REVIEW ARTICLE

Caspases: the executioners of apoptosis

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Apoptosis is a major form of cell death, characterized initially by a series of stereotypic morphological changes. In the nematode *Caenorhabditis elegans*, the gene *ced-3* encodes a protein required for developmental cell death. Since the recognition that CED-3 has sequence identity with the mammalian cysteine protease interleukin-1β-converting enzyme (ICE), a family of at least 10 related cysteine proteases has been identified. These proteins are characterized by almost absolute specificity for aspartic acid in the P_1 position. All the caspases (ICE-like proteases) contain a conserved QACXG (where X is R, Q or G) pentapeptide active-site motif. Caspases are synthesized as inactive proenzymes comprising an N-terminal peptide (prodomain) together with one large and one small subunit. The crystal structures of both caspase-1 and caspase-3 show that the active enzyme is a heterotetramer, containing two small and two large subunits. Activation of caspases during apoptosis results in the cleavage of critical cellular substrates, including poly(ADP-ribose) polymerase and lamins, so precipitating the dramatic morphological changes of apoptosis. Apoptosis induced by CD95 (Fas/APO-1) and tumour necrosis factor activates caspase-8 (MACH/FLICE/Mch5), which contains an N-terminus with FADD (Fas-associating protein with death domain)-like death effector domains, so providing a direct link between cell death receptors and the caspases. The importance of caspase prodomains in the regulation of apoptosis is further highlighted by the recognition of adapter molecules, such as RAIDD [receptor-interacting protein (RIP)-associated ICH-1/CED-3-homologous protein with a death domain]/CRADD (caspase and RIP adapter with death domain), which binds to the prodomain of caspase-2 and recruits it to the signalling complex. Cells undergoing apoptosis following triggering of death receptors execute the death programme by activating a hierarchy of caspases, with caspase-8 and possibly caspase-10 being at or near the apex of this apoptotic cascade.

INTRODUCTION

Apoptosis is an important process in a wide variety of different biological systems, including normal cell turnover, the immune system, embryonic development, metamorphosis and hormone-dependent atrophy, and also in chemical-induced cell death [1–3]. Inappropriate apoptosis is implicated in many human diseases, including neurodegenerative diseases such as Alzheimer's disease and Huntington's disease, ischaemic damage, autoimmune disorders and several forms of cancer [4,5]. Apoptosis is a major form of cell death, characterized by a series of distinct morphological and biochemical alterations [1,6]. Apoptotic cell death occurs in two phases: first a commitment to cell death, followed by an execution phase characterized by dramatic stereotypic morphological changes in cell structure [7], suggesting the presence in different cells of a common execution machinery [8]. Apoptosis is characterized by condensation and fragmentation of nuclear chromatin, compaction of cytoplasmic organelles, dilatation of the endoplasmic reticulum (frequently in a subplasmalemmal distribution), a decrease in cell volume and alterations to the plasma membrane resulting in the recognition and phagocytosis of apoptotic cells, so preventing an inflammatory response [1] (Figure 1). The nuclear alterations, which are the pre-eminent ultrastructural changes of apoptosis, are often associated with internucleosomal cleavage of DNA [9], recognized as a 'DNA ladder' on conventional agarose gel electrophoresis and long considered as a biochemical hallmark of apoptosis. These DNA ladders are derived from large fragments of DNA of 30–50 and 200–300 kbp, which may in terms of higher-order chromatin structure represent loops and rosettes of DNA [10–12]. Internucleosomal cleavage of DNA now appears to be a relatively late event in the apoptotic process, which in some models may be dissociated from early critical steps [13,14]. Nevertheless, its measurement is simple and it is often used as a major criterion to determine whether a cell is apoptotic.

Whereas early studies concentrated on the role of nucleases in apoptosis, more recently a role has been proposed for a number of different proteases, including serine proteases, calpains and proteasomes (reviewed in [15–18]). Most attention has focused on the interleukin-1β (IL-1β)-converting enzyme (ICE)-like proteases, due partly to the enormous progress made by Horvitz and his colleagues in understanding programmed cell death in the nematode *Caenorhabditis elegans*. During normal development, 131 cells of the 1090 cells generated die by apoptosis [2]. Two genes, *ced-3* and *ced-4*, are vital for cell death in *C. elegans*, while the *ced-9* gene antagonizes their function and prevents cell death [19]. The CED-9 protein bears sequence similarity to mammalian Bcl-2, which acts to prevent cell death in mammals. No mammalian homologue of CED-4 has yet been identified. The CED-3 protein bears marked sequence similarity to, and identity with, mammalian ICE [20]. This seminal finding, together with the observation that overexpression of ICE induces apoptosis, suggests that ICE may play a key role in the induction of apoptosis [20,21]. Further evidence supporting a critical role for

Abbreviations used: Ac, acetyl; AMC, 7-amino-4-methylcoumarin; CPP32, 32 kDa cysteine protease; CRADD, caspase and RIP adapter with death domain; DED, death effector domain; DNA-PK, DNA-dependent protein kinase; $DNA\text{-}PK_{CS}$, catalytic subunit of DNA-PK; FADD/MORT1, Fas-associating protein with death domain; ICE, interleukin-1β-converting enzyme; ICH, *Ice* and *ced-3* homologue; $ICH\text{-}1_L$ and $ICH\text{-}1_S$, long and short isoforms respectively of ICH-1; IL-1β, interleukin-1β; PARP, poly(ADP-ribose) polymerase; RAIDD, RIP-associated ICH-1/CED-3-homologous protein with a death domain; Rb, retinoblastoma protein; RIP, receptor-interacting protein; TNF, tumour necrosis factor; TNFR-1, TNF receptor; TRADD, TNFR-1-associated death domain protein; U1-70 kDa, 70 kDa protein component of the U1 small nuclear ribonucleoprotein; Z-VAD.FMK, benzyloxycarbonyl-Val-Ala-Asp(OMe) fluoromethyl ketone.

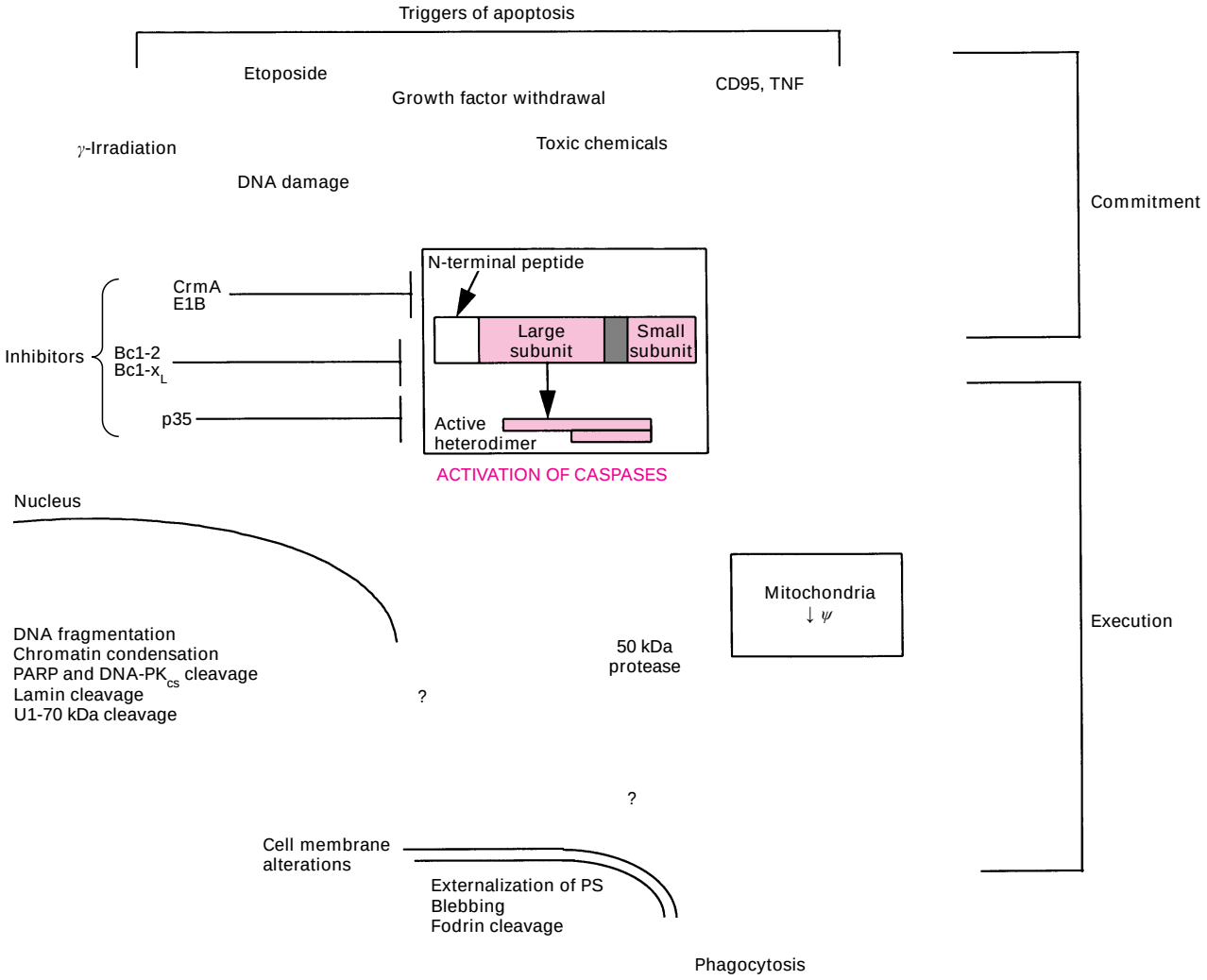


Figure 1 Activation of caspases represents a major control point in apoptosis

Apoptosis involves an initial commitment phase followed by an execution phase. Activation of the caspases results in nuclear, plasma-membrane and mitochondrial changes. The latter include the release of a 50 kDa protease, which may be responsible for some of the cellular changes associated with apoptosis. ψ, mitochondrial membrane potential; PS, phosphatidylserine. See the abbreviations footnote for other definitions.

Table 1 Members of the caspase family

Caspases-3, -7 and -9 have only one cleavage site between the large and small subunits, whereas the other caspases have two potential aspartate cleavage sites, resulting in removal of a linker region. Degrees of inhibition by cowpox viral serpin CrmA: +++, potent inhibition; ±, very weak inhibition; ?, not known.

Caspase	Other names	Active site	Cleavage site(s) between large and small subunits	CrmA inhibition
Caspase-1	ICE	QACRG	WFKD↓S; FEDD↓A	+++
Caspase-2	Nedd2, ICH-1	QACRG	DQQD↓G; EESD↓A	±
Caspase-3	CPP32, Yama, apopain	QACRG	IETD↓S	±
Caspase-4	ICE_{rel}II, TX, ICH-2	QACRG	WRVD↓S; LEED↓A	+++
Caspase-5	ICE_{rel}III, TY	QACRG	WRVD↓S; LEAD↓S	?
Caspase-6	Mch2	QACRG	DVVD↓N; TEVD↓A	±
Caspase-7	Mch3, ICE-LAP3, CMH-1	QACRG	IQAD↓S	±
Caspase-8	MACH, FLICE, Mch5	QACQG	VETD↓S; LEMD↓L	+++
Caspase-9	ICE-LAP6, Mch6	QACGG	DQLD↓A	?
Caspase-10	Mch4	QACQG	SQTD↓V; IEAD↓A	±

ICE-like proteases in apoptosis is the ability of specific protease inhibitors, including the cowpox viral serpin CrmA [21–23] and baculovirus p35 [24], to inhibit apoptosis (see below).

