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Bcl-2 family proteins regulate the release of apoptogenic cytochrome c by the mitochondrial channel VDAC

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During transduction of an apoptotic (death) signal into the cell, there is an alteration in the permeability of the membranes of the cell's mitochondria, which causes the translocation of the apoptogenic protein cytochrome *c* into the cytoplasm, which in turn activates death-driving proteolytic proteins known as caspases^{1,2}. The Bcl-2 family of proteins, whose members may be anti-apoptotic or pro-apoptotic, regulates cell death by controlling this mitochondrial membrane permeability during apoptosis^{3–5}, but how that is achieved is unclear. Here we create liposomes that carry the mitochondrial porin channel (also called the voltage-dependent anion channel, or VDAC) to show that the recombinant pro-apoptotic proteins Bax and Bak accelerate the opening of VDAC, whereas the anti-apoptotic protein Bcl-x_L closes VDAC by binding to it directly. Bax and Bak allow cytochrome *c* to pass through VDAC out of liposomes, but passage is prevented by Bcl-x_L. In agreement with this, VDAC1-deficient mitochondria from a mutant yeast did not exhibit a Bax/Bak-induced loss in membrane potential and cytochrome *c* release, both of which were inhibited by Bcl-x_L. Our results indicate that the Bcl-2 family of proteins bind to the VDAC in order to regulate the mitochondrial membrane potential and the release of cytochrome *c* during apoptosis.

Bax- and Bak-dependent changes in mitochondrial membrane permeability that lead to loss of membrane potential ($\Delta\psi$) and cytochrome *c* release^{6–8} are mediated by a polyprotein channel called the permeability transition (PT) pore^{6,8,9}, which includes VDAC, the adenine nucleotide translocator (ANT) and cyclophilin D (refs 10, 11). VDAC is an abundant protein in the outer mitochondrial membrane which forms a large voltage-gated pore in planar lipid bilayers¹², and acts as the pathway for the movement of substances in and out of the mitochondrion. Bax and Bak interact with the PT pore^{8,9}. Bax binds to ANT and can sensitize ANT and PT pores in liposomes to atractyloside, an ANT ligand⁹.

During our search for Bcl-x_L-binding proteins in mitochondria using co-immunoprecipitation with an anti-Bcl-x_L antibody, we detected three proteins of relative molecular masses 33K, 18K and 13K (Fig. 1a). Partial amino-acid sequencing of the 33K protein revealed a match with rat VDAC. Co-immunoprecipitation followed by western blot analysis confirmed the interaction between Bcl-x_L and VDAC in isolated mitochondria (Fig. 1b) and also in Bcl-x_L-expressing HepG2 cells (Fig. 1c). No co-immunoprecipitable interaction of Bcl-x_L with Tom 40 (an integral outer-membrane protein) or with F₁-ATPase (an inner-membrane protein) was detected (data not shown), indicating that the interaction between Bcl-x_L and VDAC was specific. As the PT pore is a polyprotein

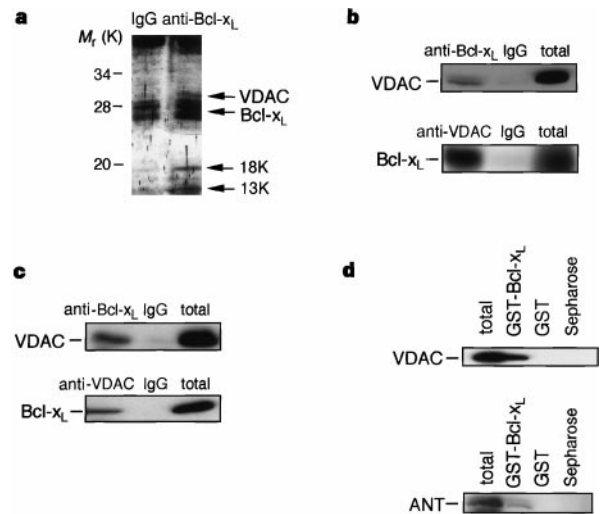


Figure 1 Interaction of Bcl-x_L with VDAC. **a**, Bcl-x_L-binding proteins. Rat liver mitochondria (1 mg ml⁻¹) were incubated with rBcl-x_L (20 mg ml⁻¹) for 5 min and their lysates were immunoprecipitated with anti-Bcl-x_L antibody or rabbit IgG. Immune complexes were analysed by SDS-PAGE and silver staining. **b**, Interaction of rBcl-x_L with VDAC in mitochondria. Mitochondria were incubated with rBcl-x_L, lysed and immunoprecipitated as in **a**, but also with anti-VDAC monoclonal antibody or normal mouse IgG. Anti-VDAC and anti-Bcl-x_L antibodies were used for western blotting. An aliquot of mitochondria (total) was used as the control. **c**, Interaction of rBcl-x_L with VDAC in HepG2 cells. Lysates of human Bcl-x_L-expressing HepG2 cells were immunoprecipitated as for **b**. **d**, Direct interaction between Bcl-x_L and VDAC or ANT. (See Methods for details.) Bound VDAC and ANT were analysed by western blotting; 'total' represents the amount of each protein used.

