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A net +1 frameshift permits synthesis of thymidine kinase from a drug-resistant herpes simplex virus mutant

(clinical isolate/pathogenesis/latency/acyclovir/in vitro transcription-translation)

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ABSTRACT Clinical resistance to antiviral drugs requires that a virus evade drug therapy yet retain pathogenicity. Thymidine kinase (TK)-negative mutants of herpes simplex virus are resistant to the drug, acyclovir, but are attenuated for pathogenicity in animal models. However, numerous cases of clinical resistance to acyclovir have been associated with viruses that were reported to express no TK activity. We studied an acyclovir-resistant clinical mutant that contains a single-base insertion in its tk gene, predicting the synthesis of a truncated TK polypeptide with no TK activity. Nevertheless, the mutant retained some TK activity and the ability to reactivate from latent infections of mouse trigeminal ganglia. The mutant expressed both the predicted truncated polypeptide and a low level of a polypeptide that comigrated with full-length TK on polyacrylamide gels and reacted with anti-TK antiserum, providing evidence for a frameshifting mechanism. In vitro transcription and translation of mutant tk genes, including constructs in which reporter epitopes could be expressed only if frameshifting occurred, also gave rise to truncated and full-length polypeptides. Reverse transcriptase–polymerase chain reaction analysis coupled with open reading frame cloning failed to detect alterations in tk transcripts that could account for the synthesis of full-length polypeptide. Thus, synthesis of full-length TK was due to an unusual net +1 frameshift during translation, a phenomenon hitherto confined in eukaryotic cells to certain RNA viruses and retrotransposons. Utilization of cellular frameshifting mechanisms may permit an otherwise TK-negative virus to exhibit clinical acyclovir resistance.

Herpes simplex virus (HSV) is an important human pathogen, especially in patients with AIDS. A major advance in antiviral therapy has been the use of acyclovir to treat HSV infections, but acyclovir resistance is a problem of increasing clinical significance in immunocompromised patients (1). Clinical resistance implies that HSV can mutate to evade drug therapy and retain pathogenicity. Because the sensitivity of HSV to acyclovir is due largely to the viral thymidine kinase (TK), which activates the drug (2), HSV tk mutations can confer acyclovir resistance (3). Indeed, there have been numerous cases of patients who suffered severe HSV disease despite acyclovir therapy and shed acyclovir-resistant viruses that were reported to express no detectable TK activity and/or full-length TK polypeptides (4–13).

Although TK is not essential for viral replication in cell culture, it is important for viral pathogenesis in animal models. In particular, TK− mutants fail to reactivate from latent infections of mouse sensory ganglia (14–16), due to the tk mutation (16). Thus, the association of virus that appears TK− with severe HSV disease has been puzzling. One possible resolution of this paradox is that the clinical isolates expressed low levels of TK that were not detected. There are HSV mutants that are severely impaired for TK activity and thus acyclovir-resistant, yet express low levels of TK that are sufficient for certain pathogenic phenotypes, including the ability to reactivate (17–20).

We report here a clinical acyclovir-resistant isolate that encodes a gene predicted to express an inactive truncated TK polypeptide due to a single-base insertion mutation. Despite this, the virus retains a low level of TK activity and the ability to reactivate from latency and expresses both the predicted truncated polypeptide and low levels of full-length TK polypeptide. We show that full-length TK expression is due to a net +1 frameshift during translation. The results provide a potential mechanism for clinical acyclovir resistance and have uncovered an unusual example of frameshifting that may have unique mechanistic features.

MATERIALS AND METHODS

Cells and Viruses. Vero cells were propagated and maintained as described (21). Plaque-purified HSV-1 clinical isolates 294.1 and 615.9 and the tk deletion mutant dlsptk have been described (14, 22). Mutant K5DGI was isolated from the wild-type laboratory strain KOS by selection with 40 μM ganciclovir (C.B.C.H., unpublished results) and plaque-purified three times. Viruses were grown and titrated as described (23).

Plaque Autoradiography. [32P]labeled deoxyctydine plaque autoradiography was performed as described (24), except that a methylcellulose overlay (0.5%) was used instead of human immune serum globulin.

