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**11 FRET-based fluorogenic substrates were constructed using the pentapeptide template Asp-Glu-X<sub>2</sub>-Asp-X<sub>1</sub>', and evaluated with caspase-3, caspase-7 and cathepsin B. The sequence Asp-Glu-Pro-Asp-Ser was able to selectively quantify caspase-3 activity *in vitro* without notable caspase-7 and cathepsin B cross-reactivity, while exhibiting low  $\mu\text{M}$   $K_M$  values and good catalytic efficiencies ( $7.0\text{--}16.9 \mu\text{M}^{-1} \text{min}^{-1}$ ).**

Caspases (cysteine-aspartate proteases) are a family of endopeptidases that play a key role in the controlled initiation, execution, and regulation of apoptosis, and are essential in the development and homeostasis of mammals.<sup>1</sup> Their deregulation can lead to a number of human pathologies including autoimmune diseases,<sup>2</sup> neurodegenerative disorders<sup>3</sup> and cancer.<sup>4</sup> Caspases are produced as procaspases and undergo post-translational activation by the 'caspase cascade' following apoptotic stimuli and initiation of the extrinsic, intrinsic, or granzyme B apoptotic pathways.<sup>5</sup> Inactivation of the apoptotic intrinsic pathway is often regarded as a 'hallmark of cancer' as it leads to the uncontrolled proliferation of cells.<sup>6</sup> The intrinsic pathway responds to intercellular stress triggers, including oncogene activation and DNA damage, and therefore is often targeted in the treatment of cancer.<sup>7</sup> In addition, since caspases are usually directly involved in the early stages of apoptosis, they are attractive targets for molecular imaging, especially executioner caspase-3, which is down regulated in a variety of cancers.<sup>8</sup>

Current methods of caspase-3 detection include the use of antibodies<sup>9</sup> and fluorescent inhibitors.<sup>10</sup> In addition, FRET-based fluorogenic substrates, consisting of either small molecule fluorophores<sup>11</sup> or fluorescent fusion proteins,<sup>12</sup> have been developed, typically applying the substrate sequence Asp-Glu-Val-Asp (DEVV).<sup>13</sup> Commercially available substrates, such as Ac-Asp-Glu-Val-Asp-AFC (AFC = 7-amino-4-trifluoromethyl-coumarin)

## Eliminating caspase-7 and cathepsin B cross-reactivity on fluorogenic caspase-3 substrates†

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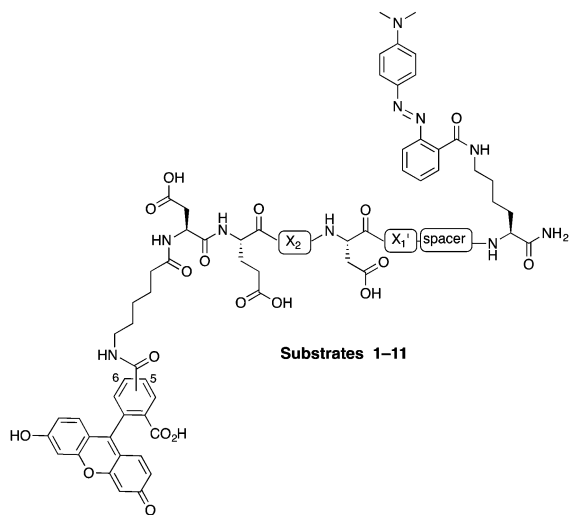
and MCA-Asp-Glu-Val-Asp-Ala-Pro-Lys-DNP (MCA = 7-methoxy-coumarin-4-yl)acetyl, (DNP = dinitrophenyl), have been utilised to analyse caspase-3 activity in cell lysates; however, they are unable to measure active caspase in intact cells for real-time analysis due to their inability cross the cell membrane and poor optical properties. Asp-Glu-Val-Asp-NucView™, which displays fluorescence upon cleavage and subsequent DNA binding, can be used to measure caspase-3 activity in cell-based assays.<sup>14</sup> All the above substrates are, however, based on the recognition sequence Asp-Glu-Val-Asp and therefore cross-react especially with caspase-7 and cathepsin B.<sup>15</sup> Low expression of proapoptotic caspase-7 is also associated with many cancers, and cathepsin B is often overexpressed in cancerous cells, highlighting the necessity to develop substrates and probes that can detect caspase-3 activation without cross-reactivity with these other enzymes. Recently, caspase-3 selectivity over other caspase isoforms was achieved by incorporation of unnatural amino acids into a pentapeptide recognition sequences to enable imaging of caspase-3 activity in live cells.<sup>16</sup> Similarly, substitution of glutamic acid in Asp-Glu-Val-Asp with pentafluorophenylalanine gave 4.5-fold selectivity over caspase-7 *in vitro* along with good selectivity over isoforms 6, 8, 9 and 10.<sup>17</sup>