channel that includes VDAC, co-immunoprecipitation of Bcl-x_L and VDAC from the mitochondria and cells did not necessarily indicate their direct interaction. VDAC purified from rat liver mitochondria efficiently bound to a fusion protein between glutathione-S-transferase and Bcl-x_L (GST-Bcl-x_L), however, indicating that Bcl-x_L interacted directly with VDAC; similar results were obtained when recombinant VDAC was used (data not shown). ANT purified from rat heart bound only weakly to GST-Bcl-x_L (Fig. 1d), consistent with earlier observations⁹.

As Bcl-x_L binds VDAC, we tested the effect of Bcl-x_L on VDAC activity by using VDAC purified from rat liver mitochondria and reconstituted into liposomes. These VDAC liposomes could take up radiolabelled sucrose, whereas plain or heat-denatured VDAC-containing liposomes could not; uptake was greatly reduced in VDAC liposomes preincubated with a polyanion VDAC inhibitor (Fig. 2a), indicating that this sucrose uptake must be mediated by VDAC. Addition of recombinant (r)Bcl-x_L to VDAC liposomes inhibited VDAC-mediated sucrose uptake in a pH-dependent manner (Fig. 2b): Bcl-x_L functioned at acidic pH, consistent with observations that rBcl-x_L acts as an ion channel in synthetic lipid membranes only under acidic conditions^{13–16}. However, when both rBcl-x_L and VDAC were incorporated together into liposomes, Bcl-x_L was able to function at pH 7.3 (Fig. 2c), suggesting that incorporation of Bcl-x_L into the lipid membranes was favoured at lower pH. Although the VDAC has been reported to close below pH 5.0 (ref. 22), our VDAC liposomes showed no difference in behaviour between pH 5.2 and 7.3 (data not shown). VDAC was inhibited by rBcl-x_L in a concentration-dependent manner (Fig. 2d), and two Bcl-x_L mutants (mt-1; F131V, D133A; mt-7; VNW at 135–137 changed to ALL) having partial and no anti-apoptotic activity, respectively¹⁷, gave partial and no inhibition of VDAC-mediated sucrose uptake (Fig. 2d), indicating that those two activities could be linked. As shown in Fig. 2e, mt-1 and mt-7, respectively, bound

VDAC weakly and not at all, indicating that the inhibition of VDAC by Bcl-x_L depends on Bcl-x_L binding to VDAC. VDAC was also inhibited by Bcl-x_L in VDAC liposomes made with recombinant VDAC (Fig. 2f), confirming that VDAC is targeted by Bcl-x_L.

We next tested the effect of Bax on VDAC activity and found that rBax enhanced VDAC-mediated sucrose uptake at pH 5.2 (Fig. 3a), but that uptake of sucrose into plain liposomes incorporating Bax but without VDAC was low (Fig. 3a), indicating that the rBax-enhanced sucrose uptake by VDAC liposomes is mediated not by a putative Bax channel but by the effect of Bax on VDAC. We confirmed this by adding polyanion in the presence of Bax to VDAC liposomes, which significantly inhibited sucrose uptake

(Fig. 3a). As the interaction of VDAC and Bax was not inhibited by polyanion (data not shown), and as polyanion inhibited VDAC activity (Fig. 2a) but not Bax channel activity, as assessed by movement of rhodamine 123 (data not shown), we conclude that Bax enhances VDAC activity. Results were similar for VDAC liposomes made with recombinant VDAC, and when pro-apoptotic Bak (lacking the C-terminal 21 amino-acid residues) was used in place of rBax (Fig. 3b). With liposomes containing both rBax and VDAC, Bax could function at pH 7.3 (data not shown). Consistent with the effect of Bax and Bak on VDAC activity, rBax and rBak could bind purified VDAC (Fig. 3c). Binding between endogenous Bax and VDAC occurred in apoptotic but not intact PC12 cells