Since the recognition of the similarity between CED-3 and ICE in 1993, a further nine related ICE-like proteases have been identified. Several reviews have appeared on ICE and ICE-related proteases [7,15,16,25–29]. Due to the flurry of activity to isolate new family members, confusion has arisen as a result of different groups isolating the same protease. In order to resolve this, a unified nomenclature has recently been suggested [30] (Table 1). The trivial name proposed for all family members is caspase, the 'c' denoting a cysteine protease and the 'aspase' referring to the ability of these enzymes to cleave after an aspartic acid residue. Individual family members are then referred to in order of their publication, so ICE, the first family member, is caspase-1. Caspases are synthesized as inactive proenzymes, which are activated following cleavage at specific aspartate cleavage sites. Phylogenetic analysis of the caspases reveals that there are three subfamilies: an ICE subfamily, comprising

caspases-1, -4 and -5, a CED-3/CPP32 (32 kDa cysteine protease) subfamily, comprising caspases-3, -6, -7, -8, -9 and -10, and an ICH-1 (where ICH is *Ice* and *ced-3* homologue)/Nedd2 subfamily (Figure 2a and Table 2).

The presence of a family of structurally related caspases in cells raises a number of important questions in relation to their potential roles in cell death. (1) Are all caspases required for cell death, or are some members more important than others? (2) Do all modes of cell death utilize the same caspases? (3) Are caspases activated in series or in parallel? (4) Is one caspase at the apex of an apoptotic cascade? (5) How are these enzymes regulated in order to prevent their unwanted activation and the subsequent demise of the cell? (6) Are there normal cellular substrates for these enzymes? (7) What are their critical cellular substrates that lead to cell death? (8) Do specific caspases degrade specific proteolytic substrates during the apoptotic process? (9) Are the caspases pre-existing or are they synthesized in response to apoptotic stimuli? (10) Are the caspases tissue-specific? In this review, individual caspases will be discussed, paying particular attention to ICE, as most is known about this enzyme, and a detailed consideration of its properties is extremely helpful in understanding those of other family members. Then some of the known protein substrates of the caspases and their relationship with apoptosis will be reviewed.

ICE (CASPASE-1)

Structure and function

Early work on caspase-1 concentrated on its role in cleaving the inactive 31 kDa cytokine pro-IL-1β at Asp-116–Ala-117 to generate the active 17 kDa mature form of IL-1β, a key mediator of inflammation [31,32]. Purification and cloning of caspase-1 revealed that it is a 45 kDa protein (p45). Active ICE comprises two subunits of 20 kDa and 10 kDa (p20 and p10 respectively), both of which are required for catalytic activity and are derived from a single proenzyme following removal of an 11 kDa N-terminal peptide (prodomain) and a 2 kDa linker peptide (Figure 3) [33,34]. This scheme serves as a useful model for other caspases, although not all possess linker regions and the sizes of the prodomains vary (Figure 3). All four cleavage sites in p45, i.e. Asp-103, Asp-119, Asp-297 and Asp-316, arise at Asp–Xaa bonds (Figure 3), suggesting that active caspase-1 may be derived by autoproteolysis [33,34]. Following the initial cleavage at Asp-297–Ser-298, autoproteolysis occurs in a series of steps, generating fragments of increasing activity and eventually producing p20/p10 ICE [35,36]. Caspase-1 is found predominantly in the cytoplasm of cells as the p45 pro-form [37], although some is also localized to the external cell surface membrane, where it activates pro-IL-1β to its mature form during secretion [38]. Caspase-1 is a novel type of cysteine protease containing an active-site cysteine residue (Cys-285) in the p20 subunit, the mutation of which results in loss of activity. Substrate specificity studies revealed that caspase-1 has a strong preference for aspartic acid adjacent to the cleavage site in the P_1 position, a small hydrophobic amino acid (Gly or Ala) in the P'_1 position, and also a requirement for four amino acids to the left of the cleavage site [33,39]. Acetyl-Tyr-Val-Ala-Asp-CHO (Ac-YVAD.CHO, where CHO is aldehyde) and Ac-YVAD-7-amino-4-methylcoumarin (Ac-YVAD-AMC) were synthesized as a potent competitive reversible inhibitor and a fluorimetric substrate respectively for caspase-1 [33].

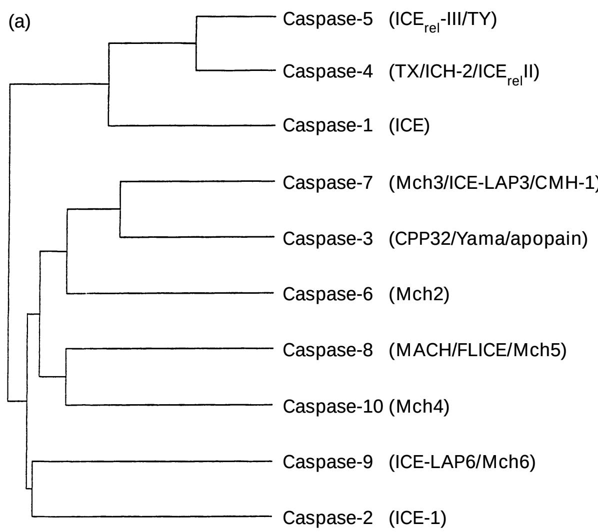
The X-ray crystal structure of caspase-1, in complex with specific tetrapeptide inhibitors that bind in the S_1–S_4 sites normally occupied by a peptide substrate, has been determined. The active enzyme is a tetramer of two p20 subunits surrounding two adjacent p10 subunits, with most of the area of contact between the dimers occurring between the p10 subunits [40,41]. Interactions between the p20 C-terminus and the p10 N-terminus also contribute to the stability of the homodimer. The active site spans both the p20 and p10 subunits, so explaining the requirement for both subunits for activity. Cys-285 and His-237 form a catalytic dyad in the active site of caspase-1. The active-site pentapeptide, Gln-Ala-Cys-Arg-Gly (QACRG), is in the p20 subunit. However, amino acid residues involved in forming the Asp pocket include Arg-179, Gln-283, Arg-341 and Ser-347, with only the first two residues being contributed by the p20 subunit. The two arginine residues (Arg-179 and Arg-341) form hydrogen bonds with the P_1 Asp residue of the substrate, and mutation of these residues results in the loss of catalytic activity [41]. Side chains of residues of p10 from Val-338 to Pro-343 interact with P_2–P_4 sites of the inhibitor [41]. Based on the crystal structure, two models were proposed for maturation of the proenzyme. In the first, two precursor p45 proteins associate and are then processed, with the p10 subunit from one caspase-1 molecule complexing with the p20 subunit from another caspase-1 molecule, so creating the active site. The alternative, but less favoured, model suggested processing followed by association of the subunits [41]. Using various active-site mutants, it has been shown that oligomerization of caspase-1 is required for autoprocessing [42] and that hetero-oligomerization may occur between different caspase homologues, but the *in vivo* relevance of this is not known. Using the yeast two-hybrid system, the prodomain of caspase-1 is absolutely required for dimerization and autoproteolysis, suggesting a regulatory rather than a structural role for the prodomain [43]. Using reverse transcriptase–PCR, four alternatively spliced isoforms of caspase-1 were identified that have differing effects on apoptosis [44].

Caspase-1 and apoptosis

Early studies pointed to a role for caspase-1 in the induction of apoptosis. CED-3 and caspase-1 share 28% sequence identity, and the active-site pentapeptide, QACRG, is completely conserved (Table 2) [20]. Overexpression of the murine ICE gene induces apoptosis in Rat-1 fibroblasts, which is abrogated by point mutations in the cysteine or glycine residues of the active-site pentapeptide and by either *bcl-2* or *crmA* [21]. The *crmA* gene (a cytokine response modifier gene) encodes a 38 kDa serpin that is a specific inhibitor of caspase-1, so preventing the proteolytic processing of IL-1β and thereby helping to suppress the response to viral infection [45]. As apoptosis is a major mechanism by which a host attempts to clear virally infected cells, viruses have evolved proteins that inactivate apoptosis in order to infect the host. Dorsal root ganglion neurons, which undergo apoptosis on withdrawal of nerve growth factor, are also protected by *crmA*, suggesting that caspase-1 may be involved in neuronal death in vertebrates [22].

Mice deficient in caspase-1 develop normally, appear healthy and are fertile, with no apparent abnormalities, suggesting that there are no gross defects in normal physiological processes involving apoptosis [46,47]. Macrophages from caspase-$1^{-/-}$ mice are equally susceptible to ATP-induced apoptosis as those from wild-type mice. Thymocytes from caspase-$1^{-/-}$ mice and wild-type mice show a similar susceptibility to apoptosis induced by dexamethasone or γ-irradiation, but thymocytes from the caspase-$1^{-/-}$ mice are somewhat more resistant to apoptosis induced by anti-CD95 (Fas/APO-1) antibody [46,47]. These results suggest that caspase-1 in itself is not involved in most forms of apoptosis, or that another caspase may substitute in the

(a)



(b)

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caspase-5  .......... .......... .......... ......MFKG ILQSGLDNFV INHMLKNNVA GQTSIQTLVP NTDQKSTSVK KDNHKKKTVK MLEYLGKDVL   64
caspase-4  .......... .......... .......... .......... .......... .......... .......... ........MA EGNHRKKPLK VLESLGKDFL   22
caspase-1  .......... .......... .......... .......... .......... .......... .......... ........MA DKVLKEKRKL FIRSMGEGTI   22
caspase-7  .......... .......... .......... .......... .......... .......... .......... .......... .......... ..........
caspase-3  .......... .......... .......... .......... .......... .......... .......... .......... .......... ..........
caspase-6  .......... .......... .......... .......... .......... .......... .......... .......... .......... ..........
caspase-8  .......... .......MDF SRNLYDIGEQ LDSEDLASLK FLSLDYIPQR KQEPIKDALM LFQRLQEKRM LEESNLSFLK ELLFRINRLD LLITYLNTRK   83
caspase-10 MKSQGQHWYS SSDKNCKVSF REKLLIIDSN LGVQDVENLK FLCIGLVPNK KLEKSSSASD VFEHLLAEDL LSEEDPFFLA ELLY.IIRQK KLLQHLNCTK   99
caspase-9  .......... .......... .......... .......... .......... .......... .......... ........MD EADRRLLRRC RLRLVEELQV   22
caspase-2  .......... .......... .......... .......... .......... .......... ....MAADRG RRILGVCGMH PHHQETLKKN RVVLAKQLLL   36

