. National Institutes of Health, Bethesda, MD; http://rsb.info.nih.gov/ij/). The basolateral-to-apical area ratio was $3.1 \pm 0.2$ ($n = 31$) and cannot account for the differential budding seen with both viruses (Fig. 2C). We confirmed that G deletion...
does not alter the localization of other viral proteins (Fig. 2D). These data demonstrate that G does not dictate the preferential site of virus production (5).

We tested whether preferential budding was due to an inability of VSV to assemble and bud from the apical surface. Titration of supernatant from the apical surface revealed infectious virions (Fig. 1B). Particles released from both surfaces were indistinguishable by negative-stain TEM (Fig. 3A). To examine budding at the plasma membrane, we limited particle release by using a clone harboring mutations in the M late domains (rVSV M LD^−), i.e., PPy and PSAP mutated to AAPA and AAAA, respectively (16, 17). Ultrathin-section TEM of cells infected with rVSV M LD^− revealed bullet-shaped virions on both surfaces (Fig. 3A).

We next examined the composition of particles from both cell surfaces. Although glycosylation has been shown not to determine the segregation of G (18), it is possible that G glycosylation differs in virions released from the two surfaces. Peptide-N-glycosidase F (PNGase) treatment of particles from the apical and basolateral compartments showed similar glycosylations (Fig. 3B). Using N as a measure of particles, the average amounts of G and M per par-
particle were not found to differ significantly (Fig. 3C) and the relative numbers of basolateral and apical particles per PFU were not significantly different (2.3-fold ± 1.1-fold; P > 0.05 [Student’s t test]; n = 5).

The factors that trigger VSV assembly and budding are not known. Virions can be produced without G, demonstrating that G is dispensable for assembly (19). However, sequences in G increase budding efficiency (20, 21), and viral ribonucleoprotein (vRNP) localization to G microdomains has been proposed to initiate assembly (22). In addition, the trigger for condensation of the open vRNP into the nucleocapsid-M protein complex is unknown. We show that budding is polarized in the presence or absence of G and that the localization of other VSV proteins cannot account for this phenotype. Additionally, we demonstrate
functional VSV assembly at the apical surface, which does not generate defective particles. We hypothesize that the preferential budding is due to an increase in the efficiency of initiation or completion of assembly at the basolateral surface. A cellular protein(s) required for efficient condensation could be localized basolaterally, or a structural feature, such as tension, of the basolateral region could be more permissive to assembly. The requirements for clathrin-mediated endocytosis differ at the apical and basolateral surfaces in polarized epithelial cells because of tension differences (23). It is possible that generation of the high membrane curvature in VSV particles requires a low-tension environment.

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