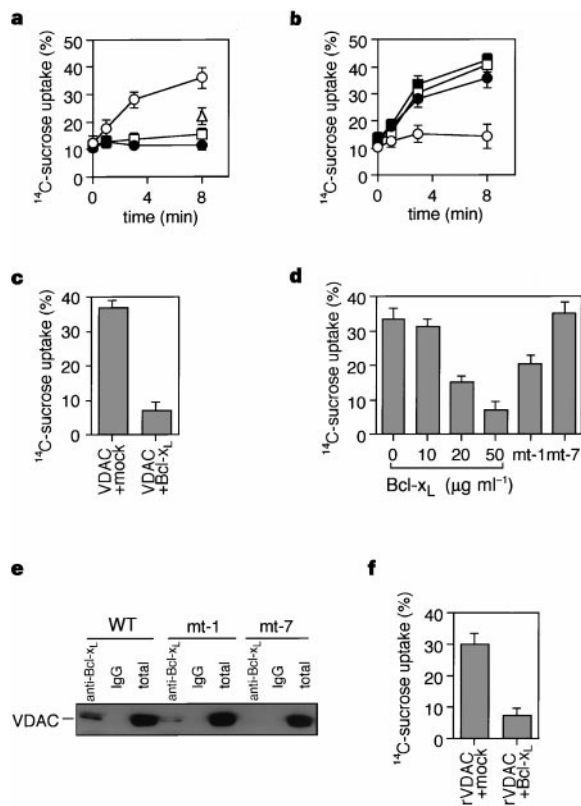


Figure 2 Inhibition of VDAC activity by Bcl-x_L in VDAC liposomes. **a**, Sucrose uptake by VDAC liposomes. Plain liposomes (filled circles), VDAC liposomes (open circles), heat-denatured VDAC liposomes (open squares), and VDAC liposomes with polyanion (100 μg ml⁻¹) (open triangle) were incubated with ¹⁴C-sucrose for the indicated times at pH 5.2 (see Methods). Liposomes were recovered, dissolved in 2% SDS and their ¹⁴C-sucrose content counted. **b**, Inhibition of VDAC activity in VDAC liposomes by Bcl-x_L. VDAC liposomes were incubated with ¹⁴C-sucrose and either rBcl-x_L (20 μg ml⁻¹) (open symbols) or mock protein (filled symbols) at pH 5.2 (circles) and pH 7.3 (squares), and ¹⁴C-sucrose uptake was measured (see Methods). **c**, Inhibition of VDAC activity by Bcl-x_L at neutral pH in liposomes containing VDAC and rBcl-x_L. Purified VDAC and rBcl-x_L were both embedded together into liposomes (see Methods), which were then incubated with ¹⁴C-sucrose at pH 7.3 for 3 min and their ¹⁴C-sucrose uptake measured. **d**, Inhibition of VDAC activity by Bcl-x_L in a dose-dependent manner and effect of Bcl-x_L mutants. VDAC liposomes were incubated with ¹⁴C-sucrose and rBcl-x_L, rBcl-x_L mutant mt-1 or mt-7 protein at 20 μg ml⁻¹ at pH 5.2 for 3 min, and ¹⁴C-sucrose uptake was measured. **e**, Interaction of Bcl-x_L mutants with VDAC. Experiments as in Fig. 1b were done using rBcl-x_L and rBcl-x_L mutants mt-1 and mt-7. Mitochondrial lysates immunoprecipitated with anti-Bcl-x_L antibody or rabbit IgG were western-blotted with anti-VDAC antibody. WT, wild type. **f**, Inhibition of VDAC activity by Bcl-x_L in liposomes incorporating recombinant VDAC. VDAC liposomes were incubated with ¹⁴C-sucrose and rBcl-x_L at pH 5.2 for 3 min and their ¹⁴C-sucrose uptake measured.

