

Research

Open Access

Analysis of HIV-1 Vpr determinants responsible for cell growth arrest in *Saccharomyces cerevisiae*

Xiao-Jian Yao^{1,2}, Nicole Rougeau¹, Ghislaine Duisit¹, Julie Lemay¹ and
Éric A Cohen*¹

Address: ¹Laboratoire de Rétrovirologie Humaine, Département de Microbiologie et Immunologie, Faculté de Médecine, Université de Montréal, Montréal, Québec H3C 3J7, Canada and ²Current address : Dept. of Medical Microbiology, University of Manitoba, Basic Medical Sciences Building, 730 William Avenue, Winnipeg, Manitoba R3E 0W3, Canada

Email: Xiao-Jian Yao - yao2@cc.umanitoba.ca; Nicole Rougeau - nicole.rougeau@umontreal.ca; Duisit Ghislaine - g.duisit@umontreal.ca; Julie Lemay - j.lemay@pasteur.fr; Éric A Cohen* - eric.cohen@umontreal.ca

* Corresponding author

Published: 16 August 2004

Received: 30 June 2004

Retrovirology 2004, 1:21 doi:10.1186/1742-4690-1-21

Accepted: 16 August 2004

This article is available from: <http://www.retrovirology.com/content/1/1/21>

© 2004 Yao et al; licensee BioMed Central Ltd.

This is an open-access article distributed under the terms of the Creative Commons Attribution License (<http://creativecommons.org/licenses/by/2.0>), which permits unrestricted use, distribution, and reproduction in any medium, provided the original work is properly cited.

Abstract

Background: The HIV-1 genome encodes a well-conserved accessory gene product, Vpr, that serves multiple functions in the retroviral life cycle, including the enhancement of viral replication in nondividing macrophages, the induction of G2 cell-cycle arrest, and the modulation of HIV-1-induced apoptosis. We previously reported the genetic selection of a panel of di-tryptophan (W)-containing peptides capable of interacting with HIV-1 Vpr and inhibiting its cytostatic activity in *Saccharomyces cerevisiae* (Yao, X.-J., J. Lemay, N. Rougeau, M. Clément, S. Kurtz, P. Belhumeur, and E. A. Cohen, *J. Biol. Chem.* v. 277, p. 48816–48826, 2002). In this study, we performed a mutagenic analysis of Vpr to identify sequence and/or structural determinants implicated in the interaction with di-W-containing peptides and assessed the effect of mutations on Vpr-induced cytostatic activity in *S. cerevisiae*.

Results: Our data clearly shows that integrity of N-terminal α -helix I (17–33) and α -helix III (53–83) is crucial for Vpr interaction with di-W-containing peptides as well as for the protein-induced cytostatic effect in budding yeast. Interestingly, several Vpr mutants, mainly in the N- and C-terminal domains, which were previously reported to be defective for cell-cycle arrest or apoptosis in human cells, still displayed a cytostatic activity in *S. cerevisiae* and remained sensitive to the inhibitory effect of di-W-containing peptides.

Conclusions: Vpr-induced growth arrest in budding yeast can be effectively inhibited by GST-fused di-W peptide through a specific interaction of di-W peptide with Vpr functional domain, which includes α -helix I (17–33) and α -helix III (53–83). Furthermore, the mechanism(s) underlying Vpr-induced cytostatic effect in budding yeast are likely to be distinct from those implicated in cell-cycle alteration and apoptosis in human cells.

Background

Human immunodeficiency virus 1 (HIV-1) Vpr is a small virion-associated protein that is incorporated into virions

through a specific interaction with the p6 domain of the p55^{gag} precursor protein [1,2]. Increasing evidence suggests that Vpr plays important roles during HIV-1

replication and pathogenesis. First, virion-associated Vpr has been shown to act early in viral infection as a facilitator of HIV-1 preintegration complex (PIC) entry through the limiting nuclear pore. This activity of Vpr is thought to be responsible for Vpr's ability to enhance HIV-1 replication in nondividing cells, most notably in terminally differentiated macrophages [3-5]. Second, expression of Vpr induces a G2 cell cycle arrest, which is thought to indirectly enhance viral replication by increasing transcription from the HIV-1 long terminal repeat (LTR) [6,7].

Even though the molecular mechanism of Vpr-mediated cell-cycle G2 arrest is still obscure, it has been known that Vpr expression leads to inactivation of the mitotic p34cdc2/cyclinB complex in human cells [8,9] as well as in fission yeast *Schizosaccharomyces pombe* (*Sc. Pombe*) [10-14]. Involvement of protein phosphatase 2A (PP2A), Wee1, Cdc25C, and 14-3-3 proteins has also been implicated [8-12,14] but the host cell proteins directly engaged by Vpr are not yet identified. Noteworthy, HIV-1 Vpr expression induces also a growth arrest in *Saccharomyces* (*S.*) *cerevisiae* [15-17]. Deletion mapping studies showed that the C-terminal 33 amino acids, including the H(S/F)RIG motif, contributed to this cytostatic effect [15,18]. Although this region has also been implicated in Vpr-mediated cell-cycle dysregulation in mammalian and *S. Pombe* cells [19-25], the molecular mechanism of Vpr-growth arrest in budding yeast is thought to be distinct since growth arrest occurs independently of any evident block at the G2/M transition [16]. Accordingly, it has been reported that the G2/mitosis transition in budding yeast is regulated differently than in mammalian cells and fission yeast [26,27]. Indeed, Vpr cytostatic effect observed in *S. cerevisiae* has been proposed to result from gross mitochondrial dysfunction [17] and/or cytoskeletal defects [16], rather than a cell cycle G2 arrest.

In addition to nuclear import and cytostatic activities, HIV-1 Vpr exhibits cytotoxic properties. Elevated intracellular expression or addition of extracellular Vpr or derived peptides results in proapoptotic effects in human cells including neurons [6,28,29] as well as cytotoxicity in budding and fission yeasts [30,31]. Jacotot *et al.* have provided evidence indicating that extracellular Vpr or peptides derived from Vpr C-terminus induce mitochondrial dysfunction in human cells by a mechanism involving a specific binding to the adenine nucleotide translocator (ANT), a component of the permeability transition pore complex (PTPC) in the mitochondrial membrane. The resulting mitochondrial membrane permeabilization (MMP) leads to a decreased membrane potential and the release of cytochrome c and apoptosis inducing factor (AIF) [32,33]. This Vpr-mediated MMP is thought to initiate cell death through both caspase-dependent and independent mechanisms in human cells

as well as cytotoxicity in budding yeast [32-37]. In addition, it has also been shown that extracellular Vpr is capable of forming cation-selective ion channels in planar lipid bilayers, which can depolarize intact cultured neurons, thus leading to cell death [28].

