Vesicular Stomatitis Virus Oncolysis of T Lymphocytes Requires Cell Cycle Entry and Translation Initiation

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Vesicular stomatitis virus (VSV) is a candidate oncolytic virus that replicates and induces cell death in cancer cells while sparing normal cells. Although defects in the interferon antiviral response facilitate VSV oncolysis, other host factors, including translational and growth regulatory mechanisms, also appear to influence oncolytic virus activity. We previously demonstrated that VSV infection induces apoptosis in proliferating CD4+ T lymphocytes from adult T-cell leukemia samples but not in resting T lymphocytes or primary chronic lymphocytic leukemia cells that remain arrested in G0. Activation of primary CD4+ T lymphocytes with anti-CD3/CD28 is sufficient to induce VSV replication and cell death in a manner dependent on activation of the MEK1/2, c-Jun NH2-terminal kinase, or phosphatidylinositol 3-kinase pathway but not p38. VSV replication is specifically impaired by the cell cycle inhibitor olomoucine or rapamycin, which induces early G1 arrest, but not by aphidicolin or Taxol, which blocks at the G1/S or G2/M phase, respectively; this result suggests a requirement for cell cycle entry for efficient VSV replication. The relationship between increased protein translation following G0/G1 transition and VSV permissiveness is highlighted by the absence of mTOR and/or eIF4E phosphorylation whenever VSV replication is impaired. Furthermore, VSV protein production in activated T cells is diminished by small interfering RNA-mediated eIF4E knockdown. These results demonstrate that VSV replication in primary T lymphocytes relies on cell cycle transition from the G0 phase to the G1 phase, which is characterized by a sharp increase in ribogenesis and protein synthesis.

Oncolytic viruses constitute a promising novel therapeutic approach for cancer (reviewed in references 9, 10, and 47). Vesicular stomatitis virus (VSV), an RNA virus belonging to the Rhabdoviridae family, possesses intrinsic oncolytic properties that permit cancer cell destruction while sparing normal cells (8, 53). VSV is exquisitely sensitive to the antiviral effects of the interferon (IFN) pathway and therefore fails to replicate efficiently in primary cells that contain a functional IFN system (6, 73, 74). However, VSV replicates to high titers in trans- 

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levels of the p27kip1 protein are present in resting T cells, preventing G1- to S-phase transition by inhibiting the cyclin E/cdk2 complex (41). The activity of p27kip1 is regulated at two levels, acting in early G1 and in G1/S transition: p27kip1 is sequestered by CycD/cdk complexes, and free p27kip1 is degraded via the proteasome pathway by cyclin E/cdk2-dependent and -independent mechanisms that require MEK and PI3K activation (reviewed in references 20, 32, 50, and 62). Once free from p27kip1, newly synthesized cyclin E and cyclin A along with cdk2 orchestrate the G1/S-phase transition. The mitogen stimulated kinase Akt controls the stability of cyclin E as well as the subcellular localization of Cip/Kip proteins (46, 70). It is now evident that activation of the MAPK and PI3K cascades following TCR/CD28 stimulation regulates the cell cycle by acting at both the transcriptional and posttranslational levels on cdk inhibitory protein and cyclin molecules (2, 14).

Cell cycle progression is tightly linked to protein synthesis and ribogenesis, since optimal cell size is required to enter and successfully complete the cell division process. Mammalian target of rapamycin (mTOR) is a central coordinator of protein synthesis and cell cycle progression (34, 61), although the mechanisms by which mTOR mediates these events are not fully understood. It has been proposed that mTOR controls protein translation through two distinct mechanisms that in turn are crucial for cell cycle progression (28, 29). One branch is regulated by phosphorylation of eIF4E binding protein by mTOR, leading to its dissociation from eIF4E (37, 63). Free eIF4E can then be phosphorylated by MAPK-interacting protein 1 (Mnk1), resulting in the activation of eIF4E and enhanced ribosome recruitment to the translational start site. In T cells, extracellular signal-regulated kinase (ERK) is an upstream regulator of Mnk1 and therefore directly involved in the activation of eIF4E throughout the cell cycle. The second branch relies on phosphorylation of the ribosomal S6 kinase 6 (S6K1) by mTOR: translation initiation, elongation, and/or ribosome biogenesis is stimulated by as yet poorly defined mechanisms involving S6K1-mediated phosphorylation of the 40S ribosomal protein S6 and eIF3 (translation initiation factor 3) (3, 65). The relationship between protein translation and cell cycle control is highlighted by the fact that rapamycin, the activity of p27kip1 is regulated at two 

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were fixed in 4% formaldehyde and stained with crystal violet. Plaques were counted, and titers were calculated in PFU per milliliter.

