

Cite this: *Chem. Sci.*, 2020, **11**, 8567

All publication charges for this article have been paid for by the Royal Society of Chemistry

Pinkment: a synthetic platform for the development of fluorescent probes for diagnostic and theranostic applications†

Maria Weber, ^{†ab} Hai-Hao Han, ^{†cd} Bo-Han Li, ^{†ce} Maria L. Odyniec, ^a Charlotte E. F. Jarman, ^a Yi Zang, ^c Steven D. Bull, ^a Amanda B. Mackenzie, ^{gh} Adam C. Sedgwick, ^{†f} Jia Li, ^{*ce} Xiao-Peng He ^{†d} and Tony D. James ^{†*a}

Reaction-based fluorescent-probes have proven successful for the visualisation of biological species in various cellular processes. Unfortunately, in order to tailor the design of a fluorescent probe to a specific application (*i.e.* organelle targeting, material and theranostic applications) often requires extensive synthetic efforts and the synthetic screening of a range of fluorophores to match the required synthetic needs. In this work, we have identified **Pinkment-OH** as a unique "plug-and-play" synthetic platform that can be used to develop a range of ONOO[−] responsive fluorescent probes for a variety of applications. These include theranostic-based applications and potential material-based/bioconjugation applications. The as prepared probes displayed an excellent sensitivity and selectivity for ONOO[−] over other ROS. *In vitro* studies using HeLa cells and RAW 264.7 macrophages demonstrated their ability to detect exogenously and endogenously produced ONOO[−]. Evaluation in an LPS-induced inflammation mouse model illustrated the ability to monitor ONOO[−] production in acute inflammation. Lastly, theranostic-based probes enabled the simultaneous evaluation of indomethacin-based therapeutic effects combined with the visualisation of an inflammation biomarker in RAW 264.7 cells.

Received 29th April 2020

Accepted 27th July 2020

DOI: 10.1039/d0sc02438d

rsc.li/chemical-science

Introduction

There is a growing need for new and effective diagnostic tools that can evaluate biomarkers involved in inflammatory based diseases.^{1–6} Inflammation is the innate defence mechanism of the body that recognises damaged cells, pathogens and

infections. The inflammatory response often results in the generation of reactive oxygen species/reactive nitrogen species (ROS/RNS), which are involved in the functional regulation of M1 and M2 macrophages.^{7,8} The M1 pro-inflammatory phenotype is induced by lipopolysaccharide (LPS), which triggers the generation of ROS from NADPH using NADPH oxidase (NOX).⁹ This production of ROS regulates an array of cellular events including the activation of the nuclear factor kappa-B (NF-κB), the production of cytokines and cell survival whereas, high levels of ROS are associated with programmed cell death, *i.e.* apoptosis.^{7,10–14} The high sensitivity and high spatial and temporal resolution of fluorescent probes allow us to visualise these key cellular events. Our group and others have focused on the fluorescence-based detection of ROS/RNS such as ONOO[−], H₂O₂ and HOCl.^{1,15–21} To achieve the selective detection of a particular ROS requires the careful consideration of both fluorophore and reactive motif. In this regard, resorufin is a particularly attractive fluorophore due to its red shifted fluorescence and easy to functionalise scaffold. Pioneering work led by Chang *et al.* developed peroxyresorufin-1 (PR1) for H₂O₂ detection whereby resorufin is masked with boronic esters.^{22,23} Boronic esters have been identified as a relevant sensing group for both H₂O₂ and ONOO[−] detection. However, in an environment with both species present, boronic esters preferentially react with ONOO[−] due to the inherent faster reactivity of ONOO[−] in comparison to H₂O₂.²⁴ Previously, we have

^aDepartment of Chemistry, University of Bath, Bath, BA2 7AY, UK. E-mail: t.d.james@bath.ac.uk

^bCentre for Doctoral Training, Centre for Sustainable & Circular Technologies, University of Bath, Bath, BA2 7AY, UK