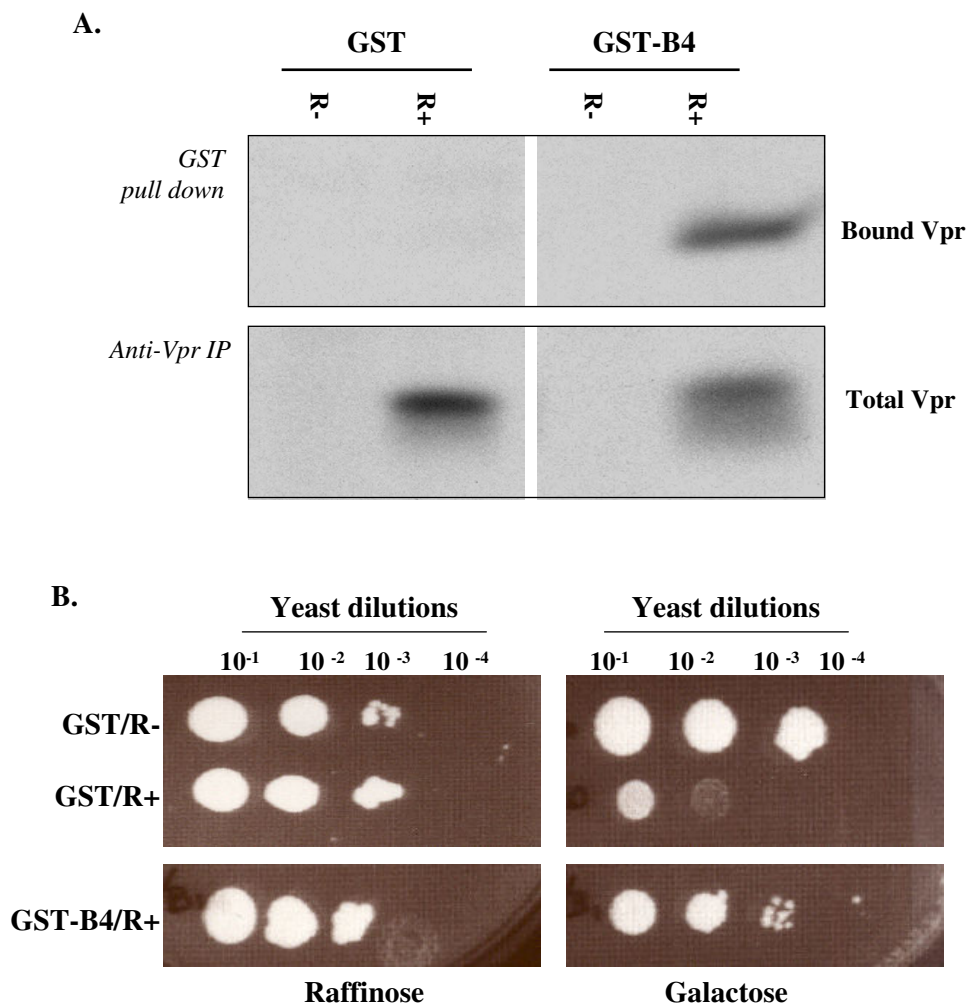
In a previous report, we have shown that expression of genetically-selected glutathione-S-transferase (GST)-fused di-tryptophan (di-W)-containing peptides inhibited Vpr-mediated growth arrest in *S. cerevisiae* presumably by interacting with Vpr [38]. Interestingly, these, di-W-containing peptides were also able to inhibit Vpr biological activities, including nuclear import, cell cycle G2 arrest and apoptosis, in mammalian cells or HIV-1 infected T cells [38]. Even though the inhibitory effect of these di-W-containing peptides correlated with their ability to interact with Vpr in budding yeast, the detailed mechanism underlying their mode of action remains to be defined. In addition, it is still unclear whether the growth arrest activity of Vpr in budding yeast is related to specific biological activities of Vpr in human cells. In this study, we have performed a mutagenic analysis of Vpr to identify Vpr domains important for di-W peptide binding and cytostatic activity in *S. cerevisiae*. Results reveal that the inhibitory di-W-containing peptides target specifically a functional domain of Vpr directly involved in growth arrest in budding yeast. Furthermore, several previously well-characterized Vpr mutants unable to induce cell-cycle dysregulation and/or apoptosis in mammalian cells still exhibit strong growth arrest activity in budding yeast, indeed suggesting that Vpr carries out distinct functions in *S. cerevisiae*.

Results

Analysis of Vpr sequence and/or structural determinants implicated in the interaction with di-W-containing peptides

We have previously used a genetic selection system in *S. cerevisiae* budding yeast and selected a panel of di-W-containing GST-peptides that specifically inhibit Vpr-mediated yeast growth arrest function presumably through their ability to bind HIV-1 Vpr [38]. In this study, we further investigated the molecular mechanism of this inhibition using a newly selected GST-fused di-W peptide WWSFKSV (GST-B4), which displayed an enhanced ability to bind Vpr and inhibit its growth arrest activity in budding yeast (Fig. 1A and 1B).

Structural studies performed with synthetic forms of Vpr indicate that Vpr is characterized by a well-defined gamma turn (14-16)-alpha helix (α -helix I: 17-33)-turn (34-36), followed by an alpha helix (α -helix II: 40-48)-loop (49-54)-alpha helix (α -helix III: 55-83) domain and ends with a very flexible C-terminal arginine-rich sequence [39]. The α -helical determinants were shown

**Figure 1**

GST-B4 peptide binds to HIV-1 Vpr in *S. cerevisiae* and rescues cell growth. (A) GST pull-down from yeast extracts. *S. cerevisiae* HPI6 strain co-transformed with GST or GST-B4 plasmids and (R⁺) or (R⁻) Vpr expressor were metabolically-labeled with 150 μ Ci of ³⁵S-Translabel in Vpr-inducible medium. Half volume of the cell extract was used for GST pull-down, while the remaining lysates were subjected to immunoprecipitation with polyclonal anti-Vpr antiserum. Total and GST-bound radiolabeled Vpr proteins were detected by autoradiography after SDS-PAGE. (B) GST-B4 suppression of Vpr-induced cell growth arrest. Yeast co-transformants were grown in non-inducible selective medium for two days. Similar number of yeast cells were then serially diluted, spotted onto either Vpr non-inducible (Trp⁻/Ura⁻, 2% raf) or Vpr-inducible plates (Trp⁻/Ura⁻, 2% gal) and incubated for 3 to 5 days to evaluate their growth rates. This data is representative of results obtained in two independent experiments

to be required for Vpr virion incorporation, nuclear localization and oligomerization [39-44] and are believed to be involved in heterologous protein binding [45]. The arginine rich C-terminal region of Vpr has not been shown to have a predicted structure, however this region harbors protein phosphorylation sites and plays an important role in cell cycle G2 arrest and the nuclear localization of the protein in mammalian cells [6,31,46]. To further investigate the sequence and/or structural require-

ment of Vpr for GST-B4 binding, mutations were introduced in p424Gal1-Vpr expressor to target different regions of Vpr (Fig. 2A). The N-terminal Q3R mutant was shown to affect Vpr proapoptotic activity during HIV-1 replication [47]. Four amino acids Glu21, Leu23, Glu25 and Ala30 were separately changed to Lys or Phe (E21K, L23F, E25K and A30F) in order to disrupt the amphipaticity of the first α -helix [39] (Fig. 2A). The F34I was introduced in a γ -turn region which is just after the α -helix I