Reactivation from Latency. Seven-week-old CD-1 mice were inoculated with 2 × 106 plaque-forming units of virus via the cornea as described (20). Thirty days after inoculation, trigeminal ganglia were excised and tested for the presence of reactivable virus by a dissociation protocol (25), modified as described (16).

PCR and Conventional Sequencing. Virion “mini-prep” DNA was prepared (26). The DNA was ethanol-precipitated and the tk gene was amplified by PCR as described (27) except that annealing was at 60°C and oligonucleotide primers corresponding to nt −220 to −203 and nt 1348 to 1327 of the KOS tk gene (28) were used. These PCR products, processed as described (29), or cloned plasmid DNAs were

Abbreviations: HSV, herpes simplex virus; TK, thymidine kinase; RT, reverse transcriptase.

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**Plasmids.** The tk genes of 294.1 and 615.9 were amplified by PCR as described above using the primer corresponding to nt −220 to −203 and a primer corresponding to nt 45, 564–45, 582 of the HSV-1 strain 17 sequence (30), which lies downstream of the EcoRI site in the glycoprotein H gene. The amplified DNAs were digested with Bgl II and EcoRI and inserted into BamHI/EcoRI-digested pGem-7ZF(+) (Promega) to yield plasmids pBH15 and pBH13, respectively. The inserts were sequenced to ensure that secondary mutations were not present. To construct plasmids pBX1 and pBX2, we started with pTKWT, which contains the 1.9-kbp EcoRI-Pvu II tk fragment from KOS inserted into the EcoRI and Smal I sites of pGem-32Zf(+) (Promega) and pTK2N0, which contains the Kpn I-BamHI 3.4-kbp tk fragment from KSDG1 in pGem-7ZF(+). Plasmid pSVTK1 was then constructed by inserting the EcoRI–Xba I fragment from pTKWT into pSVK3 (Pharmacia). Plasmid pSVTKN0 was constructed by inserting the EcoRI–Xba I fragment from pTK2N0 into pSVK3. Plasmids pBX1 and pBX2 entailed the insertion of the Bgl II–Xba I fragment from pSVTK1 and pSVTKN0, respectively, into pBlueScript II KS+(+) (Stratagene) at the BamHI and Xba I sites. pBX22 was constructed by replacing the Sac I tk fragment of pBX2 downstream of the KSDG1 mutation with that of pBX1. Plasmid pBX15 was constructed by replacing the Styl I–Xba 1 fragment of pBX1 with the Nco I–Xba I fragment from HSV pol plasmid pDP1 (31). Sequence confirmation that the junction of tk and pol sequences was in-frame. The mutant version (pBX16) of this fusion construct was constructed by exchanging the Sac I fragment of pBX2 into pBX15. Plasmids pBH3 and pBH4 were constructed in several steps. First, the fragments between the Sac I sites in the tk gene and the vector in plasmids pBX1 and pBX22 were deleted to yield plasmids pBS1 and pBS2, respectively. The EcoRV fragments including the 5′ ends of the tk genes from these plasmids were then replaced with a blunt-ended 1.1-kbp Sal I fragment that encodes the N-terminal portion of HSV Pol from plasmid p911 (32) to form pBH1 and pBH2, respectively. These were cut with Sac I and blunt-ended, and the 2.2-kbp Pvu II fragment from p911 that encodes the C-terminal portion of HSV Pol was inserted to yield pBH3 and pBH4, respectively.

**In Vitro Transcription and Translation.** In vitro transcription and translation were performed as described (33).

**Protein Analysis.** Vero cells in 60-mm dishes were mock-infected or infected at a multiplicity of 3 and incubated at 37°C. Five hours after infection, [35S]methionine (DuPont/NEN) was added to 100 μCi/ml (1 Ci = 37 GBq). Two and a half hours later, the medium was removed, and the monolayer was washed three times with phosphate-buffered saline (PBS) and then scraped into 1 ml of PBS. The cells were pelleted by low-speed centrifugation at 4°C and resuspended in 1 ml of IP buffer (33). These lysates were then incubated with rabbit preimmunized sera and formalin-fixed *Staphylococcus A* (GIBCO/BRL) overnight at 4°C and microcentrifuged. The resulting supernatants or reticulocyte lysates were subjected to immunoprecipitation as described (33) using antisera specifically reacting with HSV-1 TK (kindly provided by W. C. Summers, Yale University, New Haven) or the C-terminal portion of HSV-1 Pol (EX3; kindly provided by K. Weisshart and C. Knopf, Deutsches Krebsforschungszentrum, Heidelberg; ref. 34). 35S-labeled polypeptides were separated on SDS/polyacrylamide gels and visualized by fluorography with Amplify (Amersham) by using preflashed film. The ratio of full-length to truncated products was quantified by densitometry using a Microtek scanner and normalized for the number of methionine residues in each product.