                                                                                                             →Large
                                                                                                              subunit
caspase-5  HGVFNYLAKH DVLTLKEEEK K..KYYDAKI EDKALILVDS LR.KNRVAHQ M......... ..FTQTL... ........LN MDQKITSVKP LLQIEA....  135
caspase-4  TGVLDNLVEQ NVLNWKEEEK K..KYYDAKT EDKVRVMADS MQEKQRMAGQ M......... ..LLQTF... ........FN IDQISPNKKA HPNMEA....   94
caspase-1  NGLLDELLQT RVLNKEEMEK V..KRENATV MDKTRALIDS VIPKGAQACQ ICITYICEED SYLAGTLGLS ADQTSGNYLN MQDSQGVLSS FPAPQAVQDN  120
caspase-7  .......... .......... .......... .......... .......... .......... .......... .........M ADDQGCIEEQ GVEDSANEDS   21
caspase-3  .......... .......... .......... .......... .......... .......... .......... .......... .......... ...MENTENS    7
caspase-6  .......... .......... .......... .......... .......... .......... .......... .......... .......... ..........
caspase-8  EEMERELQTP GRAQISAYRV MLYQISEEVS RSELRSFKFL LQEEISKCKL DDDMNLLDIF IEMEKRVILG EGKLDILKRV CAQINKSLLK IINDY..EEF  181
caspase-10 EEVERLL..P TRQRVSLFRN LLYELSEGID SENLKDMIFL LKDSLPK... TEMTSLSFLA FLEKQGKIDE DNLTCLEDLC KTVVPKLLRN IEKYKREKA.  193
caspase-9  DQLWDVLLSR ELFRPHMIED IQ.RAGSGSR RDQARQLIID LETRGSQALP LFISCLEDTG QDMLASFLRT NRQAGKLSKP TLENLTPVVL RPEIRKPEVL  121
caspase-2  SELLEHLLEK DIITLEMREL IQAKVGSFS. ..QNVELLNL LPKRGPQAFD AFCEALRETK QGHLEDMLLT TLSGLQHVLP PLSCDYDLSL PFPVCESCPL  133

caspase-5  .GPPESAEST NILKLCPREE FLRLCKKNHD EI........ ..YPIKKRED RRRLALIICN TKFD...... ....HLPARN GAHYDIVGMK RLLQGLGYTV  214
caspase-4  .GPPESGEST DALKLCPHEE FLRLCKERAE EI........ ..YPIKERNN RTRLALIICN TEFD...... ....HLPPRN GADFDITGMK ELLEGLDYSV  173
caspase-1  PAMPTSSGSE GNVKLCSLEE AQRIWKQKSA EI........ ..YPIMDKSS RTRLALIICN EEFD...... ....SIPRRT GAEVDITGMT MLLQNLGYSV  200
caspase-7  VDAKPDRSSF VPSLFSKKKK N.....VTMR SIKTTRDRV. PTYQYNMNFE KLGKCIIINN KNFDKV.... ...TGMGVRN GTDKDAEALF KCFRSLGFDV  108
caspase-3  VDSKSIK.NL EPKIIHGSES M.....DSGI SLDNS..... ....YKMDYP EMGLCIIINN KNFHKS.... ...TGMTSRS GTDVDAANLR ETFRNLKYEV   85
caspase-6  ...MSSASGL RRGHPAGGEE N.....MTET DAFYKREMFD PAEKYKMDHR RRGIALIFNH ERFFWH.... ...LTLPERR RTCADRDNLT RRFSDLGFEV   85
caspase-8  SKERSSSLEG SPDEFSNGEE LCGVMTISDS PREQDSESQT LDKVYQMKSK PRGYCLIINN HNFAKAREKV PKLHSIRDRN GTHLDAGALT TTFEELHFEI  281
caspase-10 IQIVTPPVDK EAESYQGEEE L.....VSQT DVKTFLEALP RAAVYRMNRN HRGLCVIVNN HSFT...... ....SLKDRQ GTHKDAEILS HVFQWLGFTV  278
caspase-9  RPETPRPVDI GSGGFGDVGA L...ESLRGN A......... .DLAYILSME PCGHCLIINN VNFCRES... ....GLRTRT GSNIDCEKLR RRFSSLHFMV  201
caspase-2  YKKLRLSTDT VEHSLDNKDG P...VCLQVK PCTPEFYQTH FQLAYRLQSR PRGLALVLSN VHFTGEK... ....ELEFRS GGDVDHSTLV TLFKLLGYDV  223
                                                                                             o

caspase-5  VDEKNLTARD MESVLRAFAA RPEHKSSDST FLVLMSHG.. .....ILEGI CGTAHKKKKP DVLLYDTIFQ IFNNRNCLSL KDKPKVIIVQ ACRGEKHGEL  307
caspase-4  DVEENLTARD MESALRAFAT RPEHKSSDST FLVLMSHG.. .....ILEGI CGTVHDEKKP DVLLYDTIFQ IFNNRNCLSL KDKPKVIIVQ ACRGANRGEL  266
caspase-1  DVKKNLTASD MTTELEAFAH RPEHKTSDST FLVFMSHG.. .....IREGI CGKKHSEQVP DILQLNAIFN MLNTKNCPSL KDKPKVIIIQ ACRGDSPGVV  293
caspase-7  IVYNDCS.CA KMQDLLKKAS EEDHTNAACF ACILLSHGEE .......NVI YGK.....DG V.TPIKDLTA HFRGDRCKTL LEKPKLFFIQ ACRGTELDDG  194
caspase-3  RNKNDLT.RE EIVELMRDVS KEDHSKRSSF VCVLLSHGEE .......GII FGT.....NG P.VDLKKITN FFRGDRCRSL TGKPKLFIIQ ACRGTELDCG  171
caspase-6  KCFNDLK.AE ELLLKIHEVS TVSHADADCF VCVFLSHGEG .......NHI YAY.....DA K.IEIQTLTG LFKGDKCHSL VGKPKIFIIQ ACRGNQHDVP  171
caspase-8  KPHDDCT.VE QIYEILKIYQ LMDHSNMDCF ICCILSHGDK .......GII YGT.....DG QEPPIYELTS QFTGLKCPSL AGKPKVFFIQ ACQGDNYQKG  368
caspase-10 HIHNNVTKVE MEMVLQKQKC NPAHADGDCF VFCILTHGRF .......GAV YSS.....DE ALIPIREIMS HFTALQCPRL AEKPKLFFIQ ACQGEEIQPS  366
caspase-9  EVKGDLTAKK MVLALLELAR .QDHGALDCC VVVILSHGCQ ASHLQFPGAV YGT.....DG CPVSVEKIVN IFNGTSCPSL GGKPKLFFIQ ACGGEQKDHG  295
caspase-2  HVLCDQTAQE MQEKLQNFAQ LPAHRVTDSC IVALLSHGVE .......GAI YGV.....DG KLLQLQEVFQ LFDNANCPSL QNKPKMFFIQ ACRGDETDRG  311
                                             ♦□□                                                  o ♦□

   large ←                            →small
   subunit                             subunit
caspase-5  WVRDSPASLA VISSQSSENL EA........ ....DSVCKI HEEKDFIAFC SSTPHNVSWR DRTRGSIFIT ELITCFQK.Y SCCCHLMEIF RKVQKSFEVP  394
caspase-4  WVRDSPASLE VASSQSSENL EE........ ....DAVYKT HVEKDFIAFC SSTPHNVSWR DSTMGSIFIT QLITCFQK.Y SWCCHLEEVF RKVQQSFETP  353
caspase-1  WFKDSVGVSG NLSLPTTEEF ED........ ....DAIKKA HIEKDFIAFC SSTPDNVSWR HPTMGSVFIG RLIEHMQE.Y ACSCDVEEIF RKVRFSFEQP  380
caspase-7  IQADSGPIND T......... .DA....... ....NPRYKI PVEADFLFAY STVPGYYSWR SPGRGSWFVQ ALCSILEE.H GKDLEIMQIL TRVNDRVARH  272
caspase-3  IETDSGVDDD M......... .AC....... ....H...KI PVEADFLYAY STAPGYYSWR NSKDGSWFIQ SLCAMLKQ.Y ADKLEFMHIL TRVNRKVATE  246
caspase-6  VIPLDVVDNQ TEKLDTNITE VDA....... ....ASVYTL PAGADFLMCY SVAEGYYSHR ETVNGSWYIQ DLCEMLGK.Y GSSLEFTELL TLVNRKVSQR  250
caspase-8  I....PVETD SEEQPYLEMD LSS....... ....PQTRYI PDEADFLLGM ATVNNCVSYR NPAEGTWYIQ SLWQSLRERC PRGDDILTIL TEVNYEVSNK  453
caspase-10 V....SIEAD ALNPEQAPTS LQS....... ....S....I PAEADFLLGL ATVPGYVSFR HVEEGSWYIQ SLCNHLKKLV PRHEDILSIL TAVNDDVSRR  447
caspase-9  FEVASTSPED ESPGSNPEPD ATPFQEGLRT FDQLDAISSL PTPSDIFVSY STFPGFVSWR DPKSGSWYVE TLDDIFEQW. AHSEDLQSLL LRVANAVSVK  394
caspase-2  VDQQDGKNHA GSPGCE.ESD AG..KEKLPK M.......RL PTRSDMICGY ACLKGTAAMR NTKRGSWYIE ALAQVFSER. ACDMHVADML VKVNALIKDR  400
                                                                     ♦♦♦o ♦♦  ♦  o♦

caspase-5  .......... QAKAQMPTIE RATLTRDFYL FPGN*.....  418
caspase-4  .......... RAKAQMPTIE RLSMTRYFYL FPGN*.....  377
caspase-1  .......... DGRAQMPTTE RVTLTRCFYL FPGH*.....  404
caspase-7  FESQSDDPHF HEKKQIPCVV .SMLTKELYF SQ*.......  303
caspase-3  FESFSFDATF HAKKQIPCIV .SMLTKELYF YH*.......  277
caspase-6  RVDFCKDPSA IGKKQVPCFA .SMLTKKLHF FPKSN*....  293
caspase-8  DDKKN..... .MGKQMPQPT .FTLRKKLVF PSD*......  479
caspase-10 VDKQG..... .TKKQMPQPA .FTLRKKLVF PVPLDALSI*  479
caspase-9  .GIY...... ...KQMPGCF .NFLRKKLFF KTS*......  416
caspase-2  .EGYAPGTEF HRCKEMSEYC .STLCRHLYL FPGHPPT*..  435
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Table 2 Sequence identity of the caspases

The sequence identity between the full-length caspases shown in Figure 2(b) was analysed using the GAP program from the Genetics Compter Group.

	Identity (%)										
Caspase	1	2	3	4	5	6	7	8	9	10	CED-3
1	100	22	30	55	50	22	26	22	25	22	29
2		100	22	27	22	28	22	26	33	28	28
3			100	33	30	33	52	33	37	33	34
4				100	77	28	22	20	22	21	26
5					100	22	25	22	24	22	25
6						100	33	35	33	35	35
7							100	33	32	33	33
8								100	22	41	26
9									100	33	29
10										100	25

caspase-$1^{-/-}$ mice. The only exception is the suggestion of a role for caspase-1 in CD95-induced apoptosis in thymocytes. However, no autoimmmune pathologies are seen in the caspase-$1^{-/-}$ mice similar to those caused by the *lpr*/*lpr* mutation in the murine locus [48].

Further support for a role for caspase-1 in CD95-induced cell death was provided by the findings of a decrease in CD95-induced death due to CrmA, caspase-1 inhibitory peptides and caspase-1-specific antisense oligonucleotides [49,50], together with a small transient increase in a caspase-1-like activity prior to an increase in a CPP32 (caspase-3)-like proteolytic activity [51]. However, this elevation in a caspase-1-like activity has not been demonstrated to be essential for CD95-mediated apoptosis [51]. A role for caspase-1 has also been proposed in the apoptosis of mammary epithelial cells following loss of the extracellular matrix [52] and in DNA-damage-induced interferon regulatory factor-1-dependent T-lymphocyte apoptosis [53]. Similarly, caspase-1 is activated by growth factor deprivation, and suppression of this activation by growth factors such as insulin-like growth factor-1 and insulin also inhibits cell death [54]. In contrast, caspase-1 activity and apoptosis are uncoupled in macrophages undergoing apoptosis [55]. While there is some experimental support for a role for caspase-1 in apoptosis, in particular in CD95-mediated apoptosis, most data (see also below) suggest that other caspases may be of greater significance than caspase-1.

ICH-1/Nedd2 (CASPASE-2)

Nedd2 was originally identified using subtraction cloning as a developmentally down-regulated gene in mouse brain [56,57]. Using a murine *Nedd2* cDNA, a human foetal brain cDNA library was screened at low stringency, and *Ich-1*, the human homologue of *Nedd2*, was identified [58]. Both *Nedd2* and *Ich-1* encode proteins similar to caspase-1, and sequence alignment shows conservation of many important residues, including the active-site pentapeptide QACRG (Table 1 and Figure 2) [57,58]. The *Ich-1* mRNA is alternatively spliced into two forms, one encoding a protein of 435 amino acids (ICH-1_L) and the other encoding a protein of 312 amino acids (ICH-1_S; a truncated form of ICH-1_L) [58]. Overexpression of *Ich-*1_L in some, but not all, cell types results in apoptosis, whereas overexpression of *Ich-*1_S suppresses apoptosis induced by serum withdrawal, suggesting that *Ich-1* may play a role in both the positive and negative regulation of programmed cell death [58]. The enzymic activities of ICH-1_L/Nedd2 are required to cause cell death, as overexpression of mutant *Ich-*1_L*/Nedd2* (with a Ser or Gly respectively replacing the active-site Cys) results in loss of activity [57,58]. During embryonic development, *Nedd2* is expressed at relatively high levels in various tissues, including the central nervous system, liver, kidneys and lungs [57]. Both the kidney and central nervous system are associated with high levels of programmed cell death during development [59]. *Nedd2* is also expressed to varying extents in several adult tissues, including post-mitotic neurons [57].