^cNational Centre for Drug Screening, State Key Laboratory of Drug Research, Shanghai Institute of Materia Medica, Chinese Academy of Sciences, 189 Guo Shoujing Rd., Shanghai 201203, PR China. E-mail: jli@simm.ac.cn

^dKey Laboratory for Advanced Materials & Feringa Nobel Prize Scientist Joint Research Centre, School of Chemistry and Molecular Engineering, Frontiers Center for Materiobiology and Dynamic Chemistry, East China University of Science and Technology, 130 Meilong Rd., Shanghai 200237, PR China. E-mail: xphe@ecust.edu.cn

^eUniversity of Chinese Academy of Sciences, No. 19A Yuquan Road, Beijing 100049, PR China

^fDepartment of Chemistry, University of Texas at Austin, 105 East 24th Street A5300, Austin, Texas 78712-1224, USA. E-mail: a.c.sedgwick@utexas.edu

^gDepartment of Pharmacy and Pharmacology, University of Bath, Bath, BA2 7AY, UK

^hCentre for Therapeutic Innovation, University of Bath, Bath, BA2 7AY, UK

† Electronic supplementary information (ESI) available: Synthetic procedures, ¹H, ¹³C NMR, and mass spectra, UV-Vis and fluorescence spectroscopic analyses, and other materials. See DOI: 10.1039/d0sc02438d

‡ These authors contributed equally to this work.

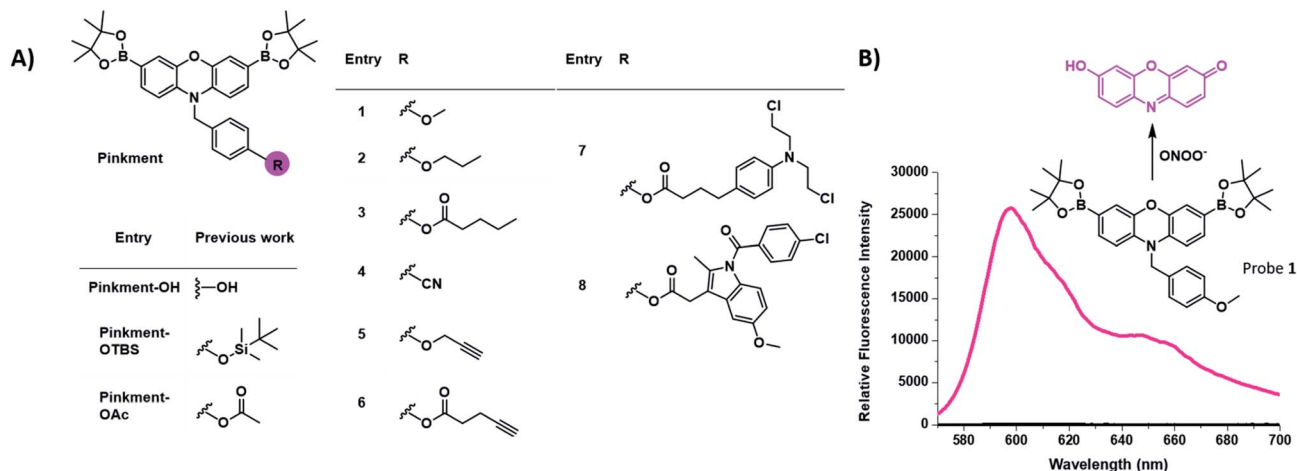


Fig. 1 (A) Chemical structure of the resorufin-based probes for the sensing of ONOO^- , including the previously reported **Pinkment-OH** “plug and play” scaffold and dual analyte probes **Pinkment-OTBS** and **Pinkment-OAc**.¹⁰ (B) Unexpected fluorescence turn on response of **1** in the presence of ONOO^- .