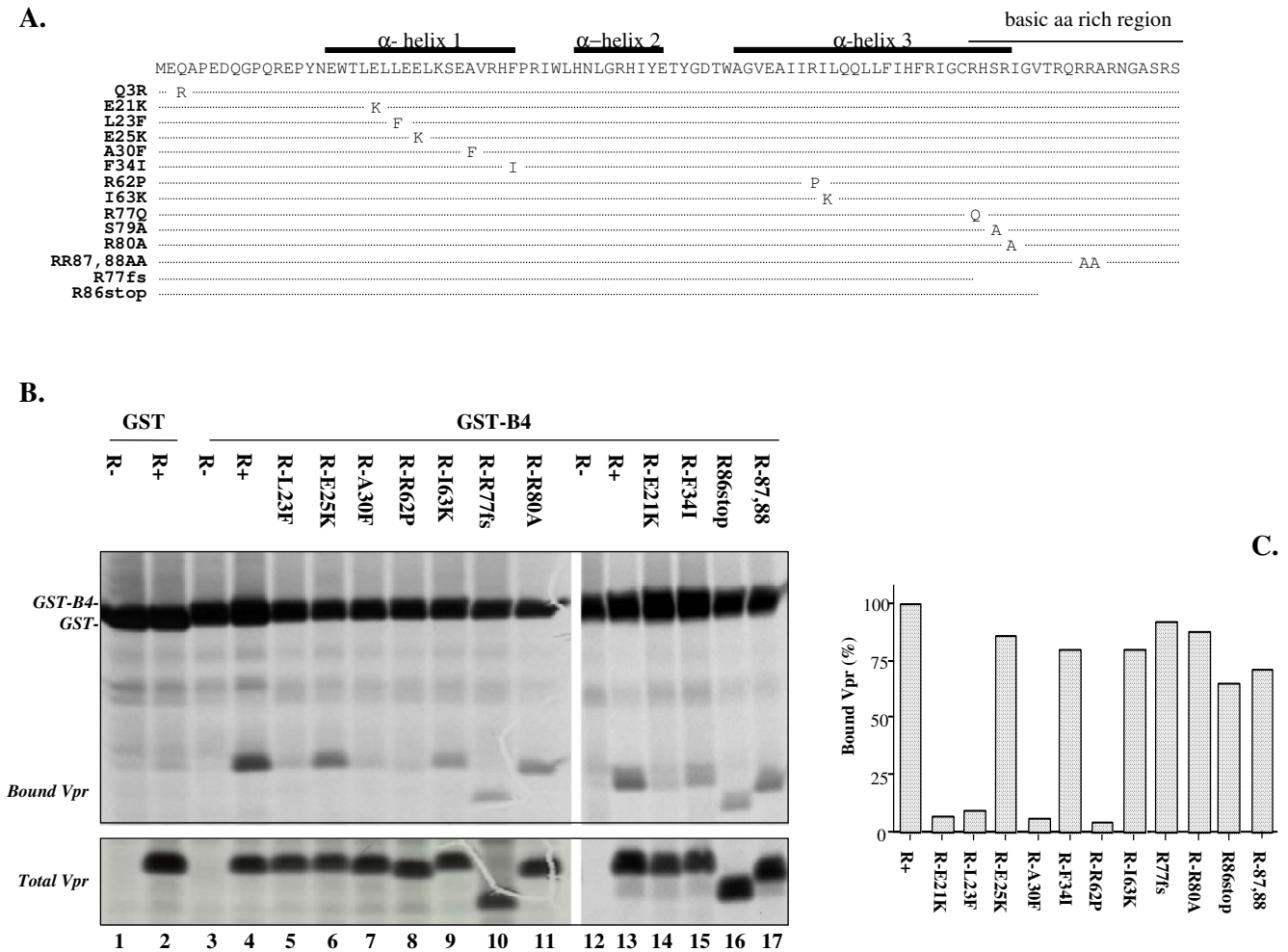


Figure 2

HIV-1 Vpr mutants exhibit differential GST-B4 binding abilities. Each Vpr mutant used in this study with the exact location of the introduced mutation is described (A). (B) GST pull-down using a panel of Vpr mutants. Assays were performed as described in Fig. 1A. Protein extracts were prepared from radiolabeled cells expressing GST (lanes 1–2) or GST-B4 proteins (lanes 3–17) alone (R-), or in presence of wild-type Vpr (R+) or different mutant proteins, as indicated. Vpr bound to GST-B4 (upper panel) and the total amount of Vpr as determined using immunoprecipitation with anti-Vpr antiserum (lower panel) were separated by SDS-PAGE and detected after autoradiography. (C) The percentage of GST-B4-bound Vpr relative to the total amounts of Vpr for each mutant was quantified by autoradiography scanning and the level of wild type Vpr bound to GST-B4 was arbitrarily set as 100%. These data are representative of at least two independent experiments.

[39]. The R62P and I63K mutations introduced in the third helix were aimed at interfering with the integrity of the α -helix and are known to abolish Vpr nuclear localization [41]. Four mutants in the C-terminal region, including, R77Q, S79A, R80A and R87, 88, were generated to replace positively-charged arginine residues or to remove the critical phosphorylation site (Ser 79) of the protein. Vpr mutants S79A and R80A were reported to be defective for cell cycle G2 arrest activity in mammalian cells, while the proapoptotic activity of R77Q was severely attenuated

[6,24,48]. In addition, a frameshift mutation (R77fs) [40] and a truncation mutation (R86stop), which prematurely terminate the protein at amino acid 77 and 86 respectively were also constructed.

To determine the impact of the Vpr mutations on GST-B4 peptide binding, HP-16 yeast co-transformed with mutated-Vpr expressors and either GST or GST-B4 vectors were radio-labeled in Vpr-inducible medium and subjected to GST pull-down assays (Fig. 2B), as described in

Materials and Methods. Moreover, the amount of wild type Vpr or each mutant bound to GST-B4 peptide was evaluated by laser densitometric scanning of bands in autoradiograms and normalized to the total amounts of Vpr and GST proteins that were expressed in each transformant. The amounts of wild type Vpr bound to GST-B4 was arbitrarily set as 100% (Fig. 2C). Results of figure 2B reveal that all Vpr mutants were expressed at comparable levels, as determined by Vpr immunoprecipitation of induced-cell lysates with the exception of Vpr (R77fs), which indeed was previously reported to be less stable than wild type Vpr [40] (Fig. 2B, lower panel). While no Vpr interacted with GST (Fig. 2B, upper panel, lane 2), similar levels of wild type Vpr, E25K, F34I, I63K, R77fs, R80A, R87, 88 and R86stop mutants were pulled-down with GST-B4 (Fig. 2B, upper panel and 2C). Similar results were obtained for Vpr mutants Q3R, R77Q, S79A (data not shown). In contrast, E21K, L23F, A30F and R62P mutants, which are respectively located in α -helix I and α -helix III regions, were not co-pulled down with GST-B4 (Fig. 2B (upper panel, lanes 5, 7, 8 and 14) and 2C). Taken together, these results suggest that the integrity of the N-terminal α -helix I and the α -helix III of Vpr are crucial for GST-B4 binding, whereas the C-terminal domain is dispensable for the interaction.

Vpr mutants defective for GST-B4 binding are unable to arrest yeast cell growth

We next tested the growth arrest activity of these Vpr mutants in HP-16 yeast. Growing yeast cells transformed with the empty vector (R-), wild-type (R+) or mutated Vpr expressors were serially diluted and spotted onto either a Vpr non-inducible plate (Trp^r, 2% raf) or a Vpr-inducible plate (Trp^r, 2% gal). Cell growth was evaluated following an incubation of 3–5 days at 30°C (Fig. 3). In Vpr non-inducible plate, all yeast transformants grew at similar rate (Fig. 3, left panel). Upon galactose induction, while the empty vector (R-)-transformed yeast grew efficiently (Fig. 3, lanes 1, 8 and 15), the wild-type Vpr (lanes 2, 9 and 16), the Q3R mutant and all proteins mutated in the C-terminal region, including R77Q, S79A, R80A exhibited a profound growth arrest activity (Fig. 3, right panel (lanes 10,13, 14 and 18)). Similar results were obtained for R-87,88 and R86stop mutants (data not shown), indicating that the C-terminal arginine-rich region of Vpr is not involved in budding yeast growth arrest activity. Of note, R77fs showed an impaired growth arrest activity (Fig. 3, lane 17), which is most likely due to the shorter half-life of this truncated protein, as reported before [40]. In contrast, expression of helices I and III Vpr mutants, E21K, L23F, A30F and R62P, which displayed a strong attenuation of binding to GST-B4, did not lead to HP-16 budding yeast growth arrest (Fig. 3, right panel, lanes 3, 4, 6 and 11). On the contrary, helix I or III mutants E25K, F34I, and I63K, which were able to interact with GST-B4, still

exhibited growth arrest activity, even though at reduced levels as compared to wild-type Vpr (Fig. 3, right panel, 5, 7 and 12). These results indicate that Vpr helices I and III represent an important functional domain involved in growth arrest in budding yeast.