Two recent studies have addressed the question of which Asp cleavage sites are important in the processing of Nedd2 [60,61]. The Asp-333 → Ala mutant lacks apoptotic activity and does not produce p20 and p10 fragments, suggesting it as the cleavage site at the C-terminus of p20. Asp-347 was identified as the Asp residue at the N-terminus of p10. Asp-135 appears to be a cleavage site upstream of p20, as cell death activity and processing are prevented when it is mutated [60,61]. The proposed cleavage sites in Nedd2 are conserved in caspase-2 (Figure 3). Caspase-2 may be activated *in vitro* by caspase-1, caspase-3 and granzyme B [61]. Recently, the cleavage of caspase-2 to its catalytically active subunits during the execution phase of apoptosis in the human monocytic tumour cell line THP.1 was demonstrated [62]. Caspase-2 was cleaved early during the apoptotic process, but it was not possible to discern whether its cleavage preceded that of other caspases. As yet, no specific intracellular protein substrates of caspase-2 have been identified.

CPP32/YAMA/APOPAIN (CASPASE-3)

Caspase-3 is one of the key executioners of apoptosis, being responsible either partially or totally for the proteolytic cleavage of many key proteins, such as the nuclear enzyme poly(ADP-ribose) polymerase (PARP), which are cleaved in many different systems during apoptosis (see below). Using the DNA sequence encoding the active site of caspase-1 and CED-3 to search an expressed sequence tag database, a human sequence was identified, cloned and shown to encode a 32 kDa cysteine protease, called CPP32 [63]. Independently, two other groups identified caspase-3, one naming it Yama (the Hindu god of death) and the other apopain [64,65]. Caspase-3, a member of the CED-3 subfamily of caspases (Table 2 and Figure 2b), is widely distributed, with high expression in cell lines of lymphocytic origin, suggesting that it may be an important mediator of apoptosis in the immune system [63]. Based on the known cleavage site of PARP (DEVD↓G), Ac-DEVD-AMC was

Figure 2 (a) Phylogenetic relationships and (b) sequence alignment of the caspases

Phylogenetic relationships were determined and polypeptide sequences for the human forms of the caspases aligned using the PILEUP algorithm (Genetics Computer Group, Madison, WI, U.S.A.). The relationships are based on the full-length proenzymes, which is appropriate as the prodomains clearly play a functional role. The dendogram is not affected if the same analysis is carried out using caspases without their prodomains. Amino acid residues are numbered to the right of each sequence. The QACXG motif is conserved in all family members and is boxed. A coloured arrow above the aligned sequences indicates the position of the catalytic cysteine residue. Amino acids that align with residues within ICE that have been shown by the X-ray crystal structure to be involved in binding P_1 Asp (○), in catalysis (□) and adjacent to substrate P_2–P_4 amino acids (◆) are indicated. The underlined sequences represent the FADD/MORT1 (see the text) homology domains in caspase-8 and caspase-10.

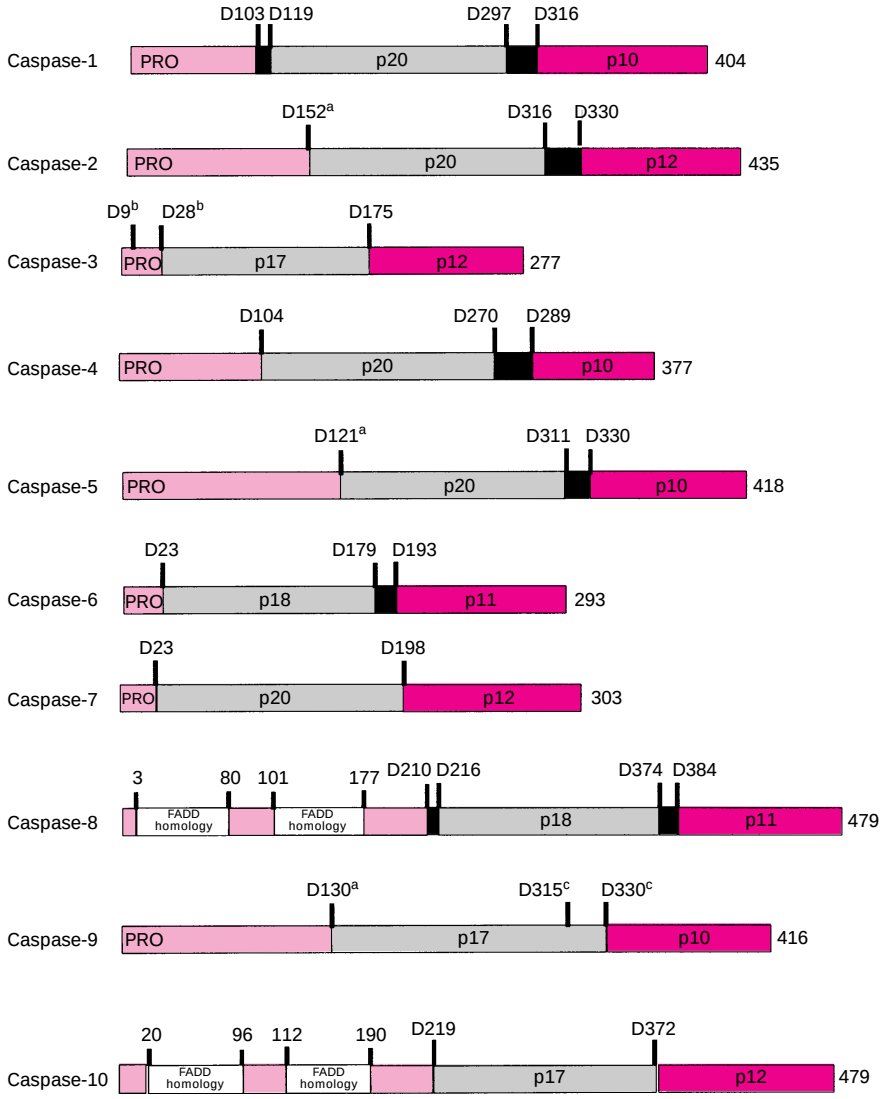

Figure 3 Proenzyme organization of the caspases

Caspases are synthesized as proenzymes, with a N-terminal peptide or prodomain (PRO), and two subunits sometimes separated by a linker peptide (black box). Based on caspase-1 and caspase-3, active enzymes are heterotetramers of two large (~ 20 kDa; p20) and two small (~ 10 kDa; p10) subunits. The proenzymes are cleaved at specific Asp residues (D*n*, where *n* is the position in the protein). The numbers at the right-hand side are the numbers of amino acids in the protein. [a]Exact cleavage site not known; [b]the cleavage site of caspase-3 may be at Asp-9 or Asp-28 [65–67]; [c]caspase-9 is cleaved preferentially at Asp-330 by caspase-3 and at Asp-315 by granzyme B [82]. Caspase-2 cleavage sites are based on equivalent sites being present in Nedd2 [60,61]. FADD represents the domains of caspase-8 and caspase-10 that are homologous to the DED of FADD/MORT1.

synthesized as a model substrate, and Ac-DEVD.CHO and its biotinylated derivatives were synthesized as specific inhibitors of PARP cleavage and as affinity ligands for purification of the protease. Using electrospray MS and N-terminal sequence analysis, the active enzyme was shown to be composed of two subunits of 17 kDa and 12 kDa, derived from the precursor protein by cleavage at Asp-28–Ser-29 and Asp-175–Ser-176 [65] (Figure 3). While the initial cleavage is probably between the large and small subunits, it has been suggested that processing within the prodomain occurs initially at Asp-9, not at Asp-28 [66,67].

During the execution phase of apoptosis, caspase-3 is responsible either wholly or in part for the proteolysis of a large number of substrates, each of which contains a common Asp-Xaa-Xaa-Asp (DXXD) motif (Table 3), similar to that originally described in PARP [68]. In comparison with caspase-1, caspase-3 has no linker peptide and the prodomain is much shorter (Figures 2b and 3). Caspase-3 prefers a DXXD-like substrate, whereas caspase-1 prefers a YVAD-like substrate [65]. Both enzymes have an almost absolute requirement for an Asp in the P_1 position and both can tolerate a fair degree of substitution in the P_2 and P_3 positions, but in the P_4 position caspase-1 prefers a hydrophobic amino acid such as Tyr, whereas caspase-3 has a marked preference for an Asp. The three-dimensional structure of a complex of caspase-3 with DEVD.CHO, a potent tetrapeptide aldehyde inhibitor, shows that, although caspase-3 resembles caspase-1 in overall structure, its S_4 subsite is very different in size and chemical composition and accounts for their differences in specificity [69]. The S_4 subsite of caspase-1 is a large shallow hydrophobic depression that readily accommodates a tyrosyl side chain, while the analogous site in caspase-3 is a narrow pocket that closely surrounds the P_4 Asp side chain [69].

Table 3 Protein substrates of caspases

Abbreviation: SREBP, sterol regulatory element binding protein.

Protein substrate	Cleavage motif	Caspase(s)	Function of substrate	References
PARP	DEVD↓G	3,7	DNA repair enzyme	68, 104
U1-70 kDa	DGPD↓G	3	Splicing of RNA	106
DNA-PK_{CS}	DEVD↓N	3	DNA double-strand-break repair	106, 107
Gas2	SRVD↓G	?	Component of microfilament system	126
Protein kinase C δ	DMQD↓N	3	Cleaved to active form in apoptosis	130, 131
Pro-IL-1β	YVHD↓A	1	Cleaved to mature active cytokine	32–34
D4-GDP dissociation inhibitor	DELD↓S	3	Regulator of Rho GTPases	110
Lamin A	VEID↓N	6	Assist in maintaining nuclear shape	113–116
Heteroribonuclear proteins C1 and C2	?	3,7	Processing of pre-mRNA	108
Huntingtin	DXXD	3	Huntington disease gene product	111
SREBP-1 and SREBP-2	DEPD↓S	3,7	Sterol regulatory element binding proteins	109
Fodrin	DETD↓S?	?	Membrane-associated cytoskeletal protein	127–129
Rb (see the text)	DEAD↓G	3	Cell cycle regulatory protein	112, 133, 134

The Trp residue at position 348 and an inserted 10-amino-acid sequence at position 381 (for ease of comparison, the residue numbers used are those of the analogous residues in caspase-1) play a crucial role in defining the size and shape of the S_4 subsite of caspase-3 and are also conserved in all known members of the CED-3 subfamily (Figure 2b). The activation of caspase-3 to either of its catalytically active p17 or p12 subunits has been demonstrated in cells undergoing apoptosis [70–72].

Caspase-3-deficient mice, generated by homologous recombination, are smaller than their littermates and die at 1–3 weeks of age. Thymocytes from caspase-3-deficient mice show a similar sensitivity to apoptosis induced by a number of different stimuli, including CD95, anti-CD3, staurosporine and dexamethasone. Brain development in these deficient mice is markedly affected, with a variety of hyperplasias being observed from embryonic day 12. Pyknotic clusters of apoptotic cells, observed at sites of major morphogenetic change in normal brain development, are not seen in the deficient mice, indicative of decreased apoptosis in the absence of caspase-3. This demonstrates that caspase-3 plays a critical role during morphogenetic cell death in the mammalian brain and also that mutation of a mammalian homologue of *Ced-3* leads to decreased cell death and a supernumerary cell population during development, emphasizing that the basic cell death machinery is evolutionarily conserved. The restricted phenotype also raises the possibility that other caspases may be important in other tissues or cell types [73].