In this study, internally quenched fluorogenic substrates to selectively detect caspase-3 over caspase-7 and cathepsin B were designed and synthesised, and evaluated against human recombinant caspase-3, caspase-7 and cathepsin B. A focused 11-member library of internally quenched substrates was designed incorporating a pentapeptide recognition sequence (X<sub>4</sub>-X<sub>3</sub>-X<sub>2</sub>-X<sub>1</sub>-X<sub>1</sub>'). Residue X<sub>4</sub> is where the most variability is found within substrates of the caspase family, with preference absolute for aspartic acid for caspase-3 and -7.<sup>18</sup> Caspases are not as selective for the X<sub>3</sub> position, although glutamic acid is by far the most favoured residue.<sup>18</sup> Caspase-3 and -7 both prefer hydrophobic residues at the X<sub>2</sub> position, with caspase-7 having far more specific requirements than caspase-3, retaining a higher preference for valine.<sup>18a</sup> This gives rise to the possibility of improving specificity towards caspase-3 by altering the X<sub>2</sub> position.<sup>18a,19</sup> Similarly, substitution of valine at the X<sub>2</sub> position

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**Fig. 1** Design of the internally quenched substrate library, incorporating a pentapeptide recognition sequence Asp-Glu- $X_2$ -Asp- $X_1'$  (caspases cleave between Asp and  $X_1'$ ). The amino-terminus bears a 6-aminohexanoic acid (Ahx) spacer and 5(6)-carboxyfluorescein (mixture of isomers) as the donor fluorophore, and the carbon-terminus has a methyl red (quencher) coupled to a lysine side chain. See Table 1 for each individual substrate sequences.

of Asp-Glu-Val-Asp with proline is known to abolish binding to cathepsin B.<sup>20</sup> The  $X_1'$  position was incorporated into the recognition sequence to explore if selectivity could be tuned by looking at the residue next to the cleavage/recognition site. At the  $X_1'$  position, natural caspase-3 substrates typically show a high preference for small amino acids.<sup>21</sup> Therefore, based on these known substrate requirements for caspase-3 and -7 and cathepsin B, a substrate library was designed, incorporating a FRET pair constructed using carboxyfluorescein as the donor ( $\lambda_{\text{Ex/Em}}$  492/517 nm) and methyl red (2-(*N,N*-dimethyl-4-aminophenyl)azobenzenecarboxylic acid) ( $\lambda_{\text{max}} \sim 480$  nm) as the acceptor/quencher (see Fig. 1). In the substrates, the  $X_2$  position contained either valine or proline, and  $X_1'$  glycine, alanine or serine. In addition, a 6-aminohexanoic acid (Ahx) spacer was positioned between the  $X_1'$  residue and the methyl red motif in to investigate possible steric hindrance from the quencher.