demonstrated PR1's ability to preferentially detect ONOO⁻ over H₂O₂ *in vitro*.²⁵ Consequently, we decided to investigate functionalized synthetic derivatives of PR1.²⁶ This led to the development of **Pinkment-OH** for the design of dual analyte AND-logic probes, **Pinkment-OTBS** (ONOO⁻ “AND” fluoride) and **Pinkment-OAc** (H₂O₂ “AND” esterase) using **Pinkment-OH** (Fig. 1) as a synthetic starting point. These results revealed the potential of **Pinkment-OH** to be used as a synthetic platform for the development of ONOO⁻ selective fluorescence probes with additional sensing, targeting or drug units. Here, we have serendipitously discovered that the benzyl unit of our ROS **Pinkment** fluorescent probe can be functionalized with a functional unit of choice without compromising ROS selectivity. As a result, **Pinkment-OH** was successfully shown as a synthetic platform to develop ONOO⁻ selective fluorescent probes with additional functional units (Fig. 1).

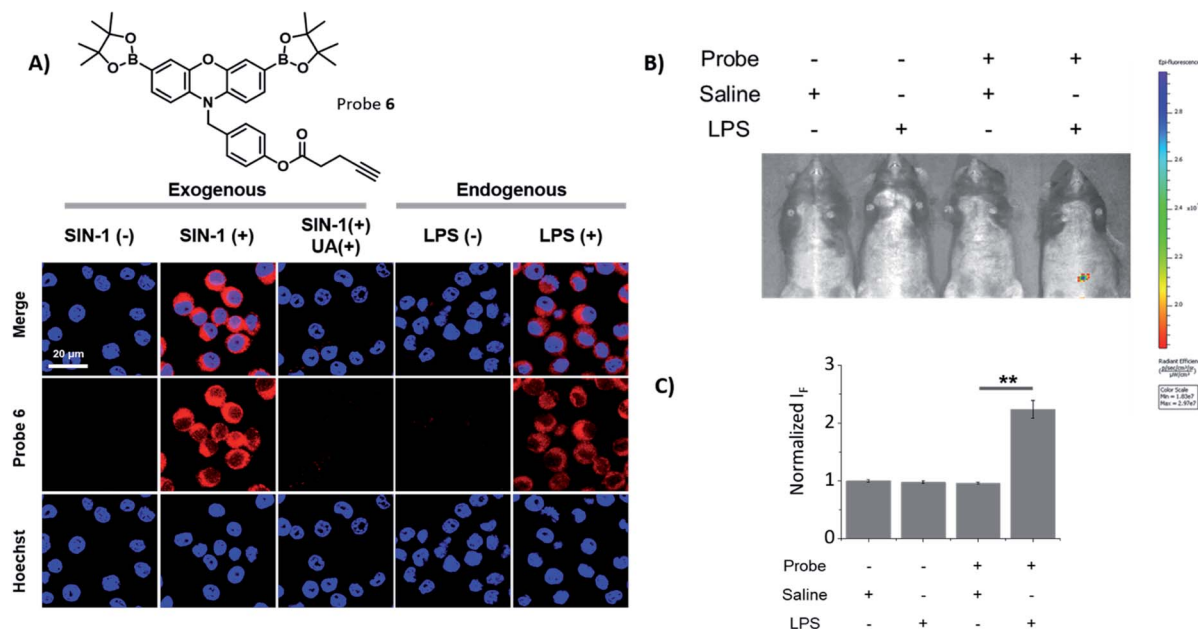
Results and discussion

Initially, our focus was on continuing the development of “AND”-based logic-gates for biological application.^{1,17,26} This led to the elaboration of probe **1**, which was accessed in a simple three step synthesis (Scheme S1†). Unexpectedly, we discovered that **1** “turned on” in the sole presence of ONOO[−] (Fig. 1B and S1†). This led to the development of **Pinkment** probes **2** and **3** to further confirm this observation. These probes were accessible from the synthetic platform **Pinkment-OH**, whose 6-step synthesis has been previously reported by our group.²⁶ Nucleophilic substitution by **Pinkment-OH** using 1-bromopropane and pentanoyl chloride respectively gave **2** and **3** in moderate yields: 50% and 51% respectively (Scheme S2 and S3†). Probes **2** and **3** showed good selectivity towards ONOO[−] over other ROS species (Fig. S2–S8†). Surprisingly, the probes demonstrated a high sensitivity towards ONOO[−] requiring concentrations in the low micromolar range. Both **2** and **3** displayed increased solubility in comparison to **1**. We decided to further explore this