siRNAs and primary human CD4+ T-lymphocyte transfection. Control and eIF4E-specific RNA interference sequences were described previously (75). Transfection of purified activated T cells was carried out by electroporation using the Nucleofector system (Amaxa, Koln, Germany), according to the protocols proposed by the furnisher. Briefly, CD4+ T cells were activated with an anti-CD3/28 monoclonal antibody combination for 48 h. T cells (10 × 10^6) were resuspended in 100 μl of T-cell Nucleofector solution (human T-cell Nucleofector kit) containing 300 pmol of double-stranded small interfering RNAs (siRNAs). After electroporation, 400 μl of prewarmed cultured medium was added to the cuvette and the cells were transferred into cultures plates containing prewarmed culture medium. At the optimal time of gene silencing (usually 48 h posttransfection), T cells were mock infected or infected with VSV at 1 MOI for 24 h.

Immunoblot analysis. Cells destined for immunoblotting were washed with PBS and lysed in lysis buffer (0.05% NP-40, 1% glycerol, 30 mM NaF, 40 mM β-glycerophosphate, 10 mM Na_2VO_4, 10 ng/ml of protease inhibitors cocktail [Sigma Aldrich, Oakville, Ontario, Canada]). The protein concentration was determined by using the Bradford assay (Bio-Rad). Whole-cell extracts (30 μg) were resolved by sodium dodecyl sulfate-polyacrylamide gel electrophoresis (SDS-PAGE) in a 10%-acrylamide gel and transferred to a nitrocellulose membrane (Hybond C Super; GE Healthcare Bio-Sciences Inc., Oakville, Ontario, Canada). Membranes were blocked in 5% nonfat dried milk in Tris-buffered saline (TBS) plus 0.1% Tween 20 for 1 h at room temperature. Membranes were then probed overnight with antibodies against VSV (1:5,000; a gift from John Bell, Ontario Cancer Institute) or human proteins—L, G, N, P, M—was detected at 24 h postinfection in T lymphocytes preincubated for 12 h with anti-CD3/CD28 (Fig. 1A). Apoptosis occurred concomitantly with viral replication as indicated by cleavage of caspase 3 (Fig. 1A). Quantification of virus titers by plaque assay revealed that T-cell activation led to a 4-log increase in the virus titer at 24 h postinfection, compared to that for resting T cells (Fig. 1B). To determine if VSV replication was directly proportional to the level of CD4+ T-cell activation, lymphocytes were stimulated with CD3/CD28 for 12, 24, or 48 h and subsequently infected with VSV for 12 or 24 h (Fig. 1C). VSV protein production was detected as early as 12 h postactivation and increased as the activation time was prolonged (Fig. 1C, lanes 4 to 9). In cells activated with CD3/CD28 for 48 h, VSV G protein levels were ~3.6-fold higher than those in cells activated for 12 h (Fig. 1C, compare lanes 5 and 9). In agreement with viral protein levels, cells activated for 48 h produced ~2-fold more virus than nonstimulated cells at 24 h (Fig. 1D). Furthermore, VSV replication in activated primary CD4+ T lymphocytes led to induction of apoptosis, as demonstrated by immunoblotting for cleaved caspase 3 (Fig. 1C, lanes 6 to 9).

Since VSV is exquisitely sensitive to IFN-mediated inhibition and therefore fails to replicate efficiently in primary cells that contain a functional IFN system, we tested the possibility that anti-CD3/CD28 treatment interfered with type I IFN (alpha/beta IFN) production. PCR analysis of type I IFN mRNA demonstrated that treatment of CD4+ T lymphocytes with anti-CD3/CD28 did not inhibit the IFN response, thus ruling out this possibility as a cause for the observed increase in viral replication (see Fig. S1 in the supplemental material). These results indicate that triggering the CD3/CD28 activation pathways is sufficient to render normal CD4+ T lymphocytes permissive to VSV replication, suggesting that downstream effectors of CD3/CD28 are critical for VSV replication and induction of apoptosis.