The substrates **1–11** (Fig. 1, Table 1) were synthesised on an Fmoc-Rink-amide linker derivatised aminomethyl polystyrene resin (1% DVB, 100–200 mesh, loading 1.2 mmol g<sup>-1</sup>) using standard Fmoc solid-phase chemistry with DIC and Oxyma as the coupling combination (ESI,† Schemes S1 and S2). Fmoc-Lys(Dde)-OH was coupled onto the Rink-linker followed by coupling of the Ahx linker (when present) and next five amino acids (Asp-Glu- $X_2$ -Asp- $X_1'$ ). With the amino-terminus Fmoc group still attached, the Dde protecting group was selectively removed with NH<sub>2</sub>OH·HCl/imidazole, followed by coupling of methyl red (in essence Fmoc-Lys(Dde)-OH is a bi-functional spacer utilising the orthogonal nature of the Fmoc and Dde protecting groups).<sup>22</sup> Finally, Ahx spacer and 5(6)-carboxyfluorescein were consecutively coupled. This modular approach allows for the changing of the quencher or conversion of the positions of the quencher and the fluorophore at final stages of the synthesis.

**Table 1** 11-membered FRET-based substrate library FAM-Ahx-Asp-Glu- $X_2$ -Asp- $X_1'$ -spacer-Lys(MR)-NH<sub>2</sub> (see Fig. 1 for structures)<sup>a</sup>

Substrate	$X_2$	$X_1'$	Spacer
<b>1</b>	Val	Gly	—
<b>2</b>	Pro	Ala	—
<b>3</b>	Pro	Ser	—
<b>4</b>	Val	—	Ahx <sup>b</sup>
<b>5</b>	Pro	—	Ahx
<b>6</b>	Pro	Gly	Ahx
<b>7</b>	Val	Gly	Ahx
<b>8</b>	Pro	Ala	Ahx
<b>9</b>	Val	Ala	Ahx
<b>10</b>	Pro	Ser	Ahx
<b>11</b>	Val	Ser	Ahx

<sup>a</sup> For the solid-phase synthesis and characterisation of the fluorogenic substrates, see ESI. <sup>b</sup> Ahx = 6-aminohexanoic acid.

After deprotection and cleavage off the resin, the substrates were purified by preparative RP-HPLC and analysed by MALDI-ToF MS.

Peptides **1–11** were initially evaluated for their ability to act as substrates for caspase-3 and -7 at 2.5, 5 and 10  $\mu\text{M}$  allowing the effects of the  $X_2$  and  $X_1'$  substitutions to be assessed. All the substrates had low background fluorescence levels and showed time dependent activation with caspase-3 (ESI,† Fig. S1). Substrates **2** (Asp-Glu-Pro-Asp-Ala) and **3** (Asp-Glu-Pro-Asp-Ser), both of which have proline at the  $X_2$  position, showed reduced activation with caspase-3 compared to the other probes; however, this activity was restored by introduction of the Ahx spacer (**8** and **10**), suggesting that the reduced cleavage of **2** and **3** arose from steric hindrance by the methyl red moiety in combination with the proline residue. In the preliminary screen, no significant preference was observed for glycine, alanine or serine at the  $X_1'$  position. Substrate **9** showed a 3 and 5-fold higher increase in fluorescence than Ac-Asp-Glu-Val-Asp-AFC (**AFC**) and MCA-Asp-Glu-Val-Asp-Ala-Pro-Lys-DNP (**MCA**), respectively (ESI,† Fig. S2). In the initial screens, caspase-7 showed significantly lower cleavage of substrates containing proline at  $X_2$  position, confirming that selectivity can be achieved by replacing valine in that position (ESI,† Fig. S3 and S4).<sup>19c</sup>

To evaluate the effectiveness of the substrates, as well as to further investigate selectivity, the  $K_M$  and  $k_{\text{cat}}$  values of **1–11** were determined for caspase-3 and caspase-7 (Table 2). All the substrates exhibited good affinity for caspase-3 ( $K_M$  values < 5  $\mu\text{M}$ ) compared to **AFC** and **MCA** ( $K_M$  values 9.8  $\mu\text{M}$  and 13.5  $\mu\text{M}$ , respectively). Substrates bearing a valine at  $X_2$  position typically showed lower  $K_M$  values than the corresponding peptides bearing a  $X_2$  proline, with the exception of substrate **10** (sequence Asp-Glu-Pro-Asp-Ser-Ahx,  $K_M$  1.8  $\mu\text{M}$ ), which showed the same binding as **11** (Asp-Glu-Val-Asp-Ser-Ahx,  $K_M$  1.7  $\mu\text{M}$ ). When the substrates were ranked by their caspase-3 catalytic efficiency ( $k_{\text{cat}}/K_M$ ), more of a division between them was observed. Peptides **2** and **8**, both bearing proline at the  $X_2$  position and alanine at the  $X_1'$ , were poor substrates for caspase-3 with  $k_{\text{cat}}/K_M$  values of 1.8 and 3.2  $\mu\text{M}^{-1} \text{min}^{-1}$ , respectively. Within the series, **6** (Asp-Glu-Pro-Asp-Gly-Ahx) and **9** (Asp-Glu-Val-Asp-Ala-Ahx) had the highest catalytic efficiency (22.2 and 24.2  $\mu\text{M}^{-1} \text{min}^{-1}$ , respectively) proving that the enzyme