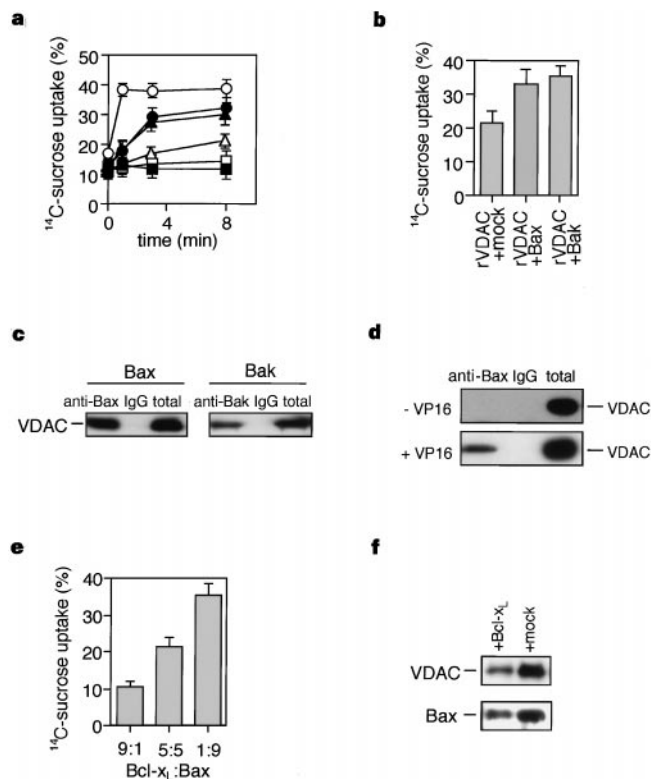


Figure 3 Enhancement of VDAC activity by Bax as well as its inhibition by Bcl-x_L. **a**, ¹⁴C-sucrose uptake into VDAC liposomes is enhanced by Bax. Plain liposomes (squares) and VDAC liposomes (circles and triangles) were incubated with ¹⁴C-sucrose, rBax (20 μg ml⁻¹) (open circles and open squares), rBax (20 μg ml⁻¹) and polyanion (100 μg ml⁻¹) (open triangles), rBaxΔB3 (20 μg ml⁻¹) (filled triangles), and mock protein (filled circles and filled squares) at pH 5.2 for the indicated times before measuring ¹⁴C-sucrose uptake. **b**, VDAC activity is increased by Bax and Bak in liposomes incorporating recombinant VDAC. VDAC liposomes were incubated with ¹⁴C-sucrose and with rBax, rBak or mock protein at pH 5.2 as in **a** and the ¹⁴C-sucrose uptake was counted at 3 min. **c**, Direct interaction of Bax and Bak with VDAC. VDAC liposomes preincubated with rBax or rBak were immunoprecipitated with anti-Bax or anti-Bak antibodies or with rabbit IgG and western-blotted with anti-VDAC antibody. An aliquot of the initial mixture (total) was used as control. **d**, Interaction of endogenous Bax with endogenous VDAC in PC12 cells. Lysates from PC12 cells (a rat pheochromocytoma cell line) preincubated with or without 50 μM VP16 for 12 h were immunoprecipitated with either an anti-mouse Bax antibody that crossreacts with rat Bax or rabbit IgG and the immune complexes western-blotted as in **c**. **e**, Antagonism of sucrose import into VDAC liposomes by Bax and Bcl-x_L. VDAC liposomes were incubated with ¹⁴C-sucrose and with rBax and rBcl-x_L at the indicated ratios (total 20 μg ml⁻¹) at pH 5.2, and ¹⁴C-sucrose uptake measured at 3 min. **f**, Inhibition of interaction with Bax and VDAC by Bcl-x_L. VDAC liposomes incubated with Bcl-x_L or mock protein for 5 min, then with rBax (all at 20 μg ml⁻¹) for 5 min, were immunoprecipitated with anti-Bax (top) or anti-VDAC (bottom) antibodies and western-blotted with anti-Bax or anti-VDAC antibody.

(Fig. 3d). rBax and rBcl-x_L were antagonistic towards VDAC (Fig. 3e). As preincubation of VDAC liposomes with Bcl-x_L significantly inhibited rBax binding to VDAC (Fig. 3f), the effect on VDAC activity of Bax and Bcl-x_L was regulated by their competitive binding to VDAC and their heterodimerization. A recombinant mutant Bax lacking its BH3 region had no effect on VDAC (Fig. 3a), indicating that this region is necessary for enhancing VDAC activity, consistent with our previous observation that the BH3 region is essential for Bak-induced mitochondrial changes⁸. We found that VDAC preparations from rat liver did not contain detectable ANT, as assessed by western blotting, and that sucrose uptake by VDAC liposomes was unaffected by the two ANT ligands atractyloside and bongkreikic acid (data not shown), indicating that we had no contamination by ANT in our VDAC preparations.