VSV requires ERK, JNK, and AKT but not p38 activation for replication in T lymphocytes. Since MAPK and PI3K signaling pathways are downstream of CD3/CD28, we postulated that activation of these pathways is required for VSV replication and oncolysis. CD4+ T-cell stimulation with CD3/CD28 antibodies resulted in enhanced ERK, JNK, Akt, and p38 phosphorylation as determined by immunoblotting with phospho-specific antibodies, while total protein levels remained unchanged (Fig. 2A, lanes 1 to 6, B, lanes 1 to 7, C, lanes 1 to 6, and D, lanes 1 to 5). To examine the essential signaling pathways downstream of CD3/CD28 required for VSV replication in T cells, small-molecule inhibitors specific for PI3K (LY294002), MEK1/2 (U0126), stress-activated protein kinase (SAPK)/JNK (SP600125), or p38 (SB203580) were used to block distinct pathways. The concentration for each of these inhibitors (20 μM, 10 μM, 20 μM, or 12 μM, respectively) was chosen based on values reported to be specific and sufficient to inhibit each kinase (2, 26, 55, 76). CD4+ T lymphocytes were pretreated for 1 h with each individual inhibitor, activated with the combination of anti-CD3/CD28 monoclonal antibodies for 12 h, and subsequently infected with VSV for 12 or 24 h. The effectiveness of the drug treatment was confirmed by the disappearance of phosphorylated substrates by immunoblotting (Fig. 2A to D). Thus, U0126 inhibited phosphorylation of ERK by MEK1/2 (Fig. 2A, compare lanes 1 to 6 to lanes 7 to 11),
SP600125 inhibited phosphorylation of JNK (Fig. 2B, compare lanes 1 to 7 to lanes 8 to 14), LY294002 inhibited phosphorylation of Akt by PI3K (Fig. 2C, compare lanes 1 to 6 to lanes 7 to 11), and SB203580 inhibited phosphorylation of p38 (Fig. 2D, compare lanes 1 to 5 to lanes 6 to 9). VSV replication was monitored by viral protein immunoblotting (Fig. 2E). Specific inhibition of the MEK1/2, JNK, or PI3K pathway impaired VSV replication, whereas VSV protein synthesis was not blocked by SB203580 at concentrations that effectively inhibited p38 phosphorylation. Interestingly, the MEK1/2, PI3K, and JNK inhibitors had no effect on VSV replication when added subsequent to CD4+ T-cell activation (data not shown).

To confirm the suppressive effect of the MEK1/2, JNK, and PI3K inhibitors on VSV replication, virus titers were assessed by plaque assay (Fig. 2F). Inhibition of the MEK1/2, JNK, or PI3K signaling pathways effectively prevented VSV virion production (P ≤ 0.0003). In agreement with the VSV protein synthesis results, inhibition of the p38 pathway had no effect on the viral titer in activated CD4+ T lymphocytes. These results demonstrate that VSV replication in primary T lymphocytes depends on the activation of the ERK, JNK, and PI3K signaling pathways.

Previous studies have demonstrated that VSV can infect both permissive and nonpermissive cells to produce viral mRNA, yet VSV protein synthesis occurs only in permissive cells (64), suggesting that cell permissiveness depends on post-transcriptional regulation of viral protein synthesis. To determine if VSV permissiveness in primary T cells is governed by a similar mechanism, the level of individual viral mRNAs in CD4+ T lymphocytes following VSV infection was investigated (Fig. 2G). Total RNA was extracted from resting or activated CD4+ T cells challenged with VSV for 24 h. RT-PCR analysis of VSV mRNAs demonstrated that both resting and activated CD4+ T lymphocytes supported VSV M and L mRNA production (Fig. 2G, lanes 2 and 4). The level of viral mRNA production remained unchanged in activated CD4+ T lymphocytes pretreated with the MEK1/2, SAPK/JNK, PI3K, or p38 inhibitor.