Table 2 Kinetic analysis of substrates 1–11 ( $n = 3$ ) with caspase-3 and caspase-7

Probe	Caspase-3			Caspase-7		
	$K_M$ ( $\mu\text{M}$ )	$k_{\text{cat}}$ ( $\text{min}^{-1}$ )	$k_{\text{cat}}/K_M$ ( $\mu\text{M}^{-1} \text{min}^{-1}$ )	$K_M$ ( $\mu\text{M}$ )	$k_{\text{cat}}$ ( $\text{min}^{-1}$ )	$k_{\text{cat}}/K_M$ ( $\mu\text{M}^{-1} \text{min}^{-1}$ )
1	2.3 ± 0.5	23.4 ± 1.4	10.3	1.2 ± 0.2	10.2 ± 0.5	8.6
2	4.6 ± 0.5	8.4 ± 0.3	1.8	n/a <sup>c</sup>	n/a	n/a
3	2.9 ± 0.5	20.1 ± 1.0	7.0	n/a	n/a	n/a
4	1.7 ± 0.3	13.4 ± 0.5	7.8	2.9 ± 0.5	10.1 ± 0.6	3.4
5	2.7 ± 0.4	36.5 ± 1.7	13.3	2.4 ± 0.5	8.2 ± 0.5	3.5
6	2.6 ± 0.4	58.4 ± 2.4	22.2	2.1 ± 0.2	17.7 ± 0.6	8.4
7	1.4 ± 0.2	20.4 ± 0.8	14.9	5.1 ± 0.9	19.9 ± 1.3	3.9
8	3.5 ± 0.5	11.1 ± 0.5	3.2	27.5 ± 8.0	3.8 ± 0.7	0.14
9	2.2 ± 0.3	53.3 ± 2.4	24.2	3.4 ± 0.3	10.7 ± 0.3	3.2
10	1.8 ± 0.3	30.7 ± 1.2	16.9	5.2 ± 0.8	2.6 ± 0.2	0.5
11	1.7 ± 0.3	19.7 ± 0.9	11.7	2.7 ± 0.4	6.4 ± 0.3	2.4
MCA <sup>a</sup>	13.5 ± 2.6	13.5 ± 1.3	1.0	15.1 ± 3.2	5.9 ± 0.7	0.4
AFC <sup>b</sup>	9.8 ± 1.9	14.7 ± 1.2	1.5	10.8 ± 2.8	11.6 ± 1.4	1.1

<sup>a</sup> MCA = MCA-Asp-Glu-Val-Asp-Ala-Pro-Lys-DNP. <sup>b</sup> AFC = Ac-Asp-Glu-Val-Asp-AFC. <sup>c</sup> Could not be determined.

can efficiently cleave substrates with proline at the  $X_2$  position. Based on the catalytic efficiency, the  $X_1'$  position overall had a slight preference for glycine and serine over alanine, especially with substrates incorporating proline at  $X_2$ .