Cytotoxic T lymphocytes kill target cells containing foreign antigens by either CD95- or granule-mediated cytotoxicity. Exocytosis of cytotoxic T lymphocyte granules allows perforin to polymerize in the target cell membrane, so facilitating entry of the granzymes, a family of serine proteases. Granzyme B also exhibits an unusual specificity for Asp in the P_1 position. *In vitro*, granzyme B can activate caspase-3, as assessed by formation of its p17 subunit as well as its ability to cleave PARP to its signature fragment [74,75]. Activation of caspase-3 by granzyme B is within the physiological range [75]. While granzyme B can activate directly caspase-3, it may also cleave another caspase which in turn activates caspase-3.

ICE_{rel}II/TX/ICH-2 (CASPASE-4) AND ICE_{rel}III/TY (CASPASE-5)

Three groups independently cloned ICE_{rel}II/TX/ICH-2 (caspase-4) [76–78] and two groups cloned ICE_{rel}III/TY (caspase-5) [76,79] (Figure 2b). Both caspase-4 and caspase-5 are members of the caspase-1 subfamily, and are more closely related to each other than to other homologues (Table 2). Caspase-4 expression, while lower than that of caspase-1, generally shows a similar tissue distribution, being found in most tissues examined with the exception of brain. Appreciable levels are found in both lung and liver, and also in ovary and placenta, where caspase-1 mRNA is barely detectable [76,77]. Caspase-5 is expressed at a much lower level than caspase-4 [76,79]. Caspase-4 and caspase-5 have different substrate specificities from that of caspase-1, being much poorer at cleaving pro-IL-1β [76–79]. Caspase-4 may be involved in the maturation of caspase-1 [78]. At high concentrations, caspase-4 cleaves PARP [80], but the biological relevance of this is unclear. Limited information is available concerning the precise sites at which caspase-4 and caspase-5 are processed. Maturation of caspase-1 results from cleavage after Asp residues at positions 119, 297 and 316, with the latter two residues being conserved in caspase-4 (Asp-270 and Asp-289) and caspase-5 (Asp-311 and Asp-330); by analogy, this probably represents the removal of a linker peptide (Table 1 and Figure 3). The Asp-119 site in caspase-1 is not conserved in caspase-4, but Asp-104 might define the cleavage site for removal of the prodomain [77]. Overexpression of caspase-4 and caspase-5 generally results in apoptosis, although in some studies apoptosis was only induced after removal of the prodomains, suggesting that the prodomains may be involved in the regulation of apoptosis [76,78].

Mch2 (CASPASE-6)

Using a PCR approach with degenerate primers encoding two highly conserved pentapeptides, QACRG and GSWFI, Alnemri and co-workers cloned Mch2 (a mammalian CED-3 homologue) from a human Jurkat T lymphocyte cDNA library [81]. Two transcripts were detected, Mch2α (1.7 kb) and Mch2β (1.4 kb), the former encoding the full-length Mch2 and the latter encoding a shorter isoform, possibly as a result of alternative splicing. Mch2α (caspase-6) encodes a 293-amino-acid protein with a predicted molecular mass of $\sim$34 kDa. Mch2β contains a deletion corresponding to nucleotides 119–385 of the Mch2α sequence (amino acids 14–102) and encodes a 204-amino-acid protein with a predicted molecular mass of $\sim$23 kDa. Mch2β lacks half of the p20 subunit and is probably catalytically inactive [81]. Expression of Mch2α, but not Mch2β, in insect cells results in the induction of apoptosis. Caspase-6 is a member of

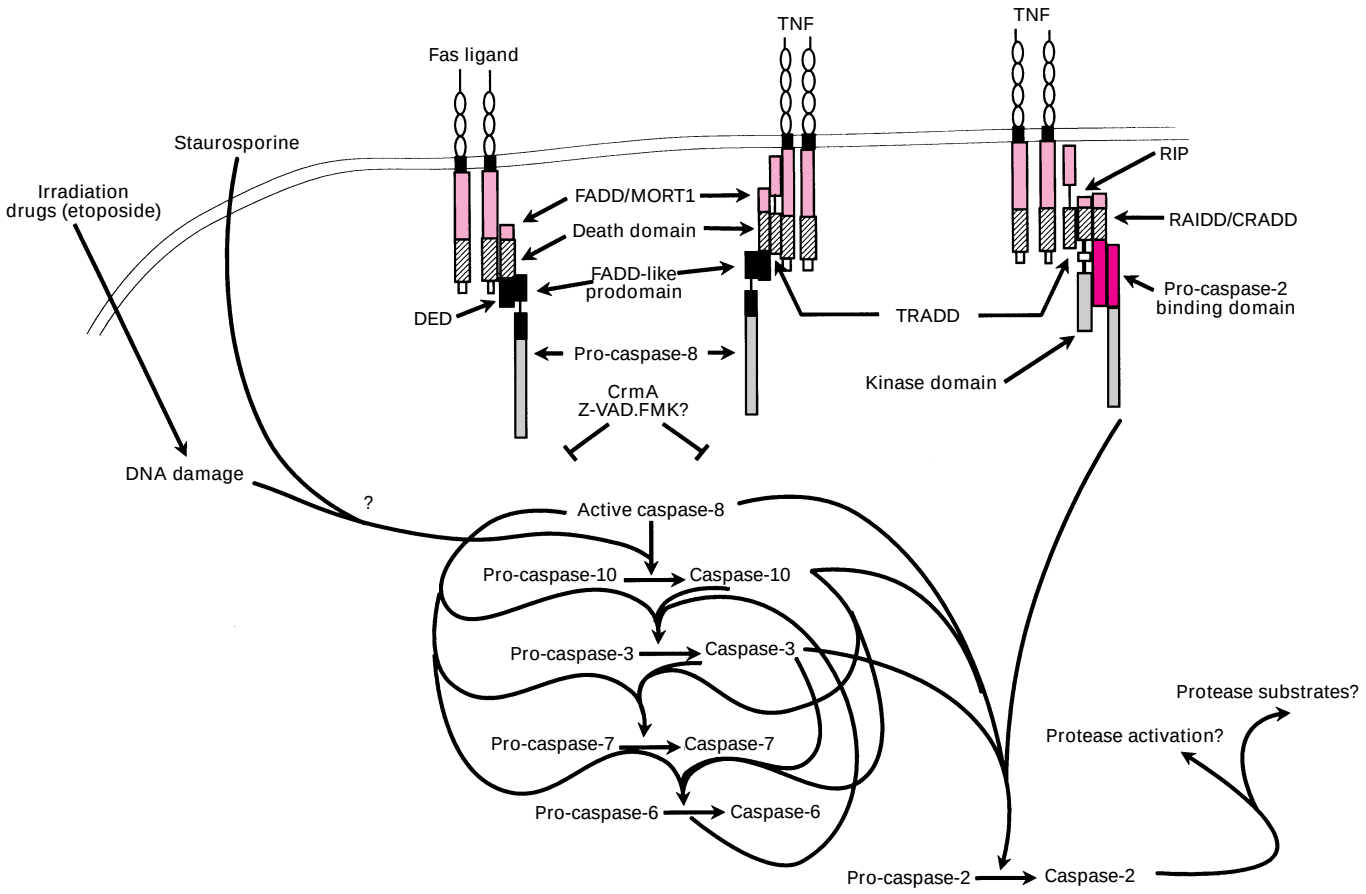

Figure 4 Hypothetical hierarchy of caspases

Apoptosis can be triggered by drugs (staurosporine), by DNA-damaging agents (etoposide or γ-irradiation) or by CD95 (Fas/APO-1) or tumour necrosis factor (TNF) interacting with their respective receptors. Both of these receptors transduce their apoptotic signals via intracellular C-terminal death domains (hatched boxes) which are involved in protein–protein interactions. Both CD95 and TNF result in the cleavage and activation of caspase-8, which can cleave all other known caspases. Caspase-10, which also cleaves all other known caspases, is activated by different stimuli via a CrmA-insensitive pathway, and may be activated following DNA damage (?). Activation of some caspases, such as caspase-6, results in their being able to cleave the caspase initially responsible for their formation, so setting up a protease amplification cycle [82]. Caspases may also be recruited to the death pathways by adapter molecules such as RAIDD/CRADD, which bind to RIP and to the prodomains of certain caspases such as pro-caspase-2 [101,102]. Part of this scheme, showing which caspase activates other caspases, is based on *in vitro* studies with purified enzymes, and requires confirmation from studies with intact cellular systems.

the CED-3 subfamily, showing high identity with caspase-3 (Figure 2a and Table 2).

Caspase-6, when expressed as a glutathione S-transferase fusion protein in *Escherichia coli*, autoprocesses and cleaves Ac-DEVD-AMC [although it is much less active ($\sim$ 150-fold) than caspase-3], but it does not cleave Ac-YVAD-AMC. Caspase-6 is also not readily inhibitable by Ac-DEVD.CHO [82]. Recombinant caspase-6 cleaves human PARP to give a smaller fragment than that seen in cells undergoing apoptosis, suggesting that caspase-6 does not play a major role in the cleavage of PARP [81]. Purified human recombinant caspase-3 cleaves ^{35}S-labelled pro-caspase-6 at three aspartate cleavage sites (Asp-23, Asp-179 and Asp-193), resulting in the formation of the large (p18) and small (p11) subunits of caspase-6 [82]. Initial cleavage appears to be at $D^{176}VVD\downarrow N^{180}$, resulting in a p13 subunit, which is then further cleaved at $T^{190}EVD\downarrow A^{194}$, resulting in the p11 subunit (Figure 3). Activation of pro-caspase-6 by caspase-3 results in an active enzyme that is capable of cleaving an artificially introduced lamin cleavage site (VEID$\downarrow$N) [82]. These data suggest that caspase-3 is activated prior to, and may be responsible for, the activation of caspase-6. However, these results are in apparent conflict with a recent study which identified and purified from hamster liver a homologue of caspase-6 that is capable of activating caspase-3 [83]. In addition, caspase-6 processes pro-caspase-3 at the $I^{172}ETD\downarrow S^{176}$ site between the large and small subunits, and this cleavage is blocked when Asp-175 is mutated to Ala [82]. Thus activation of caspase-3 can result in activation of pro-caspase-6 but, similarly, activation of pro-caspase-6 can also result in activation of caspase-3, resulting in a protease amplification cycle (Figure 4) [82]. Some caution must be exercised in the interpretation of such *in vitro* experiments, as purified or partially purified proteases may cleave substrates that they would not cleave *in vivo*, either because the ratio of enzyme to substrate would never reach such a level in the cell or because the enzyme may be located in a different subcellular environment from the substrate.

Mch3/ICE-LAP3/CMH-1 (CASPASE-7)

Caspase-7 was cloned independently in three different laboratories and named Mch3/ICE-LAP3/CMH-1 [84–86]. A member of the CED-3 subfamily, it is a 303-amino-acid protein with high

similarity to caspase-3 (Figure 2a and Table 2). An alternatively spliced isoform of caspase-7, which may act as a negative regulator of apoptosis, has been described [84]. Caspase-7 is constitutively expressed in many foetal and adult tissues, with lowest expression observed in the brain. Using a rabbit anti-peptide antibody, caspase-7 protein migrates at $\sim$ 35 kDa and is detected to a variable extent in a number of cell lines, including Jurkat T cells, where it is localized diffusely to the cytoplasm and juxtamembrane structures [85], consistent with the suggestion that the death effector machinery resides in the cytoplasm rather than the nucleus [8]. Overexpression of full-length caspase-7 in the MCF7 breast carcinoma cell line does not induce apoptosis, whereas expression of a truncated derivative, lacking the 53 N-terminal amino acids corresponding to the putative prodomain, induces apoptotic cell death [85]. Bacterially expressed caspase-7, like caspase-3, preferentially cleaves PARP and the peptide substrate Ac-DEVD-AMC, but not Ac-YVAD-AMC or pro-IL-1β. The competitive peptide aldehyde inhibitor Ac-DEVD.CHO is a potent inhibitor of both caspase-3 and caspase-7, whereas Ac-YVAD.CHO and CrmA are poor inhibitors of both of these enzymes. As caspase-3 and caspase-7 are functionally similar and have similar substrate specificities [84], cleavage of PARP during apoptosis may be due to a combination of the action of both these caspases. Active caspase-7 is made up of two subunits, similar to other caspases [66] (Figure 3). Caspase-7 is activated to its catalytically active large subunit in intact cells undergoing apoptosis [62,85,87].