FIG. 1. VSV replicates and induces apoptosis in activated CD4+ T lymphocytes. (A) Kinetics of VSV replication and caspase 3 cleavage in resting and activated CD4+ T lymphocytes. Resting CD4+ T lymphocytes were activated with anti-CD3/CD28 for 24 h. Activated and resting CD4+ T lymphocytes were mock infected or infected with VSV (1 MOI). At the indicated times postinfection, VSV replication and caspase 3 cleavage were analyzed in 20 μg of total cell lysates by SDS-PAGE followed by immunoblotting with anti-cleaved caspase 3, anti-VSV, and anti-β-actin as a loading control. (B) Infectious VSV was measured at 12, 24, and 48 h postinfection by plaque assay in Vero cells. Virus titers were determined in triplicate; each bar indicates mean ± standard deviation. (C) VSV protein levels are proportional to T-cell activation time. Purified primary T lymphocytes were incubated with anti-CD3/CD28 monoclonal antibodies for 12 to 48 h and then infected with VSV (1 MOI). At the indicated times postinfection, VSV replication and caspase 3 cleavage were assessed in 20 μg of whole-cell lysates by immunoblot analysis. The VSV N/P protein expression level was quantified and normalized to the β-actin level using the Scion Image 4.0 software program. (D) Supernatants of cells activated for 24 or 48 h were collected 12 or 24 h postinfection and virus titers determined by standard plaque assay. Assays were performed in triplicate; each bar indicates mean ± standard deviations.
FIG. 2. Activation of the MAPK and PI3K pathways is required for VSV replication. (A to D) CD3/CD28 stimulation induces PI3K and MAPK signaling in CD4⁺ T lymphocytes. Resting primary CD4⁺ T lymphocytes were mock treated (dimethylsulfoxide [DMSO]) or treated with the MEK1/2 inhibitor UO126 (A), the JNK inhibitor SP600125 (B), the PI3K inhibitor LY294002 (C), or the p38 kinase inhibitor SB203580 (D) before activation with anti-CD3/CD28. At the indicated times, cells were lysed and analyzed by immunoblotting with antibodies specific for total or phosphorylated forms of p38 MAPK, ERK1/2, Akt, and JNK. (E) Effect of MAPK and PI3K pathway inhibitors on VSV replication in T lymphocytes. Mock- and inhibitor-treated activated T lymphocytes were infected with VSV (1 MOI) for 12 h or 24 h, lysed, and subjected to immunoblot analysis with an anti-VSV antibody. Data are representative of three different experiments. (F) Effect of various MAPK and PI3K inhibitors on virus yield. CD4⁺ T lymphocytes pretreated with UO126 (UO), SB203580 (SB), SP600125 (SP), or LY294002 (LY) and activated as above were infected with VSV (1 MOI) for 24 h. Supernatants were collected and viral titers determined by standard plaque assay. The data shown are the means ± standard deviations (n = 3). Statistically significant differences are indicated by asterisks (*, P ≤ 0.00003). (G) Effect of various MAPK and PI3K inhibitors on VSV mRNA transcripts. Cells were treated as described for panel E and collected 24 h after infection for total RNA extraction; resting T cells are designated R. One microgram of RNA from each sample was subjected to RT-PCR for selective amplification of specific VSV mRNAs (M or L) and the constitutively expressed actin, as a control. PCR products were separated on a 2% agarose gel and visualized with ethidium bromide staining. The VSV M mRNA expression levels were quantified and normalized to actin levels using the Scion Image 4.0 software program.
Inhibition of ERK, JNK, or PI3K leads to cell cycle arrest in primary T lymphocytes. Because anti-CD3/CD28 stimulation of T lymphocytes induces cell proliferation through the activation of the MEK1/2, JNK, and PI3K pathways, we sought to examine the relationship between VSV replication and induction of the cell cycle by MAPK. Treatment of T lymphocytes with anti-CD3/CD28 for 48 h resulted in exit from G0 phase and cell cycle entry as demonstrated by FACs analysis of PI-labeled cells; T-cell activation led to a 30% increase in cells in S+G2/M phases of the cell cycle (Fig. 3A, compare panels a and b; Fig. 3B). As expected, addition of MEK1/2 or PI3K inhibitor for 1 h prior to CD3/CD28 stimulation decreased the percentage of cells in S+G2/M phases to background levels (3 to 5%) (P ≤ 0.007 or P ≤ 0.006, respectively) (Fig. 3A, compare panel b to panels c and f; Fig. 3B). Surprisingly, inhibition of the JNK pathway by SP600125 prevented T-lymphocyte cell cycle entry/progression, resulting in G0/G1 arrest (2%) (P ≤ 0.004) (Fig. 3A, panel d, and B). Simultaneous assessment of apoptosis by DNA content analysis showed that these inhibitors did not affect cell survival (data not shown). To our knowledge, this constitutes the first report that JNK activation is specifically required for T-lymphocyte G0/G1-phase transition. Inhibition of p38 had no effect on T-cell proliferation (Fig. 3A, panel e, and B).

To confirm that CD3/CD28-stimulated T lymphocytes underwent G0/G1 transition, the induction or degradation of proteins controlling cell cycle progression was assessed by immunoblotting. High levels of the cdk inhibitor p27kip1 were present in resting cells, whereas cyclin D3 (CycD3) and cdk4 were undetectable, thus confirming G0 arrest (Fig. 3C, lane 1). CD3/CD28 stimulation resulted in rapid degradation of p27kip1, concomitant with induction of CycD3 and cdk4 expression (Fig. 3C, lanes 2 to 5). p27kip1 downregulation and CycD3/cdk4 induction were inhibited by pretreatment with LY294002, SP600125, or U0126 but not with SB203580 (Fig. 3C). Entry into S phase was monitored by measuring hyperphosphorylation of Rb (a CyclD/cdk4 substrate) and cyclin A protein expression. As demonstrated in Fig. 3D, CD3/CD28 stimulation increased Rb phosphorylation as well as cyclin A expression, whereas pretreatment with LY294002, SP600125, and U0126—but not SB203580—abrogated both Rb hyperphosphorylation and cyclin A expression following T-cell activation. These results confirm that inhibition of MEK1/2, SAPK/JNK, or PI3K activity arrests CD4+ T lymphocytes in G0/G1 phase by preventing the expression of positive regulators of cell cycle entry, such as CycD3 and cdk4, or preventing the downregulation of cell cycle inhibitors, such as p27kip1.