unexpected result by introducing a terminal nitrile group. Probe 4 was accessible in a facile three-step synthesis (Scheme S4†) in the same manner as **1**. Again, good selectivity and sensitivity for ONOO[−] was observed (Fig. S2–S8†). From these results, we realized that the **Pinkment** benzyl unit can be functionalized with any unit of choice without compromising the ROS selectivity. Thus, we rationalized that **Pinkment-OH** offers a unique platform for the design of ONOO[−] selective fluorescence based probes that can be tailored towards a range of applications.^{27–29} This led to the development of alkyne-based **Pinkment** probes **5** and **6** that have potential to be used in “click” chemistry.²⁹ These probes were accessed from **Pinkment-OH** and prepared in moderate yields: 48% and 47% for **5**, and **6** respectively (Scheme S5 and S6†). Fluorescence studies of **5** and **6** established good sensitivity and selectivity towards ONOO[−] over other ROS (Fig. S2–S8†).

We then turned our attention to assessing the imaging capacity of probes 2 and 3 and the potential “click” based probes 5 and 6 in cells and live animals. To demonstrate their suitability as imaging tools, all four probes were evaluated for cellular toxicity in murine RAW 264.7 macrophages using a MTS cell proliferation assay. Probes 2, 3, 5 and 6 were incubated at different concentrations ranging from 5 to 40 μ M for 24 h (Fig. S9[†]). Probes 2, 5 and 6 were found to be non-toxic. In contrast, probe 3 decreased the cell viability of RAW 264.7 macrophages by 40% at a concentration of 40 μ M compared to control conditions. As a result, 3 was not taken forward for further cell studies since high concentrations of the probe are required for *in vivo* studies.

Probes **2**, **5** and **6** were shown to be non-toxic, and were evaluated with exogenous ONOO⁻, using SIN-1 (500 μM) in RAW 264.7 macrophages (Fig. 2A and S10†). Each probe alone demonstrated minimal fluorescence in cells, the addition of SIN-1 led to a significant enhancement in intracellular fluorescence at a wavelength corresponding to the dye, resorufin, therefore, suggesting the intracellular reaction of the probe with