GST-B4 inhibits the cytostatic activity of Vpr mutants and rescues cell growth

To further investigate the correlation between the inhibitory effect of GST-B4 and its Vpr-binding ability, GST or GST-B4 were co-expressed with two GST-B4-binding defective Vpr mutants E21K and L23F or with two GST-B4-binding competent mutants E25K and F34I in HP-16 yeast and the resulting cell growth was monitored in Vpr-inducible plates as described above. In agreement with the data of figure 3, in the presence of GST alone, mutants E25K and F34I induced significant yeast growth arrest, while such activity was severely impaired for B4-binding defective mutants E21K and L23F (Fig. 4, left panel). In contrast, GST-B4 co-expression strongly inhibited the growth arrest activity of the wild type Vpr, E25K and F34I mutants and indeed restored their cell growth at a level comparable to that of yeast cells expressing E21K or L23F (Fig. 4, right panel). A weak inhibitory activity of B4 was also observed with mutants E21K and L23F (lanes 3 and 4). It is possible that this may reflect a weak or instable interaction between B4 and Vpr mutants E21K and L23F, which could not be clearly detected in the binding experiments (Fig. 3). Overall, these results clearly indicate that GST-B4 specifically binds to structural determinants that are important for inducing cell growth arrest. Moreover, as described previously (38), the binding efficiency of B4 peptides correlates with the extent of the peptide inhibitory activity.

Discussion

We have previously shown that GST-fused di-W-containing peptides were able to interact with HIV-1 Vpr and as a result inhibit its multiple functions in budding yeast as well as in HIV-1 infected T cells [38]. In the present study we have further investigated the sequence and/or structural determinants required for Vpr/peptide interaction and determined their impact on Vpr cytostatic activity in budding yeast. Results clearly show that GST-fused B4 peptide interaction with Vpr involves the α -helical I and III structure of Vpr. Mutations affecting the integrity of these helical regions not only interfered with the interaction with GST-B4 peptide, but also failed to induce a cytostatic activity in budding yeast. Furthermore, Vpr mutants, including Q3R, R77Q, R80A and S79A, yet defective for cell-cycle arrest or apoptosis in mammalian cells, still induced a growth arrest in *S. cerevisiae* and displayed sensitivity to GST-B4 inhibition. Overall, these results indicate that GST-fused di-W-containing peptides directly target functional domains of HIV-1 Vpr responsible for

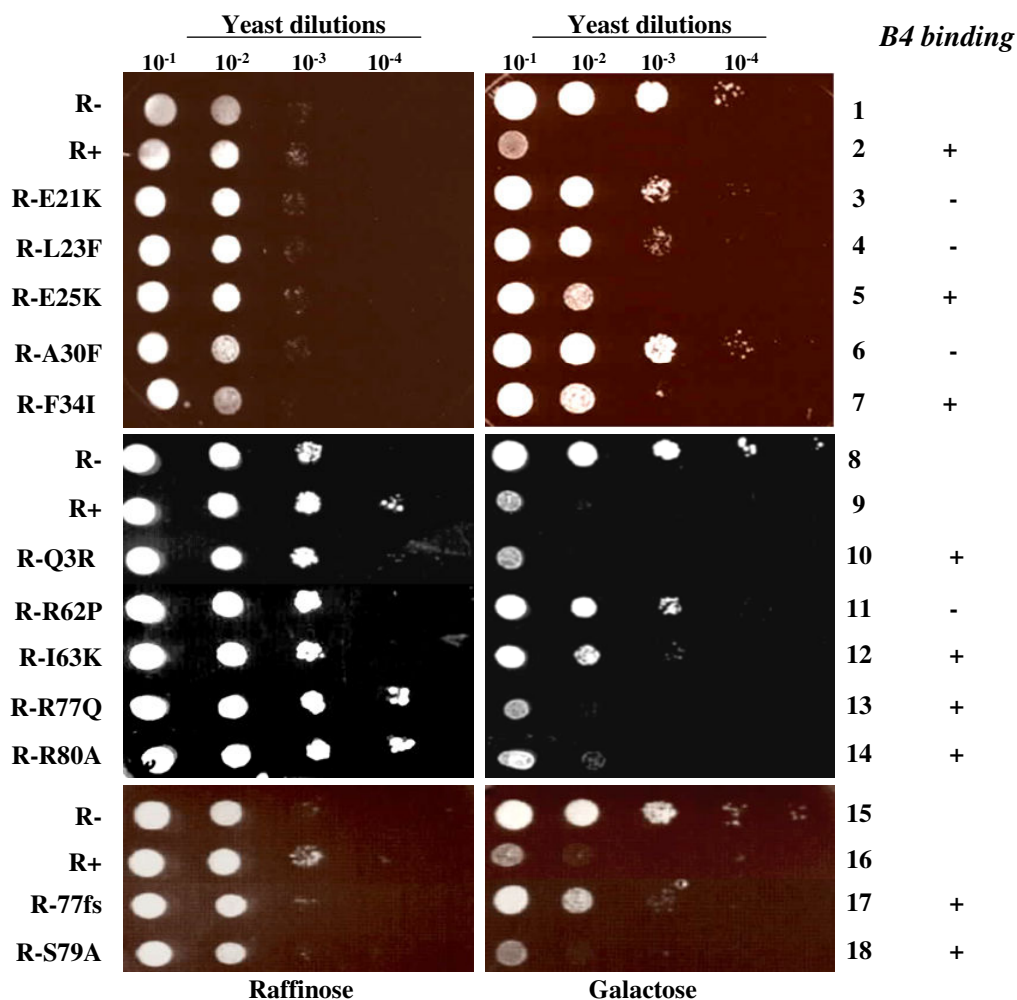


Figure 3

The growth arrest activity of different Vpr mutants. *S. cerevisiae* HPI6 yeast was transformed with the p424GalI expressor alone (R-) or coding for wild-type (R+) or each mutant, as indicated at the left of photograph, and first grown in non-inducible medium for 2 days. Then, similar amounts of transformed yeast were serially 10^x diluted and spotted onto either non-inducible (Trp-, 2% raf) or Vpr-inducible (Trp-, 2% gal) plates and incubated for 3 days to evaluate their growth rates. This data is representative of at least two independent experiments. The ability of each mutant to bind the B4 peptide is indicated on the right. (+) indicates efficient binding while (-) indicates absence of binding.

inducing growth arrest in budding yeast and strongly suggest that the mechanism(s) underlying Vpr-induced cytostatic effect in budding yeast are distinct from those implicated in cell-cycle alteration and apoptosis in mammalian cells.