Following cleavage at Asp-198 and Asp-23, granzyme B activates pro-caspase-7 to a form that cleaves PARP to its signature fragment of $\sim$ 85 kDa [66,88,89]. Using a caspase-7 protein with Asp-23 mutated to glutamate, it was demonstrated that removal of the prodomain by autoprocessing is not necessary for activity and that the p25/p12 enzyme is as active as the p20/p12 enzyme [89]. This suggested that the prodomain of caspase-7 may be involved in an as yet uncharacterized way in the regulation of caspase-7. *In vitro*, caspase-7 is a better substrate for granzyme B than is caspase-3. Pro-caspase-7 appears to exist as dimers or higher-order oligomers [89]. Incubation of Jurkat T cells with granzyme B together with a sublytic concentration of perforin results in the activation of endogenous caspase-7 prior to the induction of apoptosis. Together, these data suggest that caspase-7 may be an important intracellular effector of granzyme B-mediated apoptosis and cytotoxic T-lymphocyte-induced cell killing *in vivo*.

MACH/FLICE/Mch5 (CASPASE-8)

CD95 and the TNF receptor (TNFR-1; p55-R) are members of the TNF/nerve growth factor receptor family. Activation of these cell-surface cytokine receptors, either by their natural ligands or by agonistic antibodies, results in apoptosis. CD95 and TNFR-1 share a region of identity termed the 'death domain' that is required to signal apoptosis. Using a yeast two-hybrid system, three proteins were identified that bind to either the intracellular domains of CD95 and/or TNFR-1 through hetero-association of homologous regions found in these proteins. FADD/MORT1 (Fas-associating protein with death domain) [90,91] binds specifically to CD95, TRADD (TNFR-1-associated death domain protein) binds to TNFR-1 [92], and RIP (receptor-interacting protein) binds to both receptors [93]. Activation of CD95 initiates the association of at least four proteins (CAP1–CAP4), two of which (CAP1 and CAP2) have been identified as alternative forms of phosphorylated FADD/MORT1 [94]. A dominant-negative version of FADD, lacking the N-terminal death effector domain (DED), blocks the recruitment of the two other proteins (CAP3 and CAP4) to the death-inducing signalling complex [91], suggesting that these two proteins are downstream components of the CD95 signalling cascade. The region encompassing the 117 N-terminal amino acid residues of FADD can trigger apoptosis, and have been called DED [95].

Two groups independently identified a novel caspase, named MACH/FLICE (caspase-8), which contains both an active subunit with identity with the caspases and an N-terminal prodomain containing two domains with marked identity with the N-terminal DED of FADD/MORT1 [96,97] (Figure 3). Using nano-electrospray tandem MS, peptide sequences were obtained for CAP4 which, when used as sequence tags, identified a 3 kb cDNA that encodes a novel protein, caspase-8, of predicted molecular mass 55.3 kDa. The other group used a yeast two-hybrid screen to identify a cDNA clone with a novel sequence which binds to MORT1/FADD. This novel protein (MACH) occurs in multiple isoforms, most probably produced by alternative splicing, some of which contain a region with identity with the caspases. Northern blot analysis revealed a heterogeneity of caspase-8 transcripts which varied in amount and size in different human tissues. Few caspase-8 transcripts are detectable in testis, skeletal muscle and brain, with a relatively higher level of expression in peripheral blood leucocytes, consistent with a role for CD95-induced apoptosis in lymphocyte homoeostasis.

Caspase-8 contains two N-terminal stretches of approx. 70 amino acids that are apparently homologous to the DED of FADD. Residues 7–75 and 101–169 of caspase-8 share 39% identity (55% similarity) and 28% identity (55% similarity) respectively with the DED of FADD (residues 4–76) [97]. While the N-terminal portion of caspase-8 contains the FADD homology domains, the remainder of the protein is highly similar to the CED-3 subfamily of caspases (Figure 2a and Table 2). Instead of the active-site QACRG pentapeptide found in most caspases, caspase-8 contains the novel sequence QACQG. Caspase-8 associates with the DED of FADD. Granzyme B activates caspase-8 to an active protease which cleaves PARP to its characteristic signature fragment. Overexpression of caspase-8 results in apoptosis, and mutation of its catalytic cysteine residue abolishes its apoptotic potential. Expression of caspase-8 in the presence of isoforms with an incomplete caspase region resulted in little cell death. Similarly, these isoforms lacking a complete caspase region blocked cell death induced by CD95 and TNF, suggesting that the isoforms exert a dominant-negative effect and may be important in the regulation of apoptosis *in vivo*.

The marked heterogeneity of isoforms of caspase-8 compared with other caspases may provide a mechanism for some tissues or cells to protect themselves against CD95- or TNF-induced cell death [96]. These studies provide a critical link between activators and effectors of the cell death machinery. Oligomerization of the death domain of either CD95 or TNFR-1 allows recruitment of cytosolic adapter proteins to assemble a death-inducing signalling complex [98]. Thus CD95 (a cell death receptor) uses FADD (an adapter molecule) to interact physically with caspase-8 (a cytosolic protease) and initiate the apoptotic cascade (Figure 4). The precise mechanism by which recruitment of caspase-8 results in its activation is not known. It has been suggested that, in the latent state, the two DEDs of caspase-8 bind to each other, so preventing activation. The binding of FADD following the triggering of apoptosis by CD95 or TNF may cause a conformational change in the DED of FADD, so facilitating its binding to one of the DEDs of caspase-8, thereby disrupting the association of the two DEDs of caspase-8 and allowing its caspase domain to undergo autocatalytic activation [96,97].

Independently, Mch5 was cloned from Jurkat T cells, and its predicted sequence is almost identical with that of caspase-8 [66,96]. A small difference in the prodomain is revealed following sequence comparison of Mch5 and MACH/FLICE (G. M. Cohen, unpublished work). Bacterial expression of pro-caspase-8 generates a mature enzyme composed of two subunits, derived by processing of the proenzyme (Figure 3). Recombinant caspase-8 is able to process/activate all known caspases, including caspases-1 to -7 and caspases-9 and -10 [66,67], supporting the suggestion that it lies at the apex of an apoptotic cascade, at least from some stimuli such as CD95 or TNF [96,97].

ICE-LAP6/Mch6 (CASPASE-9)

Recently, two groups independently cloned a new member of the caspase family, ICE-LAP6/Mch6 (caspase-9) [82,99]. On searching the databases for genes related to that for caspase-7, a cDNA clone was identified that encodes a novel 416-amino-acid protein with a predicted molecular mass of $\sim$ 46 kDa. Caspase-9 is a member of the CED-3 subfamily, bearing high similarity to caspase-3 (Table 2). The major difference between caspase-9 and other family members is the active-site pentapeptide QACGG, in which a Gly is found instead of the usual Arg (Table 1). Pro-caspase-9 contains a long N-terminal putative prodomain with high similarity to the prodomains of CED-3 and caspase-2. Northern-blot analysis revealed the presence of multiple mRNA species, suggestive of alternative splicing. High levels of expression of caspase-9 are found in the heart, testis and ovary. Overexpression of caspase-9, but not of a mutant in which the catalytic Cys was replaced with an Ala, induced apoptosis in MCF7 cells.

Procaspase-9 contains two potential processing sites between its large and small subunits, $P^{312}EPD\downarrow A^{316}$ and $D^{327}QLD\downarrow A^{331}$. The latter motif is similar to the DEVD$\downarrow$G site in PARP, suggesting that caspase-9 may be activated by caspase-3, while the former motif may be a potential granzyme B cleavage site, as it contains an acidic residue in the P_3 position. Using *in vitro* mutagenesis, it was demonstrated that both caspase-3 and granzyme B activated pro-caspase-9, although to differently sized products. Asp-330 was the processing site for caspase-3, generating two products of molecular masses $\sim$ 37 kDa (p37) and $\sim$ 10 kDa (p10). Granzyme B cleaved procaspase-9 at both sites, with a marked preference for Asp-315 over Asp-330, generating an active enzyme capable of cleaving PARP to its signature fragment of $\sim$ 85 kDa. In some, but not all, studies the prodomain of caspase-9 was removed [82,99]. The ability of caspase-3 to activate pro-caspase-9 suggests that the latter is downstream of caspase-3 and, as such, may be responsible for some of the later changes seen in cells undergoing apoptosis.

Mch4 (CASPASE-10)

Searching the databases of expressed sequence tags for sequences related to caspase-3 and caspase-6 led to the cloning from Jurkat T cells of a novel cDNA encoding a 479-amino-acid protein, Mch4 (caspase-10), with a molecular mass of $\sim$ 55 kDa [66]. Caspase-10, a member of the CED-3 subfamily, is more closely related to caspase-8 than to any other caspase (Figure 2a and Table 2). Like caspase-8, caspase-10 has an active-site QACQG pentapeptide and also contains two FADD-like DEDs in its N-terminal domain, suggesting a possible role in CD95- or TNF-induced apoptosis. Mature caspase-10 is derived from a single-chain polypeptide proenzyme by cleavage at Asp-372 located between the large and small subunits (Figure 3). Northern blot analysis revealed that caspase-10 mRNA is present in most tissues, with lowest expression being observed in brain, kidney, prostate, testis and colon and higher levels in heart, liver and spleen. Recombinant caspase-10 is unusual in that it has a similar K_m for the cleavage of both Ac-DEVD-AMC and Ac-YVAD-AMC, but it is more similar to caspase-3 as it is potently inhibited by Ac-DEVD.CHO [66]. Granzyme B cleaves procaspase-10, lacking the N-terminal FADD-like domains, at $I^{369}EAD\downarrow A^{373}$. Purified recombinant caspase-10 processes all caspases, including pro-caspases-3, -7 and -10, whereas neither caspase-3 nor caspase-7 cleaves pro-caspase-10, suggesting that the latter is upstream of both caspase-3 and caspase-7 and lies at or near the apex of a cascade of proteases [66,67] (Figure 4).

GENERAL FEATURES OF THE CASPASES

Caspases are synthesized as inactive proenzymes which are activated by cleavage at specific Asp residues to active enzymes containing both large (p20) and small (p10) subunits. In some cases these subunits are separated by a linker region of unknown function but which may be involved in regulation of the activation of the caspase. All caspases contain an active-site pentapeptide of general structure QACXG (where X is R, Q or G). The amino acids Cys-285 and His-237 involved in catalysis, and those involved in forming the P_1 carboxylate binding pocket in caspase-1 (Arg-179, Gln-283, Arg-341 and Ser-347), are conserved in all the other caspases, except for the conservative substitution of Thr for Ser-347 in caspase-8 (Figure 2b). This explains the absolute requirement for an Asp in the P_1 position. However, the residues that form the P_2–P_4 binding pocket are not well conserved, suggesting that they may determine the substrate specificities of the different caspases. It is evident from studies such as those with the caspase-$1^{-/-}$ and caspase-$3^{-/-}$ mice that not all caspases are required for cell death, and that some are more important than others. The importance of the tissue specificity of individual caspases is illustrated by the effects on the brains of caspase-$3^{-/-}$ mice [73]. Alternatively spliced isoforms of many caspases may in part regulate the activity of the full-length enzyme, either by acting as dominant inhibitors or by forming inactive heteromeric complexes [58,96]. A key role for a particular caspase in apoptosis has often been inferred from its overexpression resulting in the induction of this process. However, such overexpression may lead to the caspase cleaving substrates that it does not normally recognize. In addition, injection of other proteases such as trypsin or chymotrypsin into the cytoplasm of various cell types results in the induction of apoptosis [100].