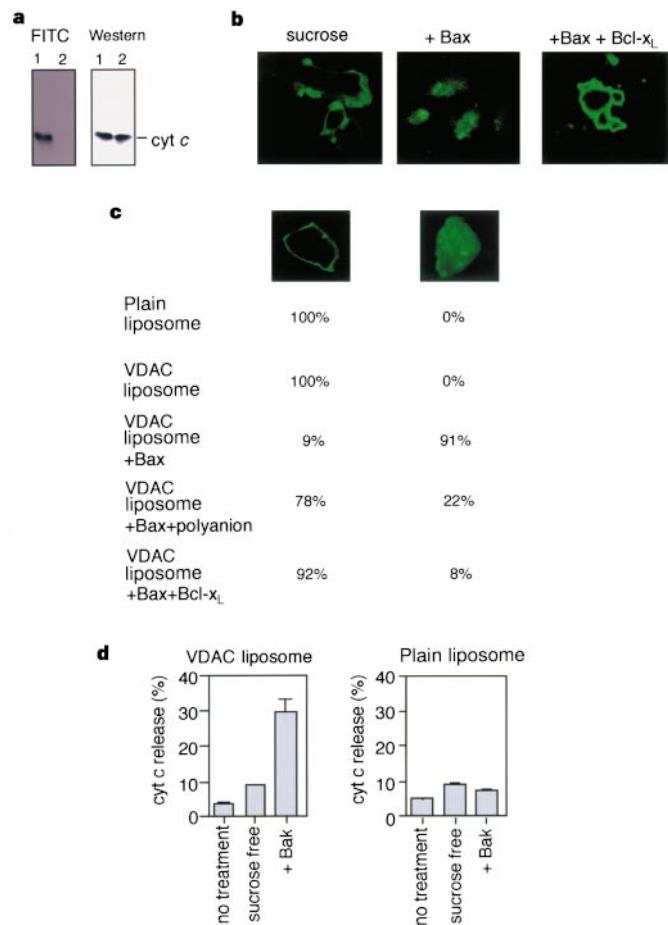


Figure 4 Induction of cytochrome *c* movement through VDAC by Bax and Bak. **a**, FITC labelled cytochrome *c* was run on SDS-PAGE (see Methods) and was detected by fluorescence (left) and western blotting with anti-cytochrome *c* antibody (right): lane 1, FITC-cytochrome *c* (25 µg); lane 2, cytochrome *c* (25 µg). **b, c**, Bax-induced import of FITC-cytochrome *c* into VDAC liposomes. VDAC liposomes (**b, c**) and plain liposomes (**c**) were incubated with FITC-cytochrome *c* and sucrose (50 mM), plus rBax (52 µg ml⁻¹), rBax (52 µg ml⁻¹) and polyanion (100 µg ml⁻¹), rBax and rBcl-x_L (both at 52 µg ml⁻¹), or without any of these at pH 5.2 for 5 min (see Methods), and were observed under a confocal fluorescence microscope. Representative photographs (original magnification, ×4,800) of VDAC-liposomes are shown in **b**. In **c**, the frequency (given as a percentage) and representative photographs of liposomes with and without influxed cytochrome *c* are shown (original magnification, ×10,000). **d**, Bak-induced cytochrome *c* release from VDAC liposomes. Plain or VDAC liposomes containing 80 mM sucrose and 0.5 mM cytochrome *c* were incubated in sucrose-free buffer with or without rBak for 30 min at pH 5.2 (see Methods). The release of cytochrome *c* was quantified spectrophotometrically (total incorporated cytochrome *c* is 100%).

As Bax and Bak induce cytochrome *c* release through PT pores of isolated mitochondria^{6–8} and as they enhance VDAC activity, we investigated whether cytochrome *c* could pass through VDAC in the presence of Bax and Bak. To monitor the movement of cytochrome *c* microscopically, we incubated fluorescein isothiocyanate (FITC)-labelled cytochrome *c* (Fig. 4a) with VDAC liposomes. In the absence of rBax, cytochrome *c* accumulated on the surfaces of plain and VDAC liposomes (Fig. 4b, c), but in the presence of rBax (Fig. 4b, c) or rBak (data not shown), cytochrome *c* accumulated inside VDAC liposomes (Fig. 4b, c). Also, polyanion significantly inhibited Bax-induced cytochrome *c* movement (Fig. 4c), indicating that Bax and Bak allowed cytochrome *c* to pass through VDAC. Bax-induced movement of cytochrome *c* was inhibited in the presence of rBcl-x_L (Fig. 4b, c). When cytochrome *c* and sucrose were initially incorporated inside VDAC liposomes, and the liposomes were then incubated with buffer, a significant amount of cytochrome *c* was released only in the presence of rBak (Fig. 4d) and rBax (data not shown); cytochrome *c* was not released by plain liposomes in the presence of rBak (Fig. 4d). Bax/Bak-dependent passage of cytochrome *c* through VDAC occurred also in the absence of sucrose (data not shown). During these experiments, the number of liposomes did not change, as assessed by flow cytometry (data not shown), and a GST-GFP (green fluorescence protein) fusion protein (*M_r* = 50K) was not released when rBax was added to VDAC liposomes containing GST-GFP (data not shown), indicating that the liposomes did not rupture and that Bax and Bak enable cytochrome *c* to pass through VDAC.

Our results indicate that Bcl-2 family proteins may target VDAC directly in order to modulate channel activity. We therefore investigated whether VDAC could be a target for Bcl-2 family proteins that are involved in regulating the apoptosis-associated loss of mitochondrial membrane potential ($\Delta\psi$) and the release of cytochrome *c*. As no mammalian cells lacking VDAC were available and because Bcl-2 family proteins can function in yeast cells^{18,19}, we used a yeast mutant deficient in VDAC1 (Δ VDAC)²⁰ and found that mitochondria isolated from the wild-type yeast lost $\Delta\psi$ and released cytochrome *c* after addition of rBax in a dose-dependent manner (Fig. 5a, d) like mammalian mitochondria, whereas rBax did not cause a loss of $\Delta\psi$ and cytochrome *c* release in mitochondria isolated from Δ VDAC yeast cells (Fig. 5b, d). However, rBax did induce both effects in mitochondria from Δ VDAC yeast transfected with the human (*h*) *vdac1* gene (Fig. 5c, d), indicating that the failure of Δ VDAC yeast mitochondria to respond to rBax was due to the absence of functional VDAC. Bax-mediated $\Delta\psi$ loss and cytochrome *c* release in yeast mitochondria were inhibited by rBcl-x_L (Fig. 5a, c, d). Results were similar when rBak was used (Fig. 5a–c, and data not shown). These results indicate that Bcl-2 family proteins target VDAC to regulate apoptosis-associated mitochondrial loss of $\Delta\psi$ and release of cytochrome *c*.