With caspase-7, substrates MCA and AFC had a  $K_M$  values of 15.1 and 10.8  $\mu\text{M}$ . At the  $X_1'$  position, caspase-7 had a clear preference for glycine with 1 and 6 having  $k_{\text{cat}}/K_M$  values of 8.6 and 8.4  $\mu\text{M}^{-1} \text{min}^{-1}$ , respectively. Substrates 2 (Asp-Glu-Pro-Asp-Ala) and 3 (Asp-Glu-Pro-Asp-Ser) showed negligible affinity to the enzyme ( $K_M$  could not be determined). Remarkably 10, which was efficiently cleaved by caspase-3 ( $k_{\text{cat}}/K_M$  16.9  $\mu\text{M}^{-1} \text{min}^{-1}$ ), was a poor substrate for caspase-7 ( $k_{\text{cat}}/K_M$  0.5  $\mu\text{M}^{-1} \text{min}^{-1}$ ) further demonstrating that the sequence Asp-Glu-Pro-Asp-Ser-(Ahx) provides good specificity for caspase-3. Fig. 2 shows a direct comparison of fluorescence increase of probes 3, 10 and 11 after incubation with caspase-3 and caspase-7.

To further examine the specificity of the substrates, reactivity with cathepsin B was evaluated (ESI,† Fig. S5). The sequences incorporating proline at the  $X_2$  position (peptides 5, 6, 8, and 10) proved to be poor substrates for cathepsin B and were cleaved with a much lower efficiency than their valine counterparts, with 5 (Asp-Glu-Pro-Asp-Ahx) showing no increase in fluorescence. Substrates 6 and 10 showed significantly reduced cleavage by cathepsin B. To establish the relative affinity of cathepsin B and caspase-3 for the same substrate, the cleavage rates by the two enzymes were directly compared, with 5, 6, and 10 showing the

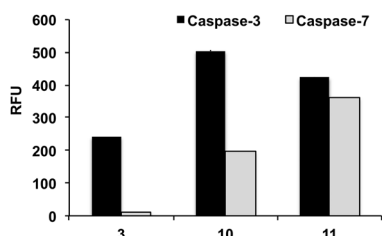


Fig. 2 Comparison of fluorescence increase ( $\lambda_{\text{ex/Em}}$  485/525 nm) with substrates 3 (Asp-Glu-Pro-Asp-Ahx), 10 (Asp-Glu-Pro-Asp-Ser-Ahx) and 11 (Asp-Glu-Val-Asp-Ser-Ahx) at 3.1  $\mu\text{M}$  ( $n = 3$ , standard deviation  $\pm 1.0$ –3.1 RFU) incubated with caspase-3 and caspase-7 (15 nM) for 60 min.

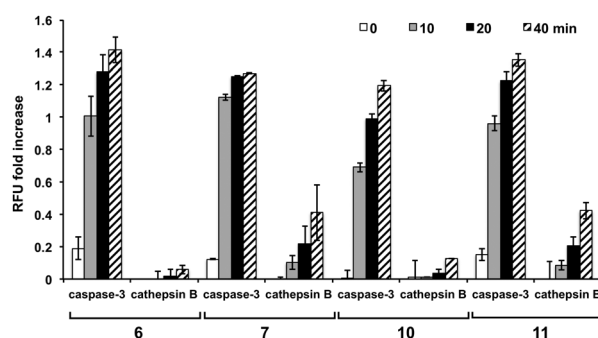


Fig. 3 Comparison of activation by caspase-3 (15 nM) and cathepsin B (25 nM) with substrates (10  $\mu\text{M}$ ,  $n = 3$ ) containing proline or valine at the  $X_2$  position (6 vs. 7 and 10 vs. 11). The fluorescence was divided by the background fluorescence (no enzyme) to give a "RFU fold increase" for each probe ( $(\text{RFU}_{\text{enzyme}}/\text{RFU}_{\text{blank}}) - 1$ ). This was done to allow comparison with the reduced fluorescence of fluorescein in the acidic cathepsin buffer (pH 5).

highest selectivity towards caspase-3 even with a 1.7-fold higher cathepsin B concentration (Fig. 3).