VSV replication is dependent on cell cycle entry and increased protein translation. Activation of the ERK, JNK, or PI3K pathway appears to confer VSV permissiveness to activated CD4+ T cells by mediating cell cycle entry, which is characterized by a sharp increase in protein translation. To test this hypothesis, activated CD4+ T lymphocytes were arrested at different stages of the cell cycle using the pharmacological inhibitors olomoucine, rapamycin, aphidicolin, nocodazole, and Taxol before challenge with VSV. FACs analysis of PI-labeled cells confirmed that CD3/CD28 stimulation induced cell cycle progression (Fig. 4A, panel b, and B). Olomoucine, a purine derivative drug that inhibits different cdk’s (36, 38), and rapamycin, an mTOR-targeting, immunosuppressive drug that blocks the elimination of p27kip1 and inactivates the kinase activity of the G1 cyclin/cdk complex (31, 40), arrested T lymphocytes in G0/G1 (97.5% and 95.9%, respectively). Aphidicolin, an inhibitor of DNA polymerase α (44, 54, 66), blocked the cell cycle between the G1 and S phases (92.3%). Taxol and nocodazole block the cell cycle in G2/M (30.3% and 15%, respectively) by modulating microtubule polymerization (16, 39) (Fig. 4A, panels c to g, and B). Simultaneous assessment of apoptosis by DNA content analysis showed that these inhibitors did not affect cell survival (data not shown). To investigate if cell cycle arrest in G0/G1 specifically impaired VSV replication, CD4+ T lymphocytes were pretreated or not with inhibitors and activated with anti-CD3/CD28 for 12 h prior to VSV infection. VSV protein synthesis was decreased by olomoucine or rapamycin (Fig. 4C, compare lanes 4 and 5 to lanes 6 and 7, and D, compare lanes 2 and 3 to lanes 4 and 5) but not with aphidicolin, nocodazole, or Taxol (Fig. 4C, compare lanes 4 and 5 to lanes 8 to 13), demonstrating that VSV replication in primary T lymphocytes is exclusively dependent on G0/G1-phase transition.

The effect of rapamycin on the cell cycle is largely dependent on its ability to inhibit mTOR, a regulator of 5′-cap-dependent translation and ribogenesis (reviewed in references 49 and 61). mTOR regulates cell growth by phosphorylating S6K and 4EBP1, and its activity is controlled through phosphorylation by the serine/threonine kinase Akt. Phosphorylation of 4EBP1 leads to its dissociation from the translation initiation factor eIF4E, which can then be phosphorylated by Mnk1 (reviewed in reference 49), resulting in activation of eIF4E and enhanced protein synthesis and not at the level of virus entry or mRNA generation.

FIG. 3. Proliferation and cell cycle progression of primary T cells is dependent on MEK1/2, JNK, and PI3K activation. (A and B) Resting CD4+ T cells were left untreated (a), treated with anti-CD3/CD28 (b), or pretreated with MEK1/2 inhibitor U0126 (UO) (c), JNK inhibitor SP600125 (SP) (d), P38 inhibitor SB203580 (SB) (e), or PI3K inhibitor LY294002 (LY) (f) before stimulation with anti-CD3/CD28. Cell cycle analysis was performed by flow cytometry on PI-labeled cells (A), and percentages of cells in S, G2, and M phase were determined as means of triplicate measurements (B). Statistically significant differences are indicated by asterisks (*, P < 0.007; **, P < 0.004; ***, P < 0.006). Results are representative of more than three independent experiments using separate donors. (C) CD3/CD28 stimulation leads to G1 progression, as demonstrated by immunoblots showing down-regulation of p27kip1 and synthesis of CycD3 and cdk4. Cell lysates were prepared at different times, and equal amounts of protein (30 μg) were resolved by SDS-PAGE followed by immunoblotting with antisera specific for p27kip1, CycD3, or cdk4. Immunoblotting against β-actin was performed as a loading control. (D) CD3/CD28 stimulation leads to G1/S-phase transition: immunoblotting for Rb and cyclin A proteins. Cells were treated and cultured as for panel A. Top panel, line indicates hyperphosphorylated Rb. An immunoblot against β-actin was used as a loading control.
ribosome recruitment to the translational start site. Thus, eIF4E activity is regulated through expression, phosphorylation, and interaction with eIF4BP1 (37, 58). We therefore investigated the phosphorylation status of mTOR (3, 78) and the levels of total and phosphorylated eIF4E (11, 59) as readouts for 5′/H11032-cap dependent translation and ribogenesis. CD3/CD28 stimulation of CD4+ T lymphocytes induced mTOR phosphorylation in a time-dependent manner (Fig. 5A, lanes 1 to 2, and B, lanes 1 to 5); eIF4E expression and phosphorylation were also induced following T-cell activation. Addition of the PI3K inhibitor LY294002 1 h prior to CD3/CD28 stimulation abolished mTOR and eIF4E phosphorylation (Fig. 5A, lane 6, and B, lanes 18 to 21), whereas the ERK inhibitor UO126 abrogated eIF4E phosphorylation only (Fig. 5A, lane 3, and B, lanes 6 to 9). A modest decrease in the total level of eIF4E was also observed in activated T cells pretreated with the ERK (UO126) or PI3K (LY294002) inhibitor, respectively. This result is in agreement with previous reports on the role of PI3K and ERK1/2 signaling in the control of protein translation (51). Surprisingly, inhibition of the JNK pathway by SB203850 had no effect on mTOR and eIF4E phosphorylation (Fig. 5A, lane 5, and B, lanes 14 to 17). These results suggest that the dependence of VSV on G0/G1-phase transition in primary lymphocytes is related to a global enhancement in protein translation that depends on mTOR and eIF4E activity.