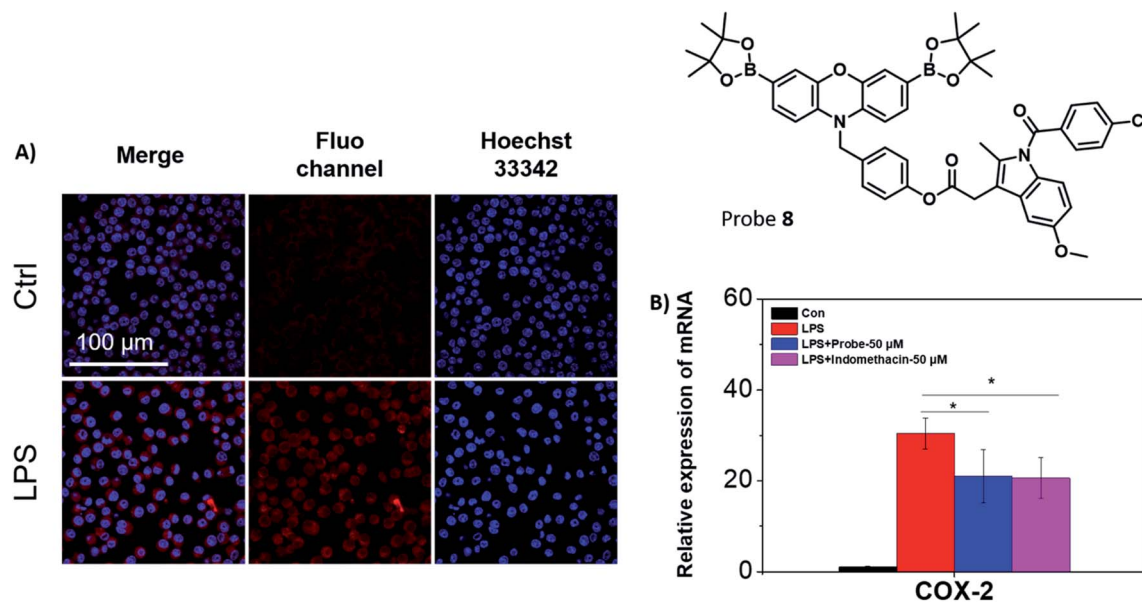


Fig. 3 (A) Confocal imaging of RAW 264.7 macrophages treated with LPS ($1 \mu\text{g mL}^{-1}$, 24 h) and then loaded with **8** (20 μM , 30 min) as indicated. Fluorescence data was collected using $\lambda_{\text{ex}} = 559 \text{ nm}$ and $\lambda_{\text{em}} = 580\text{--}650 \text{ nm}$, respectively. The cell nuclei were stained using Hoechst 33342 and fluorescence collected at $\lambda_{\text{ex}} = 405 \text{ nm}$ and $\lambda_{\text{em}} = 450\text{--}480 \text{ nm}$. Scale bar = 100 μm . $N = 3$. (B) Effect of **8** on LPS-induced COX-2 gene expression in RAW 264.7 macrophages. Cells were treated with LPS alone ($1 \mu\text{g mL}^{-1}$) or together with **8** for 24 h. Indomethacin was set as a positive control, and the relative mRNA level of COX-2 gene was normalized by GAPDH ($*p < 0.05$). $N = 4$.

inhibitor of cyclooxygenase-1 (COX-1) and cyclooxygenase-2 (COX-2), of which COX-2 is mainly responsible for the inflammatory response.³⁶ The therapeutic effects on the LPS-induced inflammatory responses in RAW 264.7 macrophages were further investigated using **8**. RAW 264.7 macrophages were treated with LPS and the expression of the pro-inflammatory gene (COX-2) was investigated using qRT-PCR in the presence or absence of **8** (Fig. 3B).³⁷ The mRNA level of COX-2 decreased in the presence of **8** (50 μM) in comparison to the LPS-induced group. A similar effect to the LPS-induced group was observed with indomethacin alone. This suggests that **8** can monitor ONOO[−] production in acute inflammation, and in addition, reduce the inflammatory response by releasing indomethacin.

Conclusions

The ability of the **Pinkment** scaffold to be functionalised with any unit of choice without compromising the overall ROS selectivity, opens up new possibilities for the design of highly specific ONOO[−] probes that can be used in a variety of applications. In this work, we have successfully illustrated the applicability of **Pinkment**-based probes for diagnostic and theranostics applications. Our probes displayed good selectivity and sensitivity towards ONOO[−] over a range of other ROS. Cellular studies with the **Pinkment** probes led to the identification of alkyne-functionalised **Pinkment** probe **6** as a suitable candidate for *in vivo* studies using an inflammatory mouse model. These promising results led us to design potential theranostic probes **7** and **8** with candidate **8** displaying promising properties *in vitro*. We believe this work demonstrates **Pinkment-OH** as a useful synthetic platform to enable the rapid

development of a ONOO[−] fluorescent probe that can be tailored to the needs of the chemical biologist. In particular, the alkyne **Pinkment** probes offer the possibility of attaching any desired unit *via* click chemistry. Therefore, we anticipate that the **Pinkment** scaffold can be further elaborated for the development of dual analyte, organelle targeting and theranostic probes for a range of diagnostic and theranostic applications.

Conflicts of interest

There are no conflicts to declare.