## Conclusions

11 FRET-based fluorogenic substrates, having a pentapeptide sequence with two variable positions, were designed and synthesised with the aim of identifying a caspase-3 selective peptide. Replacement of the valine with a proline in the traditional, non-selective Asp-Glu-Val-Asp recognition sequence yielded substrates with good selectivity over caspase-7 and cathepsin B. In particular peptide sequence Asp-Glu-Pro-Asp-Ser (substrates 3 and 10), was able to selectively quantify caspase-3 activity *in vitro* without notable caspase-7 and cathepsin B cross-reactivity. Furthermore, the binding affinities of these new substrates for caspase-3 were significantly increased (>3-fold) compared to the two widely used substrates MCA and AFC, compared to the two commercially available fluorogenic caspase-3 substrates, while also exhibiting good catalytic efficiency. The substrates based on Asp-Glu-Pro-Asp-Ser, have the potential to solve experimental issues caused by the lack of enzyme selectivity of



commonly used substrates, providing a more accurate analysis of caspase-3 activity in cancer and beyond. Application of these selective substrates to probes enabling caspase-3 imaging in cell-based assays is currently underway.

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## Notes and references

- 1 J. C. Ameisen, *Cell Death Differ.*, 2002, **9**, 367–393.
- 2 S. Nagata, *IUBMB Life*, 2006, **58**, 358–632.
- 3 R. M. Friedlander, *N. Engl. J. Med.*, 2003, **348**, 1365–1375.
- 4 (a) M. Olsson and B. Zhivotovsky, *Cell Death Differ.*, 2011, **18**, 1441–1449; (b) C. B. Thompson, *Science*, 1995, **267**, 1456–1462; (c) D. R. McIlwain, T. Berger and T. W. Mak, *Cold Spring Harbor Perspect. Biol.*, 2013, **5**, 2–28 (a008656).
- 5 I. Wang and J. Lin, *Eur. J. Cancer*, 1999, **35**, 1517–1525.
- 6 R. C. Taylor, S. P. Cullen and S. J. Martin, *Nat. Rev. Mol. Cell Biol.*, 2008, **9**, 231–241.
- 7 S. Fulda, A. M. Gorman, O. Hori and A. Samali, *Int. J. Cell Biol.*, 2010, **1**, 1–23.
- 8 (a) E. Devarajan, A. A. Sahin, J. S. Chen, R. R. Krishnamurthy, N. Aggarwal, A.-M. Brun, A. Sapino, F. Zhang, D. Sharma, X.-H. Yang, A. D. Tora and K. Mehta, *Oncogene*, 2002, **21**, 8843–8851; (b) M. D'Amelio, M. Sheng and F. Cecconi, *Trends Neurosci.*, 2012, **35**, 700–709; (c) Y. Shi, *J. Cancer Mol.*, 2005, **1**, 9–18.
- 9 X. Ai, B. Butts, K. Vora, W. Li, C. Tache-Talmadge, A. Fridman and H. Mehmet, *Cell Death Dis.*, 2011, **2**, e205.
- 10 P. Pozarowski, X. Huang, D. H. Halicka, B. Lee, G. Johnson and Z. Darzynkiewicz, *Cytometry, Part A*, 2003, **55**, 50–60.
- 11 (a) K. Bullok and D. Piwnica-Worms, *J. Med. Chem.*, 2005, **48**, 5404–5407; (b) J. R. Johnson, B. Kocher, E. M. Barnett, J. Marasa and D. Piwnica-Worms, *Bioconjugate Chem.*, 2012, **23**, 1783–1793.
- 12 X. Zhu, A. Fu and K. Q. Luo, *Biochem. Biophys. Res. Commun.*, 2012, **418**, 641–646.