**Reverse Transcriptase (RT)–PCR and Open Reading Frame Cloning.** After transcription of pBX1 and pBX22, nucleic acids were treated for 1 h at 37°C with 10 units of RNase-free DNase I (Promega). Reaction products were phenol/chloroform-extracted and ethanol-precipitated, and the RNA was used as a template for cDNA synthesis with the TK5 primer and avian myeloblastosis virus RT (Promega) by following the manufacturer's directions. One-twentieth of the resulting cDNA was then diluted in PCR amplification buffer (27) and amplified by PCR using TK9 and TK3 as described for PCR sequencing above. The resulting PCR products were cleaved with *Rsa* I and *Sac* I and treated with T4 DNA polymerase in the presence of all four dNTPs to remove the overhanging 3′ ends at the *Sac* I site, and the relevant *Rsa* I–*Sac* I fragment was isolated and ligated into *Sma* I-digested phosphatase-treated *pMR* 300 (ref. 35; plasmid kindly provided by M. Gray, Tufts University, Boston). The resulting ligation mixture was transformed into *Escherichia coli* JM109, plated, and scored on MacConkey agar as described (35, 36).

**RESULTS**

A Clinical HSV Mutant with a tk Insertion Mutation. We studied a clinical acyclovir-resistant tk mutant of HSV, 615.9, that was plaque-purified from virus isolated from a patient who suffered severe HSV esophagitis despite acyclovir therapy (22). Mutant 615.9 is genetically related to strain 294.1, which was plaque-purified from a drug-sensitive pretreatment isolate from the same patient (22). We sequenced the 615.9 and 294.1 tk genes. The only difference between the 615.9 and 294.1 tk genes was the insertion of a guanosine into a run of seven guanosines that begins at nt 540 relative to the transcriptional start site (37), thereby creating a run of eight guanosines. The insertion mutation shifts the tk mRNA sequence out of frame so that translation would be predicted to stop at a UGA codon, yielding a truncated polypeptide of 227 aa (Fig. 1). Moreover, as the shift in frame is upstream of residues reported to be critical for TK activity (38–40), the predicted truncated polypeptide would be expected to lack TK activity.

**Mutant 615.9 Retains Low TK Activity.** These sequencing results were surprising because mutant 615.9 had previously been reported to exhibit some TK activity (22). To exclude the possibility that the TK activity was due to a low level of TK+ virus in the 615.9 stock, we performed [32P]iododeoxyuridine plaque autoradiography. This technique can distinguish TK+ from TK-deficient virus by the relative intensity of labeling of plaques. Drug-sensitive TK+ strain 294.1 formed heavily labeled plaques (Fig. 2A). A tk deletion mutant *disptk*, which is completely TK− (14), failed to form labeled plaques (Fig. 2C). Mutant 615.9 anabolized the nucleoside less efficiently than 294.1, but more efficiently than *disptk* giving rise to less-intense plaques that were nevertheless clearly labeled along their rims (Fig. 2B). Similar intensities were observed among >200 plaques. Reconstruction experiments (data not shown) showed that the technique can readily detect a TK+ virus in a background of TK-deficient virus. We conclude that mutant 615.9 consists of a homogeneous population of virus that expresses a low level of TK.