siRNA against eIF4E inhibits VSV replication in activated T lymphocytes. Because it is generally accepted that VSV protein synthesis requires the cap-dependent translational machinery (8), RNA interference was next used to examine whether the high level of eIF4E found in activated T lymphocytes was required for VSV protein synthesis. Cells were stimulated with anti-CD3/CD28 treated for 48 h with siRNA directed against

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**FIG. 4.** VSV protein synthesis requires cell cycle entry. (A) Effect of pharmacological inhibitors of the cell cycle on CD3/CD28-stimulated primary T cells. Resting CD4+ T cells were left untreated (a) or pretreated with olomoucine (c), aphidicolin (d), Taxol (e), nocodazole (f), or rapamycin (g) for 1 h before stimulation with anti-CD3/CD28 for 48 h. Activated T cells are shown in panel b. Cell cycle analysis was performed by flow cytometry on PI-labeled cells. In panels A and B, percentages of cells in various phases of the cell cycle are indicated. The data shown represent the means ± standard deviations (n = 3). (C and D) Effect of rapamycin, olomoucine, aphidicolin, Taxol, and nocodazole on VSV protein synthesis. Human CD4+ T cells were treated as for panel A and then infected with VSV (1 MOI). Cells were collected 12 h or 24 h postinfection, lysed, and subjected to immunoblot analysis with anti-VSV antisera. Results are representative of more than three independent experiments using separate donors.
A. siRNA: - ctl elf4E
   α-CD3/CD28 (48h): + + +
   elf4E
   β-actin
   Lanes 1 2 3 Relative Expression 1 1.2 0.5

B. a). Resting
   G0/G1: 91.3%
   S: 0.6%
   G2/M: 21%

   b). α-CD3/CD28
   G0/G1: 80.6%
   S: 10.4%
   G2/M: 9%

   c). + sictl
   G0/G1: 84%
   S: 5%
   G2/M: 11%

   d). + sief4E
   G0/G1: 89.5%
   S: 2.3%
   G2/M: 3.2%

C. Resting
   CD3/CD28
   sictl
   sief4E
   % Cells in S+G2/M

D. siRNA: - ctl elf4E
   α-CD3/CD28 (48h): + + +
   VSV (MOI 1, 12 h.p.i.): + + +
   VSV
   β-actin
   Lanes 1 2 3 Relative Expression 1 0.9 0.5
eIF4E mRNA (Fig. 6A). A 50% decrease in the level of the eIF4E protein compared to the control siRNA was observed (Fig. 6A, compare lane 1 to lanes 2 and 3); simultaneously, siRNA directed against eIF4E induced cell cycle arrest in G0/G1 (89.5%; P < 0.005), as demonstrated by PI staining (Fig. 6B, compare panels c and d; Fig. 6C). VSV infection was performed on siRNA-treated and preactivated T lymphocytes (Fig. 6D), and by 12 h postinfection, VSV protein production was detected in control siRNA cells but a 50% decrease in the VSV N/P protein level was observed in eIF4E siRNA-expressing cells. These results demonstrate that eIF4E plays an important role in regulating VSV replication in CD4+ T lymphocytes, either through a global regulation of cellular protein synthesis that leads to G0/G1 transition or specifically through translation initiation of viral 5′-capped mRNAs.