Some caspases contain only a short prodomain (caspases-3, -6 and -7), whereas others contain long prodomains (caspases-1, -2, -4, -5, -8, -9 and -10) (Figure 3). The importance of the FADD-like prodomains of caspase-8 and possibly caspase-10 in directly linking CD95- and TNFR-1-mediated apoptosis has already been emphasized [96,97]. The significance of the other prodomains is not known, but they may be important in regulation of the activation of the caspases [43]. This possibility has been highlighted by the identification of a new adapter molecule, RAIDD (RIP-associated ICH-1/CED-3-homologous protein with a death domain)/CRADD (caspase and RIP adapter with death domain) [101,102]. RAIDD/CRADD comprises two main domains: an N-terminal domain which resembles and binds by a homophilic mechanism to the prodomain of caspase-2 and CED-3, and a C-terminal death domain that binds to RIP, a Ser/Thr kinase, which associates with CD95 and induces death [101]. The N-terminus of RAIDD/CRADD has significant identity with the prodomains of caspase-2 (residues 15–91; 31% identity), caspase-9 (residues 1–79; 28% identity) and CED-3

(residues 2–78; 24 % identity), as well as with the C-terminus of a human inhibitor of apoptosis (IAP-1) [102]. Mutation of highly conserved residues in the N-terminal prodomains of caspase-2 and CED-3 abolishes their binding to RAIDD. RAIDD binds RIP, part of the TNFR-1 signalling complex, but not FADD or TRADD, except in the presence of RIP, when it can bind the latter. RIP recruits RAIDD/CRADD, which in turn recruits caspase-2, so creating a direct link to the effector caspases [101,102] (Figure 4). Interestingly, mature caspase-2 processes its own precursor, but not other currently known caspases [102]. Thus prodomains of some caspases may enable them to be recruited specifically to facilitate the execution of the cell death programme. It remains to be determined whether there is a family of RAIDD-like molecules that can recruit other caspases with long prodomains.

PROTEIN SUBSTRATES CLEAVED BY CASPASES DURING THE EXECUTION PHASE OF APOPTOSIS

During the execution phase of apoptosis, several proteins, including PARP, lamin B and histone H1, are cleaved [103]. The number of proteins identified as being cleaved during apoptosis is increasing rapidly. The caspases responsible for these reactions are indicated in Table 3; however, other caspases may also cleave these substrates. It is also not known which caspase(s) is/are responsible for cleavage under physiological conditions, or whether there is redundancy in the proteases for these cleavages. Some caspases show overlapping specificities for some substrates (caspase-3 and caspase-7 can both cleave PARP), whereas other caspases may have a unique substrate specificity (to date, caspase-6 is the only caspase known to cleave lamins). The biological significance of these proteolytic cleavages and their relationship with the ensuing apoptotic morphology is often not known. Caspase-3 is responsible, either wholly or in part, for the proteolytic cleavage of a large number of substrates during apoptosis, including PARP, DNA-dependent protein kinase (DNA-PK), U1-70 kDa, heteronuclear ribonucleoproteins C1 and C2, sterol regulatory binding proteins, D4-GDP dissociation inhibitor, huntingtin, and almost certainly retinoblastoma protein (Rb) [104–111] (Table 3). A common feature of all these substrates is the presence of a DXXD motif (Table 3), similar to that originally described in PARP [68]. Based on the cleavage site of PARP, Ac-DEVD-AMC was designed as a fluorimetric substrate for the measurement of caspase-3 activity. However, since caspase-7 also cleaves this substrate and this reaction is also potently inhibited by Ac-DEVD.CHO, it is likely that many substrates described as being cleaved by caspase-3 will also be found to be cleaved by caspase-7.

PARP

PARP is possibly the best characterized proteolytic substrate of caspases, being cleaved in the execution phase of apoptosis in many systems, including thymocytes, HL-60 cells and breast cancer cell lines [103,104]. Intact PARP (116 kDa) is cleaved to 24 kDa and 89 kDa fragments, representing the N-terminal DNA binding domain and the C-terminal catalytic domain of the enzyme respectively [104]. This possibly conserves the cellular NAD^+ and ATP normally required for PARP activity, thereby enabling the ATP to be utilized for the execution of apoptosis [7]. Cleavage of PARP may also interfere with its key homoeostatic function as a DNA repair enzyme [105]. PARP is cleaved at the sequence DEVD↓G by a protease activity resembling ICE (prICE), but not by ICE itself [68]. Although the cleavage of PARP is often a valuable indicator of apoptosis, its biological relevance, if any, is unclear, since PARP-null mice develop normally [112]. *In vitro*, other caspases, including caspases-2, -4, -6, -7, -8, -9 and -10, when added at high concentrations, can also cleave PARP or DEVD-AMC [80]. The physiological significance of this cleavage of PARP by these caspases is still under investigation. At the present time, it appears that caspase-3 and caspase-7 are primarily responsible for PARP cleavage during apoptosis.

DNA-PK

DNA-PK, an enzyme involved in DNA double-strand-break repair, possesses a 460 kDa catalytic subunit (DNA-PK_{CS}) and a DNA binding component Ku, which is a heterodimer of 70 and 80 kDa subunits. During apoptosis in several different systems, DNA-PK_{CS}, but not Ku, is degraded by a caspase with properties similar to those of caspase-3 [105,106]. Caspase-3, but not caspases-1, -4 or -6, cleaves purified DNA-PK_{CS} to fragments of a similar size to those observed in cells undergoing apoptosis. Degradation of DNA-PK_{CS} should lead to a decrease in the DNA repair capacity of the cell, so abolishing its key homoeostatic function and facilitating the characteristic DNA degradation associated with apoptosis [105,106].

Lamins

The proteolysis of lamins, the major structural proteins of the nuclear envelope, is observed in different cells undergoing apoptosis [68,87,113–116] and may be responsible for some of the observed nuclear changes, since inhibitors of lamin cleavage prevent some of these changes [115,117]. An *in vitro* model of apoptosis has been developed in which normal nuclei, exposed to cytosol from apoptotic cells, undergo many of the characteristic biochemical and morphological changes of nuclear apoptosis, including chromatin condensation, fragmentation and margination, internucleosomal cleavage of DNA, and proteolysis of PARP and lamins [68,118]. In this model, the lamin protease is clearly distinct from the PARP protease, cleavage of PARP being significantly more rapid than that of lamins and less sensitive to inhibition by either YVAD chloromethyl ketone or tosyl-lysylchloromethane [115]. Caspase-6 (Mch2) cleaves lamin A at a conserved VEID↓N sequence to give a fragment similar to that seen in apoptotic cells and extracts [119,120]. The site of cleavage is in a well conserved α-helical rod domain, which may disrupt lamin–lamin interactions as well as interactions of lamins with other nuclear components [120]. This lamin cleavage is readily inhibited by YVAD chloromethyl ketone. Under conditions where caspase-6 cleaves lamin A, caspases-1, -3 and -7 do not, suggesting that caspase-6 may be the major laminase in cells undergoing apoptosis [119,120]. Other, as yet untested, caspases may also cleave lamins, as may a Ca^{2+}-regulated serine protease [115,121]. Pro-caspase-6 is activated in cells undergoing apoptosis induced either by anti-CD95 antibody or by staurosporine, and caspase-6 functions downstream of Bcl-2 and Bcl-x_L [119]. In CD95-treated HeLa cells, lamin B is preferentially cleaved early in apoptosis prior to cleavage of lamins A and C and internucleosomal cleavage of DNA; this suggests that B- and A-type lamins may be cleaved by different caspases [122].

U1-70 kDa

The activity of the U1 small nuclear ribonucleoprotein particle, which is essential for the splicing of precursor mRNA, is dependent on both the RNA and protein components, including U1-70 kDa. In several systems, including CD95- and TNFR-

induced apoptosis, U1-70 kDa is cleaved early in the apoptotic process to a 40 kDa fragment [105,123]. Purified caspase-3 cleaves U1-70 kDa at a DGPD↓G site, similar to the reaction observed in apoptotic cells. In lysates from apoptotic cells, the cleavage of U1-70 kDa is potently inhibited by Ac-DEVD.CHO but not by Ac-YVAD.CHO, strongly suggesting that caspase-3 or possibly caspase-7 is the major caspase responsible for its cleavage in apoptosis. Cleavage of U1-70 kDa separates the RNA binding domain from the distal arginine-rich region of the molecule, which may have a dominant-negative effect on splicing; such inhibition of splicing would block cellular repair pathways dependent on new mRNA synthesis [105].

Fodrin

During the execution phase of apoptosis, a number of important plasma-membrane changes occur, resulting in the recognition and subsequent phagocytosis of the apoptotic cell either by a professional phagocyte or by a neighbouring cell. Cleavage of important cytoskeletal proteins, including actin [124,125], Gas2 [126] and fodrin (non-erythroid spectrin) [127–129], during apoptosis may induce cell shrinkage and membrane blebbing, and alter cell survival signalling systems. α-Fodrin, an abundant membrane-associated cytoskeletal protein, is rapidly and specifically cleaved during CD95- and TNF-induced apoptosis, and this appears to be related to the membrane blebbing. Initially it was proposed that fodrin is cleaved by calpain I [127], but the cleavage is probably due to a caspase [128,129]. Fodrin contains several potential caspase cleavage sites, including a DETD↓S site only nine amino acids away from the proposed calpain cleavage site, which may have led to the initial confusion [128]. Treatment of cells with Ac-DEVD.CHO protected them from CD95-induced apoptosis, but did not prevent the proteolysis of fodrin [128], suggesting that fodrin proteolysis can be uncoupled from apoptosis and that it is mediated by a caspase other than caspase-3. If correct, this is an intriguing observation, as it suggests that some caspases (those responsible for the cleavage of fodrin) may be activated and yet apoptosis may still be prevented. An alternative possibility is that Ac-DEVD.CHO may have inhibited only some features of the apoptotic phenotype, including those used to assess apoptosis in the particular study [128]. The inhibitory characteristics of the caspase responsible for fodrin proteolysis, i.e. readily inhibited by Ac-YVAD chloromethyl ketone and relatively insensitive to Ac-DEVD.CHO, are reminiscent of caspase-6.

Protein kinase C δ and Rb

Protein kinase C δ is also specifically cleaved during apoptosis to a catalytically active fragment by caspase-3, but not by caspases-2, -4, -5, -6 and -7. Protein kinase C δ is one of the few examples of a substrate that is cleaved by caspase-3 but not by caspase-7. Interestingly, overexpression of this fragment, but not of full-length protein kinase C δ or a kinase-inactive fragment, is associated with chromatin condensation, nuclear fragmentation and cell death, suggesting that the proteolytic activation of protein kinase C δ may contribute to certain features of the apoptotic phenotype [130,131].

Rb is an important mediator of cell cycle progression and regulation. Phosphorylation of Rb by cyclin-dependent kinases inactivates its growth-suppressive functions and drives cells through the cell cycle into mitosis. More recently, an anti-apoptotic function of Rb has also been described [132]. Several groups have described the cleavage of Rb during apoptosis [111,133,134]. Interestingly, different-sized cleavage products of Rb were observed in these studies, suggesting the possible involvement of different caspases. In one study, the cleavage site of Rb was identified as a DEAD↓G motif in the C-terminal region of the molecule, suggesting the likely involvement of caspase-3. The cleaved Rb failed to bind the regulatory protein Mdm2, which may lead to apoptosis due to inactivation of Rb functions [111].