The fact that Bax and Bak enable cytochrome *c* to pass through VDAC, whereas Bcl-x_L does not, may explain how cytochrome *c* is released during apoptosis. We used the VDAC1-deficient yeast mutant²⁰ to show that VDAC is essential for Bax/Bak-induced mitochondrial $\Delta\psi$ loss and cytochrome *c* release. Although yeast cells carry VDAC1 and VDAC2, VDAC2 makes only a small contribution to the membrane permeability to metabolites.²¹ Extrapolation of these observations suggests that VDAC is essential for cytochrome *c* release during apoptosis of mammalian cells. The estimated size of the VDAC pore is ~2.6 nm, which is not large enough for folded cytochrome *c* with a similar diameter to pass through VDAC²²; indeed, VDAC liposomes did not allow the passage of cytochrome *c* (Fig. 4). Therefore Bax/Bak probably induces a conformational change in VDAC so that cytochrome *c* can pass through the channel, although it is possible that Bax/Bak and VDAC could together form a larger channel, and other unknown mechanisms may contribute to apoptotic cytochrome *c* release *in vivo*.

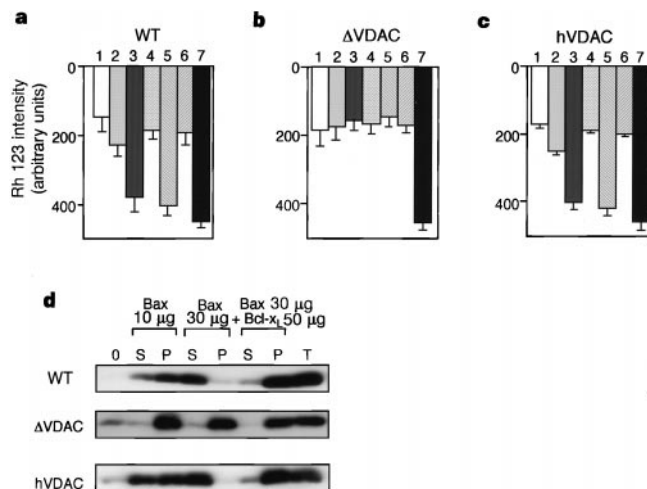


Figure 5 Requirement of VDAC for Bax/Bak-induced loss of membrane potential and cytochrome *c* release in yeast mitochondria. **a–c**, Inability of VDAC-deficient mitochondria to show rBax/rBak-induced loss of membrane potential. Mitochondria (1.0 mg ml^{-1}) isolated from wild-type (WT) yeast (**a**), VDAC1-deficient yeast (Δ VDAC) (**b**), or human VDAC1-expressing Δ VDAC (hVDAC) (**c**) yeast were incubated with: lane 2, $10 \mu\text{g ml}^{-1}$, and lanes 3, 4, $30 \mu\text{g ml}^{-1}$ rBax; lanes 5, 6, $30 \mu\text{g ml}^{-1}$ rBak; lane 1, mock, in the presence (lanes 4, 6) or absence (lanes 3, 5) of $50 \mu\text{g ml}^{-1}$ of Bcl- χ_L for 10 min, and $\Delta\psi$ was measured by rhodamine (Rh) 123 intensity; lane 7, complete loss of $\Delta\psi$ was demonstrated by incubation of

mitochondria with 1 mM CCCP for 10 min. **d**, Failure of VDAC1-deficient mitochondria to show Bax-induced cytochrome *c* release. Mitochondria (1 mg ml^{-1}) isolated from wild-type, Δ VDAC or hVDAC1-expressing Δ VDAC yeasts (hVDAC) were incubated with rBax (10 and $30 \mu\text{g ml}^{-1}$) either with or without rBcl- χ_L ($50 \mu\text{g ml}^{-1}$) for 10 min, then centrifuged: supernatants (S) and pellets (P) were western-blotted with anti-yeast cytochrome *c* antibody. '0', Supernatant of mitochondria before treatment; 'T', unspun mitochondria. Data are representative of three independent experiments.