Cell cycle entry and translation initiation renders CLL cells susceptible to VSV replication. Cell cycle transition from G0 to G1 phase—concomitant with an increase in protein translation—is essential for VSV replication in lymphocytes. Primary ex vivo CLL cells are resistant to VSV oncolysis due to Bcl-2-mediated arrest in G0/G1 phase (30, 43, 45, 56) and thus represent an interesting model for investigation of whether cell cycle induction is sufficient to confer VSV susceptibility to primary CLL cells. Ex vivo CLL samples were stimulated with PMA-ionomycin for 12 to 72 h prior to VSV infection; FACS analysis with PI-labeled cells demonstrated that treatment of CLL cells with PMA-ionomycin induced their progression through the cell cycle in a time-dependent manner, leading to an increase of cells in S+G2/M phases from 5% to 18% (Fig. 7A). Cell cycle entry was further confirmed by immunoblotting for the p27Kip1 protein, which was degraded in a time-dependent manner (Fig. 7B, compare lanes 1 to 4 to lanes 5 to 8). Interestingly, treatment of CLL cells with PMA-ionomycin induced eIF4E phosphorylation in a time-dependent manner (Fig. 7C, compare lanes 1 to 4 to lanes 5 to 8). VSV protein levels and caspase 3 cleavage were also monitored at 12 and 72 h postinfection (Fig. 7D); VSV protein decreased in unstimulated primary CLL cells (Fig. 7D, lanes 2 to 5), and no caspase 3 cleavage was observed 24 h postinfection (Fig. 7D, lanes 2 to 5). In agreement with this result, activated CLL cells produced ~3-fold more virus than unstimulated CLL cells at 48 h postinfection (Fig. 7E). Furthermore, PMA-ionomycin treatment of CLL cells stimulated VSV replication, concomitant with a time-dependent increase in the cleaved forms of caspase 3 (Fig. 7D, lanes 7 to 10). Thus, using the example of G0/G1-arrested primary CLL cells, resistance to VSV oncolysis can be overcome by pretreatment with pharmacological compounds that induce cell cycle entry and translation initiation.

DISCUSSION

The emergence of VSV as a potential oncolytic virus has made dissection of the molecular determinants of host cell permissiveness to VSV an important objective. Although promising results have been obtained with cell lines and murine cancer models (25, 27, 48), accumulating evidence indicates that certain types of cancer are partially or completely resistant to VSV oncolysis. In a previous study, we demonstrated that CD4+ T lymphocytes from proliferating primary ATL samples were susceptible to VSV oncolysis while resting primary T cells were restricted for VSV replication (17). In this study, we demonstrate that stimulation of primary human CD4+ T lymphocytes with anti-CD3/CD28 allows VSV replication and VSV-induced cell death by triggering the MAPK, PI3K, and mTOR/eIF4E pathways and cell cycle entry (Fig. 8).

Stimulation of T cells by TCR plus coreceptor engagement leads to the activation of two main signaling pathways: Ras and PI3K. The Ras pathway signals through the MAPKs ERK, JNK, and p38, whereas PI3K activates Akt. It is generally accepted that ERK, JNK, and Akt play a role in cell cycle control, but not p38 (1). Similarly, by using the pharmacological inhibitor U0126, SP600125, LY-294002, or SB203580, we demonstrated that VSV replication in primary T lymphocytes requires activation of MEK1/2, JNK, and PI3K but not p38. These inhibitors had no effect on the production of VSV mRNA but led to a decrease in viral protein levels and the virus titer, indicating that these pathways affect VSV mRNA translation but not virus entry or mRNA production. Since inhibition of any one of the kinases blocked VSV replication, it appears that the activities of MEK1/2, JNK, and PI3K are nonredundant in regard to VSV permissiveness.

VSV viral protein synthesis appears to depend on cell cycle entry, because inhibitors that blocked VSV protein synthesis also resulted in G0/G1 arrest. Indeed, pretreatment of naive T cells with U0126, SP600125, or LY294002 but not SB203580 prior to activation led to arrest in G0/G1, preventing degradation of p27Kip1 and induction of CycD3/cdk4. Remarkably, the inhibitors had no effect on VSV replication if added to preactivated T lymphocytes, suggesting that VSV infection is dependent on global activation events and not on the direct action of these kinases or their targets in viral replication. The use of pharmacological inhibitors to specifically block cell cycle progression independently of MAPK or PI3K activity confirmed that entry into the G1 phase but not progression through S or G2/M allowed VSV replication. G0/G1 cell cycle arrest induced by rapamycin or olomoucine treatment abrogated VSV replication, as did the inhibitors of CD3/CD28 signaling. In con-

FIG. 6. siRNA directed against eIF4E inhibits VSV replication in primary activated CD4+ T lymphocytes. (A) Primary CD4+ T lymphocytes were stimulated with anti-CD3/CD28 for 48 h before electroporation with eIF4E-specific siRNA or scrambled siRNA. After an additional 48-h incubation period, cells were lysed and analyzed by immunoblotting with an antibody against total eIF4E. " denotes cells electroporated without siRNA. (B) Cell cycle analysis was performed on cells described in legend to panel A by PI-labeling and flow cytometry analysis. In panels B and C, the percentages of cells in various phases of the cell cycle are indicated. The data shown represent the means ± standard deviations (n = 3). Statistically significant differences are indicated by asterisks (P < 0.005). (D) eIF4E knockdown and control cells were infected with VSV (1 MOI) for 12 h. Cells were lysed and subjected to immunoblotting with anti-VSV antisera. The eIF4E and VSV N/P protein expression levels in panels A and B were quantified and normalized to β-actin levels using the Scion Image 4.0 software program. Levels of eIF4E were expressed as percentages of levels for mock-infected cells.
Contrast, robust VSV protein expression was observed in the presence of aphidicolin or Taxol, which induced cell cycle arrest in G1/S or G2/M phase, respectively. Therefore, entry in G1 phase of the cell cycle is sufficient to render normal primary human CD4+ T lymphocytes susceptible to VSV replication.