Previous reports have indicated that the Vpr cytostatic activity in *S. cerevisiae* budding yeast was attributed to its last 63–96 amino acid (aa) and the critical domain was located in a conserved C-terminal HFRIGCRHSRIG sequence from aa 71 to 82 [15]. In contrast, our results showed that expression of a truncated Vpr encompassing

aa 1 to 77 was sufficient to induce growth arrest (Fig. 3), suggesting that the sequence of HFRIG (aa 71 to 75), but not HSRIG (aa 78 to 82) and other C-terminal region of Vpr, may constitute one important determinant for this Vpr-induced phenotype. Consistently, a mutagenic analysis by Berglez *et al.*, revealed that substitution mutations of aa His71 or Gly75 in this HFRIG sequence abolished Vpr cytostatic effect in budding yeast [18]. Interestingly, our analysis clearly reveal that the N-terminal α -helix I and the α -helix III are both contributing to Vpr cytostatic effect, which is in agreement with a previous finding by Gu *et al* showing that the Vpr F34I mutant was unable to

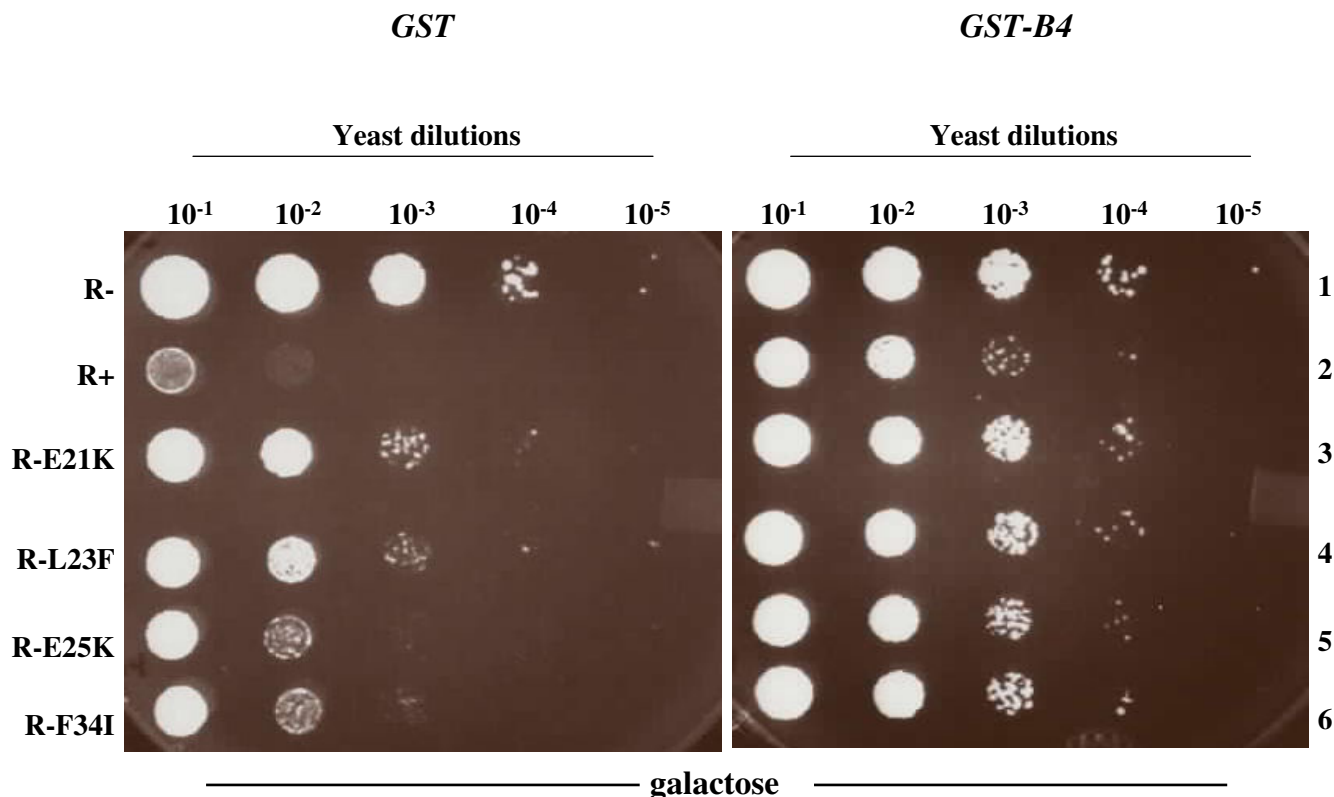


Figure 4

Comparison of GST-B4-mediated inhibition of the growth arrest activity of different Vpr mutants. *S. cerevisiae* HPI6 yeast co-expressing GST (left panel) or GST-B4 (right panel) and a panel of representative Vpr mutants, as indicated, were serially 10^x diluted and plated on Vpr-inducible and selective (Trp/Ura, 2% gal) plates as described in Fig. 3. The respective cell growth was evaluated after a 3-day incubation. This data is representative for two independent experiments.

induce a growth arrest phenotype in budding yeast [16]. On the basis of the Vpr NMR structure reported by Wecker *et al* [39], mutations E21K, L23F, E25K and A30F located within the α -helix I (from aa 17 to 33) were designed to disrupt either the negatively-charged cluster or the hydrophobic interface. With the exception of E25K mutant, all other mutations in this N-terminal α -helical region lead to the loss of Vpr cytosstatic function (Fig. 3). In addition, disruption of the third α -helix by introduction of a proline at position 62 (R62P) suppressed Vpr-induced growth arrest, suggesting that integrity of α -helices I and III was required for Vpr cytosstatic activity in budding yeast. It was also noted that E25K and I63K still induced a low level of growth arrest compared to other helical

region mutants (Fig. 3). It could be possible that E25K is somewhat external to the spatially-aligned acidic cluster D17-E21-E24 [39], and may be therefore less critical. Similarly, the I63K mutation may have a minor impact on the tridimensional structure of helix III as compared to the introduction of a proline residue as with the R62P Vpr mutant.

One striking observation of this study is that the four mutants (E21K, L23F, A30F and R62P) located in the α -helical I and III regions of Vpr, which were defective for the cytosstatic activity in budding yeast (Fig. 3) also lost the ability to interact with the inhibitory GST-B4 peptide (Fig. 2). It indicates that GST-B4 directly targets a critical

functional domain, possibly a structural cluster comprising both of α -helical I and III, that is responsible for cytostatic activity. Interestingly, the sequence of GST-B4 (GST-WWSKKS_V) reveals that, in addition to a conserved di-W motif [38], it also harbors an overlapping WxxF motif, which has been previously isolated by phage-display as a Vpr-binding motif and is present in Vpr-interacting protein uracil DNA glycosylase (UDG) [49]. Coincidentally, a bipartite domain encompassing Vpr amino acids 15–27 and 63–77 was also shown to be involved in UDG binding [50]. Based on these observations, it appears that similar regions of Vpr are involved in binding to UDG and GST-B4 through targeting of a WxxF element. However, E25K and F34I mutants, which were shown to be defective for UDG binding in two-hybrid assays [21], were still able to interact with GST-B4 *in vivo*. Such a difference may specifically rely on the hydrophobic di-W motif, which is not present in UDG [49].

Up to date, how HIV-1 Vpr induces a growth arrest in budding yeast remains an open question. During HIV-1 replication, the expression of Vpr has been shown to induce a cell cycle G2 arrest resulting from the inactivation of the mitotic p34cdc2/cyclinB complex [51]. In contrast, Vpr-mediated growth arrest in budding yeast is thought to occur through a distinct mechanism(s), since it occurs independently of any evident block at the G2/M transition [16]. In this study, we tested a panel of well-characterized Vpr mutants for their ability to growth arrest HP-16 budding yeast. Interestingly, Vpr mutants (S79A and R80A) which were previously shown to be as stable as wild type Vpr but defective for cell-cycle G2 arrest in human cells [6,19,24] still induced strong growth arrest in budding yeast. Conversely, L23F, and R62P mutants, which are competent for cytostatic effect in mammalian cells, [20,41] were unable to block yeast growth. Therefore, it can be concluded that Vpr structural determinants required for growth arrest in *S. cerevisiae* and human cells are clearly distinct, implying that different molecular mechanisms governs Vpr activities in these different cell species. Moreover, our study also demonstrates that Vpr cytostatic effect in budding yeast is not related to the cytotoxic activity of the viral protein. Vpr exhibits different cytotoxic properties that implicate distinct domains of the viral protein. First, wild-type Vpr and its first 40 N-terminal amino acids can form cation-selective ion channels in lipid bilayers [28,52]. Depolarization of the plasma membrane resulting from inward sodium current eventually induces killing of polarized cells such as neurons. On the other hand, apoptosis in T cells is thought to be triggered by transduction of full-length Vpr or its C-terminal 52–96 moiety into cells and involves mitochondrial membrane permeabilization [33,53,54]. Resulting loss of mitochondrial transmembrane potential then induces the release of apoptogenic proteins, leading to caspase-dependent