Bax and Bcl-2 have been shown to interact with ANT and Bax to sensitize ANT to its atractyloside ligand in ANT liposomes and in partially purified PT-pore liposomes⁹. However, Bax did not affect mitochondrial ADP uptake, which is mediated by ANT (our unpublished observations). Therefore Bax might modulate ANT activity after binding under certain circumstances, but our results strongly indicate that VDAC is a functional target for Bcl-2 family proteins. As Bax/Bak induces loss of $\Delta\psi$ across the inner membrane in mitochondria and as the PT pore is a polyprotein channel, the Bax/Bak-mediated conformational change of VDAC probably affects other channels in the PT pore that control inner-membrane permeability. Alternatively, interaction of Bax/Bak with ANT or ANT-related channels in the inner membrane might be directly involved in $\Delta\psi$ collapse. As PT inhibitors such as cyclosporin A and bongkreic acid can inhibit Bax/Bak-induced cytochrome *c* release in isolated mitochondria^{6,8}, VDAC-mediated cytochrome *c* release could be controlled not only by Bcl-2 family proteins but also by other components of the PT pore such as ANT (a target of bongkreic acid) and cyclophilin D (a target of cyclosporin A). Thus, various components of the PT pore seem to interact with each other. The interaction of Bcl- χ_L and Bax with ANT may direct these molecules to bind antagonistically with VDAC inside the PT pore rather than with VDAC in isolation.

Taken together, our results indicate that the Bcl-2 family of proteins target VDAC to regulate apoptosis-associated mitochondrial changes that are central to determining the survival or death of cells. □

Methods

Antibodies. Anti-pigeon cytochrome *c* monoclonal antibody (7H8.2C12), anti-yeast cytochrome *c* polyclonal antibody and anti-rat ANT polyclonal antibody were kindly provided by E. Margoliash, G. Shatz and H. H. Schmid, respectively. Anti-human VDAC monoclonal antibody (31HL), which cross-reacts with rat VDAC, was from Calbiochem. Anti-human Bcl- χ_L (L19), anti-human Bak (G23) and anti-human Bax (N20) polyclonal antibodies were from Santa Cruz Biotechnology.

Immunoprecipitation and western blot analysis. Rat liver mitochondria were isolated as described²³. Immunoprecipitation was done as described⁸ using cells, mitochondria and liposomes lysed and sonicated in lysis buffer (10 mM

HEPES, pH 7.4, 142.5 mM KCl, 5 mM MgCl₂, 1 mM EGTA, 0.5% N-P40) containing proteinase inhibitors. To detect binding between purified proteins, VDAC ($0.2 \mu\text{g}$) and ANT ($0.2 \mu\text{g}$) were incubated for 3 h either with GST-Bcl- χ_L ($0.2 \mu\text{g}$) or GST ($0.2 \mu\text{g}$) in $100 \mu\text{l}$ of the lysis buffer. Then, these proteins were incubated with glutathione (GSH)–Sepharose or Sepharose for 3 h. After brief centrifugation, beads were washed and resuspended in sample buffer for SDS–PAGE.

Protein purification. Human Bcl- χ_L , two Bcl- χ_L mutants, human Bak (lacking the C-terminal 21 amino-acid residues), human Bax, Bax lacking the BH3 region (Bax Δ BH3), and mock proteins were produced and purified as described⁸. Haemagglutinin (HA)-tagged human VDAC1 was expressed in *Escherichia coli* strain DE3 using the Xpress System (Invitrogen) and purified on an HA column. All proteins except for VDAC were dissolved in 10 mM HEPES- K^+ (pH 7.4) with 1 mM DTT, and VDAC was in VDAC buffer (10 mM Tris-Cl, pH 7.0, 1 mM EDTA, and 3% Triton-X100).

Rat liver VDAC was purified as described²⁴. Rat heart ANT was purified as described²⁵. The purity of VDAC and ANT was shown to be $>95\%$.

Reconstitution of VDAC in liposomes. Purified and recombinant VDAC were reconstituted in small unilamellar vesicles by a modification of the sonic freeze–thaw procedure²⁶. Briefly, 100 mg phospholipid (soybean, type II-S) was dissolved into 1 ml liposome medium containing 30 mM sodium sulphate and 20 mM Tricine-NaOH (pH 7.3 or pH 5.2) with or without 80 mM sucrose. After sonication, purified or recombinant VDAC protein ($200 \mu\text{g}$) was added with or without rBcl- χ_L ($200 \mu\text{g}$) and rBax ($200 \mu\text{g}$), and this suspension was subjected to two freeze–thaw cycles. Heat-denatured VDAC protein was obtained by heating at 95°C for 10 min. Then unilamellar VDAC liposomes were produced by mild sonication and fractionated on Sephadex G-50 columns. Light scattering from each fraction was measured spectrophotometrically at 520 nm , and the fraction containing 700 – 900 arbitrary units per μl was used.

A sucrose-import experiment was performed by measuring ^{14}C -sucrose uptake. Liposomes ($10 \mu\text{l}$) were incubated with $5 \mu\text{l}$ ^{14}C -sucrose (97% ; $200 \mu\text{Ci ml}^{-1}$) at 25°C and filtered by centrifugation using a 30K limiting filter (Millipore) to remove free ^{14}C -sucrose; incorporated ^{14}C -sucrose was measured in a gamma-scintillation counter (Wallac 1414).