T cells arrested in G0 phase of the cell cycle have low rates of mRNA and protein synthesis. Phosphorylation of mTOR and the translation initiation factor eIF4E is observed in T cells following CD3/CD28 stimulation, which leads to a surge in protein synthesis that allows cell cycle progression (reviewed in references 49 and 61). Our data demonstrate that the Ras pathway through ERK and the PI3K pathway through Akt regulate translation initiation and/or ribosome biogenesis, since their inhibition by U0126 and LY294002 prevented eIF4E and mTOR phosphorylation (49, 60, 63). Interestingly, JNK is also required for mTOR and eIF4E activation in T lymphocytes, since the presence of the inhibitor SP600125 prevented mTOR phosphorylation as well as eIF4E protein induction and phosphorylation following CD3/CD28 stimulation. This is to our knowledge the first report indicating that in primary T cells, JNK activation leads to mTOR and eIF4E phosphorylation. As expected, p38 inhibition had no effect on mTOR and eIF4E phosphorylation following CD3 and CD28 engagement.

Rapamycin induces G1 cell cycle arrest and blocks mRNA translation by binding to and inhibiting mTOR. This prevents phosphorylation of eIF4-BP1 and therefore blocks the release of the translation initiation factor eIF4E. Rapamycin also inhibits the phosphorylation of ribosomal S6K1, a downstream target of mTOR, further blocking translation initiation of 5'-capped and/or 5'-TOP mRNAs (13, 57, 77). In this study, we demonstrate that rapamycin blocks VSV protein production in primary activated CD4+ T lymphocytes, suggesting that mTOR-mediated translation initiation and ribosome biogenes-
sis during G1 phase are crucial for VSV replication in primary human CD4+ T lymphocytes. In contrast, Connor et al. (22) concluded that rapamycin had no effect on VSV protein synthesis in HeLa cells, although this study did not address the cell cycle status of HeLa cells following rapamycin treatment. The discrepancy might be explained by the fact that the antiproliferative effect of rapamycin is maximal in quiescent cells that express high levels of p27kip1 but not in exponentially growing cells (12, 71). In primary T cells, rapamycin induced a strong G1-phase arrest that was concomitant with inhibition of VSV replication.

eIF4E is a downstream target of mTOR that regulates cap-dependent translation (33). Considering that VSV mRNA is capped and polyadenylated, the possibility that eIF4E is directly involved in VSV replication in primary activated T cells was explored using siRNA directed against eIF4E. VSV protein synthesis was indeed inhibited in activated T lymphocytes expressing eIF4E siRNA, suggesting that this host translational factor is required for VSV replication. However, treatment of activated CD4+ T lymphocytes with eIF4E siRNA led to cell cycle arrest in G0/G1. Therefore, it was not possible to ascribe a direct role to eIF4E in VSV replication, since it is not clear whether the observed effect is a direct consequence of eIF4E inhibition or an indirect consequence of a delay in cell cycle progression.

The results obtained with primary T cells demonstrate that VSV replication in lymphocytes depends on G0/G1-phase transition. We postulated that resistance to VSV-induced oncolysis observed in ex vivo CLL samples is due to the low proliferative index of CLL cells, which are arrested in G0 phase (67). Indeed, treatment of ex vivo primary CLL samples with PMA-ionomycin to induce G0/G1 transition was sufficient to restore VSV sensitivity: PMA-ionomycin stimulation led to cell cycle entry, as demonstrated by a 13% increase in cells in S+G2/M phase, and this was sufficient to restore VSV replication. Induction of eIF4E phosphorylation was also observed in CLL cells activated with PMA-ionomycin, although—in contrast to primary T-cell samples—total levels of eIF4E remained constant. This and previous reports argue that eIF4E phosphorylation constitutes a limiting step in the induction of translation initiation (3, 11, 19, 49). Induction of apoptosis was also confirmed by increased caspase 3 cleavage compared to results obtained in untreated cells. This result constitutes the first evidence that VSV oncolysis in G0-arrested CLL cells can be augmented by pharmacological agents that stimulate exit from G0/G1.

The current study illustrates that VSV replication in primary lymphocytes is dependent on cell cycle entry and global enhancement of protein synthesis via mTOR and eIF4E activity. The results of this study may provide an incentive to explore other combinatorial approaches to overcome the resistance of different cancers to oncolytic virus therapy.

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