(37,55,48) or caspase-independent [55] cell killing. The fact that both 17–33 and 55–83 alpha-helices are required for growth arrest in *S. cerevisiae* strongly suggests that the cytostatic effect observed in budding yeast is mechanistically distinct from effects resulting from ion channels formation or mitochondria permeabilization. Consistently, Q3R, R80A, R77Q Vpr mutants, which were previously shown to be as stable as wild type Vpr, but yet defective for apoptosis induction in human cells [6,47,48] were still able to block yeast growth in a B4-sensitive way.

Conclusions

Taken together, the results presented here provide evidence that Vpr triggers growth arrest in budding yeast by an undefined mechanism that is unrelated to Vpr-induced G2 arrest and apoptosis in mammalian cells. This Vpr-induced budding yeast growth arrest can be effectively inhibited by GST-fused di-W peptide through an interaction of di-W peptide with Vpr functional domain, which includes α helix I and III. These observations would support a model in which, Vpr interacts with a di-W-containing protein in *S. cerevisiae* to induce yeast growth arrest. The question that still remains unanswered at this point is whether this Vpr cytostatic activity in budding yeast can also play an important role during HIV-1 replication and viral pathogenesis and further investigations are currently underway to address this question.

Materials and methods

Yeast strain

The *S. cerevisiae* yeast strain used in this study was the protease-deficient HP-16 strain (*MAT α ura3-52 his3 Δ 1 leu2 trp1 Δ 63 prb1-1122 pep4-3 prc1-407*) [56]. Plasmid transformation was performed using the lithium acetate method [57].

Plasmids, antisera and chemicals

The HIV-1 Vpr yeast expression plasmid (p424Gal1-Vpr) and the negative control plasmid p424Gal1-R have been previously described [38]. To generate different p424Gal1-Vpr mutant expression plasmids, each of Vpr mutant cDNAs (Fig. 2A) was generated by a two-steps polymerase chain reaction (PCR)-based method [40] by using a 5'-primer (5'-CTGCTAGCGGATAGATGGGA-3') harboring a *Bam*HI site in front of the Vpr initiation codon, a 3'-primer (5'-GCATCGCTCGAGGATCTACTGGC-3') containing a *Xho*I site after the stop codon of Vpr and the complementary oligonucleotide primers containing the desired mutations. Amplified Vpr cDNA harboring specific mutations were then cloned into the p424Gal1 vector at *Bam*HI/*Xho*I sites. The Vpr mutants L23F, E25K, A30F, R62P, I63K, R77Q, R77fs and R80A were previously described [6,41,48]. The pPGK-GST plasmid was described previously [38] while the pPGK-GST-B4 expressor was isolated and purified from an *S. cerevisiae*

HP-16 yeast colony that was resistant to HIV-1 Vpr-mediated growth arrest as previously described [38].

The rabbit anti-Vpr polyclonal serum was raised against bacterially expressed recombinant Vpr as described previously [58]. Galactose, raffinose and glucose were purchased from Sigma Inc.

Evaluation of the growth arrest activity of Vpr mutants and the anti-Vpr activity of GST-peptide in budding yeast

The experimental procedures to evaluate protein expression, Vpr growth arrest activity and the anti-Vpr activity of GST-fused di-W peptide were described previously [38]. Briefly, HP-16 yeast cells transformed with p424Gal1-wild-type/mutant Vpr plasmids or co-transformed with Vpr expressors and pPGK-GST-B4 plasmid were first grown in a Vpr non-inducible selective medium (Trp⁻ or Trp⁻/Ura^r, 2% raffinose (raf⁺)) for 2 days. Then, suspensions of transformed HP-16 yeast cells (adjusted at similar cell densities) were serially diluted and spotted onto either a Vpr non-inducible plate (Trp⁻ or Trp⁻/Ura^r, 2% raf) or a Vpr-inducible plate (Trp⁻ or Trp⁻/Ura^r, 2% gal) to evaluate the growth of each co-transformed HP16 population.

GST pull-down assay and anti-Vpr immunoprecipitation

HP16 co-transformants were radiolabeled with 150 µCi of ³⁵S-Translabel (ICN Inc.) in Vpr-inducible medium and lysed in CHAPS buffer as previously described [38]. Cell extracts were then subjected to GST pull-down assay [4,38]. Briefly, lysates were incubated with glutathione-sepharose 4B beads (Amerham Pharmacia Biotech Inc) for 2 hours at 4°C. Beads were washed 3 times and the radiolabeled protein complexes were eluted with an elution buffer (100mM reduced glutathione, 120 mM NaCl, 100 mM Tris-HCl pH 8.5) by gentle shaking at 4°C for 1 hour. Eluted protein complexes were separated by SDS-PAGE and detected by autoradiography. For Vpr expression analysis, aliquots of labeled yeast lysates were immunoprecipitated with anti-Vpr antibodies as described previously [38,40].

Authors' contributions

X-J Y designed the experiments, constructed most Vpr mutants and wrote the manuscript. NR carried out the binding assays and tested the effect of Vpr mutants on yeast cells growth. JL selected and characterized the B4 GST-di-W-containing peptide. GD participated in the design of the study and critically evaluated the manuscript. EAC participated in the design of the study and coordinated it. All authors read and approved the final manuscript.

Acknowledgments

X-J. Yao is a recipient of a Médecine-Relève 2000-Messenger Foundation Award from the Faculté de Médecine, Université de Montréal. E.A. Cohen is the recipient of the Canada Research Chair in Human Retrovirology. This

work was supported by grants from the Canadian Institute of Health Research (CIHR) and the CANVAC network of excellence to EAC.