Cytochrome *c* translocation experiment. FITC-labelled cytochrome *c* was produced as described²⁷: the FITC/cytochrome *c* molar ratio was 0.47 . FITC-labelled cytochrome *c* was detected with a lumino-image analyser (LAS-1000, Fujifilm). Liposomes ($2 \mu\text{l}$) were incubated with both sucrose (50 mM) and

FITC-labelled cytochrome *c* (50 μ M) and various proteins in a total volume of 29 μ l at pH 5.2; labelled cytochrome *c* was visualized using confocal micro-photography (LSM-745, Olympus).

For cytochrome *c* export, liposomes (1 ml) in sucrose (80 mM)-containing buffer were mixed with cytochrome *c* (100 μ M) and freeze-thawed for two cycles. After unilameralization, 20 μ l liposomes were incubated with 1 ml sucrose-free buffer with or without 20 μ g ml⁻¹ rBak for 10 min at 25 °C, then filtered by centrifugation through a 30K filter to separate liposomes from free cytochrome *c*. Free cytochrome *c* was determined from the absorbance at 408 nm.

Yeast mitochondria. AVDAC1-deficient yeast strain (Δ VDAC; M22-2) and its parent strain (M3) were used. A human VDAC1-expressing Δ VDAC yeast strain was produced by transfecting human *vdac1* cDNA using lithium acetate. Mitochondria were isolated essentially as described²⁸, using zymolyase 20T to form spheroplasts which were then homogenized. Isolated mitochondria were suspended in 0.3 M mannitol, 10 mM Tris-maleate (pH 7.4), 0.2 mM EDTA, 0.05% BSA (yMt buffer). Mitochondria (0.5 mg ml⁻¹) were incubated at 25 °C in yMT buffer plus 4.2 mM succinate. $\Delta\psi$ was measured by following the uptake of rhodamine 123 (Rh123) as described²³. For detecting the release of cytochrome *c*, mitochondria were spun, and the supernatants and pellets were western-blotted with anti-yeast cytochrome *c* antibodies.

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Interaction of E1 and hSNF5 proteins stimulates replication of human papillomavirus DNA

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Mammalian viruses often use components of the host's cellular DNA replication machinery to carry out replication of their genomes, which enables these viruses to be used as tools for characterizing factors that are involved in cellular DNA replication. The human papillomavirus (HPV) E1 protein is essential for replication of the virus DNA^{1–3}. Here we identify the cellular factor that participates in viral DNA replication by using a two-hybrid assay⁴ in the yeast *Saccharomyces cerevisiae* and E1 protein as bait. Using this assay, we isolated Ini1/hSNF5 (ref. 5), a component of the SWI/SNF complex which facilitates transcription by altering the structure of chromatin⁶. *In vitro* binding and immunoprecipitation confirmed that E1 interacts directly with

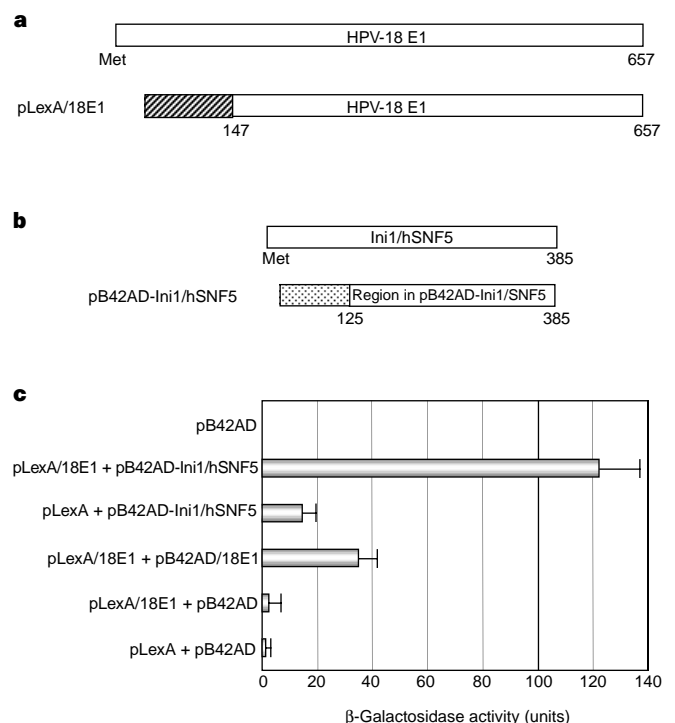


Figure 1 Interaction between HPV-18 E1 and Ini1/hSNF5 proteins. **a**, Structure of the pLexA/18E1 plasmid. Bar represents the LexA DNA binding domain for the LexA operator. **b**, Structure of pB42AD-Ini1/hSNF5. The dotted region represents an activation domain for a yeast promoter. **c**, Quantification of yeast two-hybrid interactions. Values represent the average for five different EGY48 colonies co-expressing the specified fusion proteins. Error bars indicate the standard deviation for each sample.