- 13 (a) J. W. Becker, J. Rotonda, S. M. Soisson, R. Aspiotis, C. Bayly, S. Francoeur, M. Gallant, M. Garcia-Calvo, A. Giroux, E. Grimm, Y. Han, D. McKay, D. W. Nicholson, E. Peterson, J. Renaud, S. Roy, N. Thornberry and R. Zamboni, *J. Med. Chem.*, 2004, **47**, 2466–2474; (b) R. Ganesan, S. Jelakovic, P. R. E. Mittl, A. Caffisch and M. G. Grütter, *Acta Crystallogr., Sect. F: Struct. Biol. Cryst. Commun.*, 2011, **67**, 842–850; (c) C. Köhler, S. Orrenius and B. Zhivotovsky, *J. Immunol. Methods*, 2002, **265**, 97–110; (d) L. Tyas, V. A. Brophy, A. Pope, A. J. Rivett and J. M. Tavaré, *EMBO Rep.*, 2000, **1**, 266–270; (e) A. P. Savitsky, A. L. Rusanov, V. V. Zherdeva, T. V. Gorodnicheva, M. G. Khrenova and A. V. Nemukhin, *Theranostics*, 2012, **2**, 215–226; (f) D. Maxwell, Q. Chang, X. Zhang, E. M. Barnett and D. Piwnica-Worms, *Bioconjugate Chem.*, 2009, **20**, 702–709.
- 14 H. Cen, F. Mao, I. Aronchik, R. J. Fuentes and G. L. Firestone, *FASEB J.*, 2008, **22**, 2243–2252.
- 15 (a) G. P. McStay, G. S. Salvesen and D. R. Green, *Cell Death Differ.*, 2008, **15**, 322–331; (b) M. V Onufriev, A. A. Yakovlev, A. A. Lyzhin, M. Y. Stepanichev, L. G. Khaspekov and N. V. Gulyaeva, *Biochem., Biokhim.*, 2009, **74**, 281–287; (c) A. B. Berger, K. B. Sexton and M. Bogyo, *Cell Res.*, 2006, **16**, 961–963.
- 16 (a) C. J. Vickers, G. E. González-Páez and D. W. Wolan, *ACS Chem. Biol.*, 2013, **8**, 1558–1566; (b) C. J. Vickers, G. E. González-Páez and D. W. Wolan, *ACS Chem. Biol.*, 2014, **9**, 2199–2203.
- 17 M. Poreba, P. Kasperkiewicz, S. J. Snipas, D. Fasci, G. S. Salvesen and M. Drag, *Cell Death Differ.*, 2014, **21**, 1482–1492.
- 18 (a) R. V. Talanian, C. Quinlan, S. Trautz, M. C. Hackett, J. A. Mankovich, D. Banach, T. Ghayur, K. D. Brady and W. W. Wong, *J. Biol. Chem.*, 1997, **272**, 9677–9682; (b) N. A. Thornberry, T. A. Rano, E. P. Peterson, D. M. Rasper, T. Timkey, M. Garcia-Calvo, V. M. Houtzager, P. A. Nordstrom, S. Roy, J. P. Vaillancourt, K. T. Chapman and D. W. Nicholson, *J. Biol. Chem.*, 1997, **272**, 17907–17911.
- 19 (a) D. Xue and H. R. Horvitz, *Nature*, 1995, **377**, 248–251; (b) N. J. Bump, M. Hackett, M. Hugunin, S. Seshagiri, K. Brady, P. Chen, C. Ferenz, S. Franklin, T. Ghayur and P. Li, *et al.*, *Science*, 1995, **269**, 1885–1888; (c) A. B. Berger, M. D. Witte, J.-B. Denault, A. M. Sadaghiani, K. M. B. Sexton, G. S. Salvesen and M. Bogyo, *Mol. Cell*, 2006, **23**, 509–521.
- 20 (a) L. E. Edgington, A. B. Berger, G. Blum, V. E. Albrow, M. G. Paulick, N. Lineberry and M. Bogyo, *Nat. Med.*, 2009, **15**, 967–973; (b) K. B. Sexton, M. D. Witte, G. Blum and M. Bogyo, *Bioorg. Med. Chem. Lett.*, 2007, **17**, 649–653.
- 21 (a) H. R. Stennicke, M. Renuis, M. Meldal and G. S. Salvesen, *Biochem. J.*, 2000, **350**, 563–568; (b) B. B. Wolf, *J. Biol. Chem.*, 1999, **274**, 20049–20052; (c) D. W. Nicholson, *Cell Death Differ.*, 1999, **6**, 1028–1042.
- 22 J. J. Díaz-Mochón, L. Bialy and M. Bradley, *Org. Lett.*, 2004, **6**, 1127–1129.