References

- Cohen EA, Dehni G, Sodroski JG, Haseltine WA: **Human immunodeficiency virus vpr product is a virion-associated regulatory protein.** *J Virol* 1990, **64**:3097-3099.
- Paxton W, Connor RI, Landau NR: **Incorporation of Vpr into human immunodeficiency virus type 1 virions: requirement for the p6 region of Gag and mutational analysis.** *J Virol* 1993, **67**:7229-7237.
- Popov S, Rexach M, Zybarth G, Reiling N, Lee MA, Ratner L, Lane CM, Moore MS, Blobel G, Bukrinsky M: **Viral protein R regulates nuclear import of HIV-1 pre-integration complex.** *EMBO J* 1998, **17**:909-917.
- Vodicka MA, Koepp DM, Silver PA, Emerman M: **HIV-1 Vpr interacts with the nuclear transport pathway to promote macrophage infection.** *Genes Dev* 1998, **12**:175-185.
- Heinzinger NK, Bukinsky MI, Haggerty SA, Ragland AM, Kewalramani V, Lee MA, Gendelman HE, Ratner L, Stevenson M, Emerman M: **The Vpr protein of human immunodeficiency virus type 1 influences nuclear localization of viral nucleic acids in nondividing host cells.** *Proc Natl Acad Sci U S A* 1994, **91**:7311-7315.
- Yao XJ, Moulard AJ, Subbramanian RA, Forget J, Rougeau N, Bergeron D, Cohen EA: **Vpr stimulates viral expression and induces cell killing in human immunodeficiency virus type 1-infected dividing Jurkat T cells.** *J Virol* 1998, **72**:4686-4693.
- Goh WC, Rogel ME, Kinsey CM, Michael SF, Fultz PN, Nowak MA, Hahn BH, Emerman M: **HIV-1 Vpr increases viral expression by manipulation of the cell cycle: a mechanism for selection of Vpr in vivo.** *Nat Med* 1998, **4**:65-71.
- He J, Choe S, Walker R, Di Marzio P, Morgan DO, Landau NR: **Human immunodeficiency virus type 1 viral protein R (Vpr) arrests cells in the G2 phase of the cell cycle by inhibiting p34cdc2 activity.** *J Virol* 1995, **69**:6705-6711.
- Re F, Braaten D, Franke EK, Luban J: **Human immunodeficiency virus type 1 Vpr arrests the cell cycle in G2 by inhibiting the activation of p34cdc2-cyclin B.** *J Virol* 1995, **69**:6859-6864.
- Elder RT, Yu M, Chen M, Edelson S, Zhao Y: **Cell cycle G2 arrest induced by HIV-1 Vpr in fission yeast (Schizosaccharomyces pombe) is independent of cell death and early genes in the DNA damage checkpoint.** *Virus Res* 2000, **68**:161-173.
- Elder RT, Yu M, Chen M, Zhu X, Yanagida M, Zhao Y: **HIV-1 Vpr induces cell cycle G2 arrest in fission yeast (Schizosaccharomyces pombe) through a pathway involving regulatory and catalytic subunits of PP2A and acting on both Wee1 and Cdc25.** *Virology* 2001, **287**:359-370.
- Masuda M, Nagai Y, Oshima N, Tanaka K, Murakami H, Igarashi H, Okayama H: **Genetic studies with the fission yeast Schizosaccharomyces pombe suggest involvement of wee1, ppa2, and rad24 in induction of cell cycle arrest by human immunodeficiency virus type 1 Vpr.** *J Virol* 2000, **74**:2636-2646.
- Zhao Y, Cao J, O'Gorman MR, Yu M, Yorgev R: **Effect of human immunodeficiency virus type 1 protein R (vpr) gene expression on basic cellular function of fission yeast Schizosaccharomyces pombe.** *J Virol* 1996, **70**:5821-5826.
- Zhang C, Rasmussen C, Chang LJ: **Cell cycle inhibitory effects of HIV and SIV Vpr and Vpx in the yeast Schizosaccharomyces pombe.** *Virology* 1997, **230**:103-112.
- Macreadie IG, Castelli LA, Hewish DR, Kirkpatrick A, Ward AC, Azad AA: **A domain of human immunodeficiency virus type 1 Vpr containing repeated H(S/F)RIG amino acid motifs causes cell growth arrest and structural defects.** *Proc Natl Acad Sci U S A* 1995, **92**:2770-2774.
- Gu J, Emerman M, Sandmeyer S: **Small heat shock protein suppression of Vpr-induced cytoskeletal defects in budding yeast.** *Mol Cell Biol* 1997, **17**:4033-4042.
- Macreadie IG, Thorburn DR, Kirby DM, Castelli LA, de Rozario NL, Azad AA: **HIV-1 protein Vpr causes gross mitochondrial dysfunction in the yeast Saccharomyces cerevisiae.** *FEBS Lett* 1997, **410**:145-149.
- Berglez JM, Castelli LA, Sankovich SA, Smith SC, Curtain CC, Macreadie IG: **Residues within the HFRIGC sequence of HIV-1 vpr involved in growth arrest activities.** *Biochem Biophys Res Commun* 1999, **264**:287-290.