**Mutant 615.9 Can Reactivate from Latency in Mouse Trigeminal Ganglia.** We tested the ability of mutant 615.9 to reactivate from latency in mouse trigeminal ganglia after corneal inoculation. In the mouse, truly TK− mutants are completely deficient for reactivation (14–16); for example, TK− mutant *dsackl* has failed to reactivate from any of 37 ganglia (14, 16). In contrast, 615.9 reactivated from 3 of 12 ganglia upon implant and dissociation in the presence of Vero
Fig. 1. Relevant sequences of the HSV 294 and 615.9 tk genes. For each line, the DNA sequence is presented above (starting at residue 330 from the transcriptional start site) and the predicted amino acid sequence is below with the normal TK reading frame in the three-letter code and the −1 reading frame in the single-letter code after the single guanosine insertion in mutants 615.9 and K5DG1, which shifts the translation to the −1 reading frame (vertical arrow). A stop codon that closes this frame is shown with a star. The locations of primers TK9 and TK5 (horizontal arrows) and restriction sites Rsa I, EcoRV, and Sac I are indicated. The location of a stop codon within the +1 frame is circled. The sequence between this codon and the Sac I site is shaded, as a +1 frameshift event should begin downstream of the stop codon and the signals responsible for frameshifting lie upstream of the Sac I site. A putative nucleotide binding region (aa 168–176) (38, 40) is indicated within a lightly shaded box.

cells. In plaque autoradiography experiments similar to those in Fig. 2, the reactivated viruses were indistinguishable from the inoculated virus, 615.9 (E.P. and D.M.C., unpublished results). The results indicate that 615.9 expresses sufficient TK activity for reactivation from latency.

Mutant 615.9 Expresses Both Truncated and Full-Length TK Polypeptides. To account for the TK activity and reactivation from latency of 615.9, we hypothesized that this mutant might synthesize active full-length TK via translational frameshifting (41, 42), thereby compensating for the insertion mutation. We favored this possibility over other mechanisms such as transcriptional errors because pretranslational gene expression is generally highly faithful, whereas translational frameshifting has many precedents (42). To begin to examine this possibility, we immunoprecipitated radiolabeled TK from lysates of radiolabeled 615.9-, 294.1-, and mock-infected cells by using anti-TK antiserum (Fig. 3).

Fig. 2. TK activities of HSV strains. Vero-cell monolayers were infected with 50–250 plaque forming units (confirmed by crystal violet staining) of HSV wild-type isolate 294.1 (A), mutant 615.9 (B), or tk deletion mutant d5ptk (C) and analyzed by the [¹²⁵I]iododeoxyuridine plaque autoradiography.

The major polypeptide immunoprecipitated from 615.9-infected lysates corresponded in size (~25 kDa) to that predicted from the insertion mutation (lane 3). However, small amounts of a species that comigrated with full-length TK were also observed (lane 3), consistent with our hypothesis of translational frameshifting.

Frameshifting in Vitro. To confirm the findings in infected cells and to test the frameshifting hypothesis further, we sought to reconstitute frameshifting in vitro, adopting the approach first used to examine translational frameshifting of Rous sarcoma virus (41). We cloned the 294.1 and 615.9 tk genes into a vector to permit in vitro transcription by bacteriophage SP6 RNA polymerase. We similarly cloned the tk genes from the wild-type laboratory strain KOS and the acyclovir-resistant mutant strain K5DG1, which arose spontaneously from KOS. The K5DG1 tk gene differs from the KOS tk gene (28) by the same single-base insertion found in 615.9 (Fig. 1). The two mutant tk genes also differed from each other at several nucleotides, as did their parental drug-sensitive strains, demonstrating the independence of the mutant isolates. Similar to 615.9, K5DG1 expressed small amounts of full-length TK in infected cells (Fig. 3, lane 4).

After in vitro transcription, the resulting synthetic mRNAs were translated in rabbit reticulocyte lysates (Fig. 4A). Plasmids containing the 615.9 (pBH13) or K5DG1 (pBX22) tk gene directed the synthesis of both truncated and full-length TK polypeptides (lanes 2 and 3), consistent with the results from infected cells. Both the truncated and full-length polypeptides could be specifically immunoprecipitated with anti-TK antiserum (data not shown). Densitometric scanning showed that the full-length products were at ~2% relative to truncated products.