INHIBITION OF CASPASES BY CrmA, Bcl-2 FAMILY MEMBERS, p35 AND PEPTIDE INHIBITORS

CrmA

When ectopically expressed, the *crmA* gene prevents apoptosis in a number of different systems [21,22,58,92,135–137] (Table 4). However, the ability of CrmA to inhibit apoptosis is clearly dependent on the stimulus used to induce it (Table 4). Thus there are CrmA-sensitive and -resistant pathways present in the same cell types. The recognition motif cleaved within CrmA is LVAD [138]. CrmA was originally described as a novel specific inhibitor of caspase-1 [45], but it is now apparent that it differentially inhibits different caspases. CrmA is a protease inhibitor that inhibits cell death, most probably by inhibiting one or more caspases. CrmA is a poor inhibitor of CED-3, caspase-2, caspase-3, caspase-7 and caspase-10, but an effective inhibitor of caspases-1, -4, -6 and -8 (Table 1) [58,65,67,83,84,135,138,139]. CrmA blocks both CD95- and TNFR-1-mediated cell death at much lower concentrations than are required for the inhibition of caspase-3 and caspase-7 [23,49,50,64,85]. Caspase-3 and caspase-7 are proteolytically activated following stimulation with CD95 or TNFR-1, but remain as zymogens in anti-CD95-treated CrmA-expressing cells, suggesting that CrmA inhibits a protease upstream of caspases-3 and -7 [85,140]. The effects on caspases-8 and -10 may be particularly important, as both of these caspases are capable of processing themselves and all other known caspases [67], and caspase-8 appears to be at the apex of the apoptotic cascade induced by CD95 or TNF [96,97]. Caspase-8 is very sensitive to inhibition by CrmA, whereas caspase-10 is only poorly inhibited, requiring a $\sim$1000-fold greater concentration of CrmA to give the same inhibition [67]. Thus the sensitivity of CD95-induced apoptosis to inhibition by CrmA appears to be due to inhibition of caspase-8. Overexpression of caspase-8 results in apoptosis, which is inhibited by CrmA, suggesting that caspase-8 may be the physiological target of CrmA or, alternatively, that there is a downstream CrmA-

Table 4 Bcl-2 and CrmA regulate different pathways

Apoptosis induced in the same cells by different stimuli is often CrmA-sensitive or CrmA-resistant. The former pathways are frequently Bcl-2/Bcl-x_L-resistant, while the latter are Bcl-2/Bcl-x_L-sensitive. Abbreviations: NGF, nerve growth factor; ND, not determined.; Ara-C, Cytarabine.

Treatment	Cells	CrmA-sensitive	Bcl-2/Bcl-x_L -sensitive	References
Mouse ICE	Rat-1	+++	+++	21
CED-3	Rat-1	+	+	21
Caspase-2	Rat-1, HeLa	+	+++	58,135
NGF withdrawal	Dorsal ganglion neurons	++	++	22
CD95	Jurkat, BJAB, MCF7	+++	–	135,140
Staurosporine	Jurkat T cells	–	+++	140
CD95	Lymphoma cells	+++	–	136
γ-Irradiation	Lymphoma cells	–	+++	136
CD95	U937	+++	ND	137
Ara-C	U937	–	+++	137
TRADD	HepG2, NIH 3T3	+++	–	92

sensitive protease. These results further support the suggestion that caspase-8 lies at the apex of the apoptotic cascade triggered by CD95 and TNF, and explain why CrmA is such a potent inhibitor of apoptosis resulting from these stimuli (Figure 4). In contrast, CrmA-insensitive pathways may involve caspase-10 or a closely related homologue as their most upstream caspase (Figure 4).

Bcl-2 family

Bcl-2 is the mammalian homologue of CED-9, which is a negative regulator of CED-3 [19]. Bcl-2 and related family members, such as Bcl-x_L, inhibit cell death induced by many stimuli [141,142]. Interestingly, many of the apoptotic pathways that are sensitive to inhibition by CrmA are relatively resistant to Bcl-2/Bcl-x_L, and vice versa (Table 4). These findings suggest the presence of a CrmA-sensitive (CD95)/Bcl-x_L-insensitive and a CrmA-insensitive/Bcl-x_L-sensitive pathway for the induction of apoptosis [137]. As discussed earlier, specific interactions of TRADD and FADD with an intracellular domain of TNFR-1 and CD95 respectively induce apoptosis, and both of these are inhibited by CrmA, whereas neither Bcl-2 nor the *E1B* gene product block TRADD-induced cell death [91,92]. The CrmA-sensitive pathways generally appear to involve plasma membrane receptor-mediated apoptosis, compatible with the inhibition of a specific caspase (such as caspase-8) being recruited to the cell membrane. Bcl-2/Bcl-x_L seems relatively ineffective at inhibiting this type of receptor-mediated apoptosis, but more efficacious than CrmA at inhibiting other forms of apoptosis.

Several recent studies suggest that Bcl-2 and Bcl-x_L exert their anti-apoptotic action at or before the processing of certain caspases to their catalytically active forms [140,143–145]. For example, overexpression of Bcl-2 or Bcl-x_L prevents staurosporine-induced cell death of Jurkat T cells and the processing of both caspase-3 and caspase-7, placing these negative regulators of apoptosis at or upstream of the processing of caspases-3 and -7 [140].

p35

The baculovirus *Autographa californica p35* gene product inhibits apoptosis in insects, mammals and nematodes, suggesting that it acts at a central and evolutionarily conserved part of the apoptotic pathway [24,138,146,147]. Purified recombinant p35 inhibits the activity of purified recombinant caspases, including caspases-1, -2, -3 and -4, and maximum inhibition is achieved at equimolar concentrations of p35 and the caspase. Cleavage of p35 by a caspase results in the formation of a caspase–p35 complex. The presence of such complexes *in vivo* would prevent the caspases from initiating the apoptotic cascade. The CED-3 cleavage site in p35 is DQMD↓G, which is required for protection against programmed cell death in the nematode. Interestingly, CrmA does not protect against cell death in the nematode unless its caspase-1 cleavage site (LVADC) is replaced by the CED-3 cleavage site in p35 [138].

Peptide inhibitors

In addition to the reversible inhibitors Ac-DEVD.CHO and Ac-YVAD.CHO, use of the irreversible tripeptide caspase inhibitor Z-VAD.FMK [benzyloxycarbonyl-Val-Ala-Asp(OMe) fluoromethyl ketone] has helped to elucidate the role of caspases in apoptosis, in particular in intact cellular systems. Z-VAD.FMK is a cell-permeable irreversible inhibitor of caspases whose permeability is facilitated by the presence of the benzyloxycarbonyl and OMe groups. Z-VAD.FMK is a potent inhibitor of apoptosis induced by a wide range of stimuli in a number of different systems, including thymocytes, hepatocytes, human monocytic THP.1 cells, Jurkat T cells, neuronal cells and *Drosophila melanogaster* [72,144,148–153]. Z-VAD.FMK also suppresses programmed cell death in the interdigital webs of developing mouse paws, suggesting that it may be of value in studying developmental cell death [72,154]. Z-VAD.FMK inhibits apoptosis at an early stage, as judged by its inhibition of all the ultrastructural features of apoptosis, i.e. PARP cleavage, processing of caspase-3, formation of large fragments and internucleosomal cleavage of DNA [71,72,149,150]. More recently we have shown that it inhibits the processing of caspases-2, -3, -6 and -7, suggesting that it inhibits a caspase at or near the apex of the apoptotic cascade [62]. In this regard, it is of interest that Z-VAD.FMK blocks apoptosis induced by caspase-8 [97]. Many, but not all, apoptotic cell deaths are inhibited by Z-VAD.FMK [155,156]. Whereas it completely inhibited apoptotic death induced by different stimuli in thymocytes [150,155], it had a variable effect on cell death in peripheral T cell blasts while complete sensitivity to another caspase inhibitor was maintained, suggesting the activation of different caspases at different stages of T-cell maturation [155]. Z-VAD.FMK did not inhibit Bax (a Bct2 family member)-induced cell death, although it did inhibit certain features of the apoptotic phenotype, including cleavage of nuclear and cytosolic substrates and DNA fragmentation, suggesting that Bax-induced cell death may not require caspases [156]. *In vivo*, Z-VAD.FMK prevents the normally fatal liver damage induced by anti-CD95 injection [157]. Activation of both caspase-1-like and caspase-3-like protease activities is detected in liver lysates, as is the cleavage of caspase-3 to its p17 fragment. Repeated injections of Z-VAD.FMK results in the complete survival of all animals, with no histopathological signs of liver damage. The treatment with Z-VAD.FMK does not prevent the initial early small rise in ICE-like activity, as assessed by Z-YVAD-T-amino-4-trifluoromethylcoumarin cleavage; however, it does prevent processing of caspase-3 and the increase in caspase-3-like protease activity, as assessed by Z-DEVD-T-amino-4-trifluoromethylcoumarin cleavage. This and other observations suggest that non-toxic caspase inhibitors may have potential clinical applications in fulminant hepatitis arising from viral hepatitis [157] and various neurodegenerative disorders [5,154].

A HIERARCHY OF CASPASES

All caspases are cleaved at specific Asp residues, raising the possibility that some caspases sequentially activate others, so establishing a hierarchy of caspases. Such a model has been proposed in which caspase-8 has been termed an 'initiator' protease, which activates an 'amplifier' protease such as caspase-1, which in turn activates a 'machinery' protease such as caspase-3 or caspase-7 [158]. Much of the evidence for this, and the concept of a hierarchy of caspases, is based on *in vitro* data with recombinant enzymes; the limitations of such approaches have already been discussed. It is important, where possible, to determine if such a cascade of caspases occurs in cells undergoing apoptosis. PARP cleavage generally precedes lamin cleavage in cells undergoing apoptosis [68,87,115,116]. As caspase-3 and caspase-7 cleave PARP but not lamins, and caspase-6 cleaves lamins, this suggests that, in cells undergoing apoptosis, activation of caspase-3 and caspase-7 precedes activation of caspase-6 (Figure 4). In human monocytic tumour cells undergoing apoptosis, processing of caspases-2, -3, -6 and -7 was observed, although the precise sequence of activation of these caspases was not determined [62].

Different structural features, such as specific cleavage-site motifs, in the different caspases may give clues to their activities and to which caspase lies upstream of others (Table 1; Figures 2 and 3). The presence of a DXXD motif in caspases-2, -6 and -9 (Table 1) suggested that these three caspases may be activated by caspase-3, and this has been substantiated by *in vitro* experiments. A WXXD motif occurs in all three members of the ICE subfamily (Table 1), suggesting that they may be activated by the same caspase. Similarly, IXXD and LXXD motifs recur in different caspases (Table 1), supporting the notion that there may be a small number of key caspases that activate other family members. Good candidates for such critical caspases are caspase-8 and caspase-10, because they activate all other caspases and also contain FADD-like prodomains, which permit extensive protein–protein interactions [66,67,96,97]. Stimulation with either CD95 or TNF results in the recruitment and activation of caspase-8, supporting the hypothesis that it lies at the apex of the apoptotic cascade following specific receptor-mediated activation (Figure 4). Other types of receptor-mediated activation may involve other caspases, such as caspase-10. It has been proposed that caspase-10 may be involved in many CrmA-insensitive non-receptor-mediated cell deaths, as it is poorly inhibited by CrmA [67]. Once activated, some family members may then further activate the caspase that initially caused their activation, so setting up a caspase amplification cycle (Figure 4) [82]. The presence of CrmA-sensitive and -insensitive pathways also suggests that not all cell death pathways utilize the same caspases.

While many intracellular targets of the caspases have been recognized (Table 3), the critical cellular substrates leading to cell death have not yet been identified. The mechanisms by which caspases are regulated in cells in order to prevent their unwanted demise, and the possible role of apoptosis-inhibitory proteins, will be the subject of intense investigation. The long prodomains of some caspases, such as caspase-2, may enable them to be recruited by adapter molecules such as RAIDD/CRADD, so facilitating the execution of the cell death programme [101,102]. It remains to be determined whether there is a family of RAIDD/CRADD-like molecules that can recruit other caspases with prodomains.

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