19. Di Marzio P, Choe S, Ebright M, Knoblauch R, Landau NR: **Mutational analysis of cell cycle arrest, nuclear localization and virion packaging of human immunodeficiency virus type I Vpr.** *J Virol* 1995, **69**:7909-7916.
20. Forget J, Yao XJ, Mercier J, Cohen EA: **Human immunodeficiency virus type I vpr protein transactivation function: mechanism and identification of domains involved.** *J Mol Biol* 1998, **284**:915-923.
21. Selig L, Benichou S, Rogel ME, Wu LI, Vodicka MA, Sire J, Benarous R, Emerman M: **Uracil DNA glycosylase specifically interacts with Vpr of both human immunodeficiency virus type I and simian immunodeficiency virus of sooty mangabeys, but binding does not correlate with cell cycle arrest.** *J Virol* 1997, **71**:4842-4846.
22. Chen M, Elder RT, Yu M, O'Gorman MG, Selig L, Benarous R, Yamamoto A, Zhao Y: **Mutational analysis of Vpr-induced G2 arrest, nuclear localization, and cell death in fission yeast.** *J Virol* 1999, **73**:3236-3245.
23. Sawaya BE, Khalili K, Gordon J, Srinivasan A, Richardson M, Rappaport J, Amini S: **Transdominant activity of human immunodeficiency virus type I Vpr with a mutation at residue R73.** *J Virol* 2000, **74**:4877-4881.
24. Zhou Y, Ratner L: **Phosphorylation of human immunodeficiency virus type I Vpr regulates cell cycle arrest.** *J Virol* 2000, **74**:6520-6527.
25. Mueller SM, Lang SM: **The first HxRxG motif in simian immunodeficiency virus mac239 Vpr is crucial for G(2)/M cell cycle arrest.** *J Virol* 2002, **76**:11704-11709.
26. Amon A, Surana U, Muroff I, Nasmyth K: **Regulation of p34CDC28 tyrosine phosphorylation is not required for entry into mitosis in *S. cerevisiae*.** *Nature* 1992, **355**:368-371.
27. Sorger PK, Murray AV: **S-phase feedback control in budding yeast independent of tyrosine phosphorylation of p34cdc28.** *Nature* 1992, **355**:365-368.
28. Piller SC, Ewart GD, Jans DA, Gage PW, Cox GB: **The amino-terminal region of Vpr from human immunodeficiency virus type I forms ion channels and kills neurons.** *J Virol* 1999, **73**:4230-4238.
29. Stewart SA, Poon B, Jowett JB, Chen IS: **Human immunodeficiency virus type I Vpr induces apoptosis following cell cycle arrest.** *J Virol* 1997, **71**:5579-5592.
30. Macreadie IG, Arunagiri CK, Hewish DR, White JF, Azad AA: **Extracellular addition of a domain of HIV-1 Vpr containing the amino acid sequence motif H(S/F)RIG causes cell membrane permeabilization and death.** *Mol Microbiol* 1996, **19**:1185-1192.
31. Zhao Y, Yu M, Chen M, Elder RT, Yamamoto A, Cao J: **Pleiotropic effects of HIV-1 protein R (Vpr) on morphogenesis and cell survival in fission yeast and antagonism by pentoxifylline.** *Virology* 1998, **246**:266-276.
32. Jacotot E, Ravagnan L, Loeffler M, Ferri KF, Vieira HL, Zamzami N, Costantini P, Druillennec S, Hoebeke J, Briand JP, Irinopoulou T, Daugas E, Susin SA, Coince D, Xie ZH, Reed JC, Roques BP, Kroemer G: **The HIV-1 viral protein R induces apoptosis via a direct effect on the mitochondrial permeability transition pore.** *J Exp Med* 2000, **191**:33-46.
33. Jacotot E, Ferri KF, El Hamel C, Brenner C, Druillennec S, Hoebeke J, Rustin P, Metivier D, Lenoir C, Geuskens M, Vieira HL, Loeffler M, Belzacq AS, Briand JP, Zamzami N, Edelman L, Xie ZH, Reed JC, Roques BP, Kroemer G: **Control of mitochondrial membrane permeabilization by adenine nucleotide translocator interacting with HIV-1 viral protein rR and Bcl-2.** *J Exp Med* 2000, **193**:509-519.
34. Muthumani K, Choo AY, Hwang DS, Chattergoon MA, Dayes NN, Zhang D, Lee MD, Duvvuri U, Weiner DB: **Mechanism of HIV-1 viral protein R-induced apoptosis.** *Biochem Biophys Res Commun* 2003, **304**:583-592.
35. Muthumani K, Hwang DS, Desai BM, Zhang D, Dayes N, Green DR, Weiner DB: **HIV-1 Vpr induces apoptosis through caspase 9 in T cells and peripheral blood mononuclear cells.** *J Biol Chem* 2002, **277**:37820-37831.
36. Patel CA, Mukhtar M, Pomerantz RJ: **Human immunodeficiency virus type I Vpr induces apoptosis in human neuronal cells.** *J Virol* 2000, **74**:9717-9726.
37. Stewart SA, Poon B, Song JY, Chen IS: **Human immunodeficiency virus type I vpr induces apoptosis through caspase activation.** *J Virol* 2000, **74**:3105-3111.
38. Yao X-J, Lemay J, Rougeau N, Clément M, Kurtz I S, Belhumeur P, Cohen EA: **Genetic selection of inhibitory peptides against Human Immunodeficiency Virus Type I Vpr.** *J Biol Chem* 2002, **277**:48816-48826.
39. Wecker K, Morellet N, Bouaziz S, Roques BP: **NMR structure of the HIV-1 regulatory protein Vpr in H2O/trifluoroethanol. Comparison with the Vpr N-terminal (1-15) and C-terminal (52-96 domains).** *Eur J Biochem* 2002, **269**:3779-3788.
40. Yao X-J, Subbramanian RA, Rougeau N, Boisvert F, Bergeron D, Cohen EA: **Mutagenic analysis of human immunodeficiency virus type I Vpr: role of a predicted N-terminal alpha-helical structure in Vpr nuclear localization and virion incorporation.** *J Virol* 1995, **69**:7032-7044.
41. Subbramanian RA, Yao XJ, Dilhuydy H, Rougeau N, Bergeron D, Robitaille Y, Cohen EA: **Human immunodeficiency virus type I Vpr localization: nuclear transport of a viral protein modulated by a putative amphipathic helical structure and its relevance to biological activity.** *J Mol Biol* 1998, **278**:13-30.
42. Wecker K, Roques BP: **NMR structure of the (1-51) N-terminal domain of the HIV-1 regulatory protein Vpr.** *Eur J Biochem* 1999, **266**:359-369.
43. Schuler W, Wecker K, de Rocquigny H, Baudat Y, Sire J, Roques BP: **NMR structure of the (52-96) C-terminal domain of the HIV-1 regulatory protein Vpr: molecular insights into its biological functions.** *J Mol Biol* 1999, **285**:2105-2117.
44. Singh SP, Tomkowicz B, Lai D, Cartas M, Mahalingam S, Kalyanaraman VS, Murali R, Srinivasan A: **Functional role of residues corresponding to helical domain II (amino acids 35 to 46) of human immunodeficiency virus type I Vpr.** *J Virol* 2000, **74**:10650-10657.
45. Zhao LJ, Wang L, Mukherjee S, Narayan O: **Biochemical mechanism of HIV-1 Vpr function: oligomerization mediated by the N-terminal domain.** *J Biol Chem* 1994, **269**:3231-3237.
46. Sherman MP, de Noronha CM, Heusch MI, Greene S, Greene WC: **Nucleocytoplasmic shuttling by human immunodeficiency virus type I Vpr.** *J Virol* 2001, **75**:1522-1532.
47. Somasundaran M, Sharkey M, Brichacek B, Luzuriaga K, Emerman M, Sullivan JL, Stevenson M: **Evidence for a cytopathogenicity determinant in HIV-1 Vpr.** *Proc Natl Acad Sci U S A* 2002, **99**:9503-9508.
48. Lum JJ, Cohen OJ, Nie Z, Weaver JG, Gomez TS, Yao XJ, Lynch D, Pilon AA, Hawley N, Kim JE, Chen Z, Montpetit M, Sanchez-Dardon J, Cohen EA, Badley AD: **Vpr R77Q is associated with long-term nonprogressive HIV infection and impaired induction of apoptosis.** *J Clin Invest* 2003, **111**:1547-1554.
49. BouHamdan M, Xue Y, Baudat Y, Hu B, Sire J, Pomerantz RJ, Duan LX: **Diversity of HIV-1 Vpr interactions involves usage of the WXXF motif of host cell proteins.** *J Biol Chem* 1998, **273**:8009-8016.
50. BouHamdan M, Benichou S, Rev F, Navarro JM, Agostini I, Spire B, Camonis J, Slupphaug G, Vigne R, Benarous R, Sire J: **Human immunodeficiency virus Vpr protein binds to the uracil DNA glycosylase DNA repair enzyme.** *J Virol* 1996, **70**:697-704.
51. Rogel ME, Wu LI, Emerman M: **The human immunodeficiency virus type I Vpr gene prevents cell proliferation during chronic infection.** *J Virol* 1995, **69**:882-888.
52. Piller SC, Jans P, Gage PW, Jans DA: **Extracellular HIV-1 virus protein R causes a large inward current and cell death in cultured hippocampal neurons: implications for AIDS pathology.** *Proc Natl Acad Sci U S A* 1998, **95**:4595-4600.
53. Ferri KF, Jacotot E, Blanco J, Este JA, Kroemer G: **Mitochondrial control of cell death induced by HIV-1-encoded proteins.** *Ann N Y Acad Sci* 2000, **926**:149-164.
54. Ferri KF, Jacotot E, Blanco J, Este JA, Zamzami N, Susin SA, Xie Z, Brothers G, Reed JC, Penninger JM, Kroemer G: **Apoptosis control in syncytia induced by the HIV type I-envelope glycoprotein complex: role of mitochondria and caspases.** *J Exp Med* 2000, **192**:1081-1092.
55. Roumier T, Vieira HL, Castedo M, Ferri KF, Boya P, Andreau K, Druillennec S, Joza N, Penninger JM, Roques B, Kroemer G: **The C-terminal moiety of HIV-1 Vpr induces cell death via a caspase-independent mitochondrial pathway.** *Cell Death Differ* 2002, **9**:1212-1219.
56. Park HO, Chant J, Herskowitz I: **BUD2 encodes a GTPase-activating protein for Bud1/Rsr1 necessary for proper bud-site selection in yeast.** *Nature* 1993, **365**:269-274.

57. Gietz D, St Jean A, Woods RA, Schiestl RH: **Improved method for high efficiency transformation of intact yeast cells.** *Nucleic Acids Res* 1992, **20**:1425-1430.
58. Lavallée C, Yao X-J, Ladha A, Göttlinger H, Haseltine WA, Cohen EA: **Requirement of the Pr55gag precursor for incorporation of the Vpr product into human immunodeficiency type I viral particles.** *J Virol* 1994, **68**:1926-1934.

Publish with **BioMed Central** and every scientist can read your work free of charge

"BioMed Central will be the most significant development for disseminating the results of biomedical research in our lifetime."

Sir Paul Nurse, Cancer Research UK

Your research papers will be:

- available free of charge to the entire biomedical community
- peer reviewed and published immediately upon acceptance
- cited in PubMed and archived on PubMed Central
- yours — you keep the copyright

Submit your manuscript here:
http://www.biomedcentral.com/info/publishing_adv.asp