To demonstrate frameshifting more rigorously, we then constructed plasmids pBX15 and pBX16 in which the C-terminal portion of the HSV pol gene was fused in-frame to the KOS and K5DG1 tk genes, respectively, at a Stu I site downstream of the TGA codon that terminates the truncated TK polypeptide translated from the mutant tk gene. Any bona fide full-length product specified by pBX16 would thus be recognized by anti-Pol antiserum EX3 (31), which does not recognize pol translation products that are out-of-frame (data not shown). As expected, the fusion protein directed by wild-type plasmid pBX15 reacted with both anti-Pol and anti-TK antiserum (Fig. 4B, lanes 2 and 3). Mutant plasmid pBX16 directed the synthesis of a truncated product that was recognized by anti-TK antiserum but not by anti-Pol antiserum and low levels of a full-length product that was immunoprecipitated by both antisera (lanes 5 and 6). These results
frameshifting and the lack of β-galactosidase activity. Thus, <0.2% of the mutant transcripts contained alterations that could lead to synthesis of full-length TK. As this is much less than the frequency of frameshifting observed (2%), we infer that changes in transcripts do not account for frameshifting; i.e., frameshifting occurred during translation.

**DISCUSSION**

**Unusual Aspects of the Frameshift.** The frameshift we have detected is unusual relative to those previously described in eukaryotic cells. Unlike other examples (for review, see ref. 42), it occurs in the expression of a protein that is not an RNA-dependent polymerase and the protein is encoded by a DNA virus not an RNA virus or retrotransposon. The frameshift could be a +1 slip, which has been described in yeast (44), but not higher eukaryotes, or it could be a −2 slip or larger “hop.” For now, we refer to it as a net +1 frameshift.

The mechanism of frameshifting operating here may be ribosomal frameshifting (41, 42). Our data and features of the tk sequence suggest that such frameshifting would occur between a termination codon in the +1 reading frame and the beginning of the Sac I site in the mutant tk gene (Fig. 1). Recent results support this suggestion (B.H. and D.M.C., unpublished data). However, computer-aided analysis of this region did not reveal any of the known heptanucleotide “slippery sequences” that mediate ribosomal frameshifting (41, 42, 44, 45). Moreover, the analysis did not reveal elements known to facilitate translational pausing, thereby permitting easier ribo-
somal realignment, such as termination codons, pseudoknots, or "hungry" codons recognized by known rare tRNAs (42, 44, 45). Recent work in E. coli suggests (46), however, that codons recognized by abundant tRNAs can facilitate frameshifting if there is sufficient competition for these tRNAs by other codons. Perhaps, a similar mechanism aids ribosomal realignment on the mutant tk mRNA.

A second possible mechanism for the translation of full-length TK is frameshift suppression (47). There are several examples of frameshift suppression in which a tRNA decodes four bases rather than three (e.g., a run of four guanosines for glycine, but such examples to date have entailed mutant tRNAs, rather than a naturally occurring tRNA (47). It should be interesting to determine the sequences and mechanisms that govern frameshifting in the mutant tk gene and whether such frameshifting occurs during translation of other DNA viruses or cellular genes in higher eukaryotes.

Implications for Drug Resistance and Pathogenesis. Given the importance of TK for pathogenesis in animal models of HSV infection, it has been paradoxical that many viruses associated with severe herpetic disease in humans were reported to express no detectable TK (4–13). Several of these viruses, like mutant 615.9, were reported to express truncated TK polypeptides and/or contain frameshift mutations so that they would be expected to be completely TK− (7, 13, 39). A described role for 615.9 acyclovir-resistant mutations, that express rather low levels of TK can reactivate from latency and exhibit other pathogenic phenotypes (17–20). For several of these, it has often proven difficult to detect TK activity by standard enzyme assays (18, 20); this has also been true for mutant 615.9 (E.P. and D.M.C., unpublished data). Thus, our results raise the possibility that certain clinical isolates that have been reported to be TK− might express low levels of TK due to frameshifting or other mechanisms. Continued molecular analyses of such mutants may illuminate mechanisms of clinical resistance and uncover interesting mechanisms of gene expression. We speculate that during the evolution of acyclovir-resistant virus in patients with serious HSV disease, there is selection for mutants such as 615.9 that are resistant to acyclovir yet express low levels of TK sufficient for pathogenesis. This may account for our having detected the unusual phenomenon of net +1 frameshifting in mammalian cells.

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