Acknowledgements

All animal experiments were carried out under the Guidelines for Care and Use of Laboratory Animals of Shanghai Institute of Materia Medica (SIMM), Chinese Academy of Sciences and approved by the Institutional Animal Care and Use Committee (IACUC) of SIMM (Shanghai, China). M. W. would like to thank the EPSRC for funding (i) EP/L016354/1 and the CDT in Sustainable Chemical Technologies. M. L. O. and A. C. S. would like to thank the University of Bath and EPSRC for PhD studentships. T. D. J. thanks the Royal Society for a Wolfson Research Merit Award. X. P. H. thanks the National Natural Science Foundation of China (No. 21788102, 91853201, 21722801 and 21776078), the National Key Sci-Tech Special Projects of Infection Diseases of China (2018ZX10732202), the Shanghai Municipal Science and Technology Major Project (No. 2018SHZDZX03), the International Cooperation Program of Shanghai Science and Technology Committee (No. 17520750100) and the Fundamental Research Funds for the



Central Universities (222201717003) and the Programme of Introducing Talents of Discipline to Universities (B16017) for financial support. Characterization facilities were provided through the Material and Chemical Characterization Facility (MC²) at the University of Bath (<http://go.bath.ac.uk/mc2>). In particular, we would like to acknowledge Shaun Reeksting for helping with the more advanced MS studies of the theranostic probes. All data supporting this study are provided in the ESI† accompanying this paper.

Notes and references

- X. L. Hu, N. Kwon, K. C. Yan, A. C. Sedgwick, G. R. Chen, X. P. He, T. D. James and J. Yoon, *Adv. Funct. Mater.*, 2020, **30**, 1907906.
- D. Wu, A. C. Sedgwick, T. Gunnlaugsson, E. U. Akkaya, J. Yoon and T. D. James, *Chem. Soc. Rev.*, 2017, **46**, 7105–7123.
- S. Erbas-Cakmak, S. Kolemen, A. C. Sedgwick, T. Gunnlaugsson, T. D. James, J. Yoon and E. U. Akkaya, *Chem. Soc. Rev.*, 2018, **47**, 2228–2248.
- A. C. Sedgwick, L. L. Wu, H. H. Han, S. D. Bull, X. P. He, T. D. James, J. L. Sessler, B. Z. Tang, H. Tian and J. Yoon, *Chem. Soc. Rev.*, 2018, **47**, 8842–8880.
- J. Chan, S. C. Dodani and C. J. Chang, *Nat. Chem.*, 2012, **4**, 973–984.
- K. C. Yon, A. C. Sedgwick, Y. Zang, G. R. Chen, X. P. He, J. Li, J. Yoon and T. D. James, *Small Methods*, 2019, **3**, 1900013.
- A. Weidinger and A. V. Kozlov, *Biomolecules*, 2015, **5**, 472–484.
- B. Ghesquiere, B. W. Wong, A. Kuchnio and P. Carmeliet, *Nature*, 2014, **511**, 167–176.
- A. Kumar, S. H. Chen, M. B. Kadiiska, J. S. Hong, J. Zielonka, B. Kalyanaraman and R. P. Mason, *Free Radical Biol. Med.*, 2014, **73**, 51–59.
- B. Halliwell, *Annu. Rev. Nutr.*, 1996, **16**, 33–50.
- H. Wiseman and B. Halliwell, *Biochem. J.*, 1996, **313**, 17–29.
- J. S. Beckman and W. H. Koppenol, *Am. J. Physiol.: Cell Physiol.*, 1996, **271**, C1424–C1437.
- M. Valko, D. Leibfritz, J. Moncol, M. T. D. Cronin, M. Mazur and J. Telser, *Int. J. Biochem. Cell Biol.*, 2007, **39**, 44–84.
- H. Y. Tan, N. Wang, S. Li, M. Hong, X. B. Wang and Y. B. Feng, *Oxid. Med. Cell. Longevity*, 2016, **2016**, 2795090.
- A. C. Sedgwick, R. S. L. Chapman, J. E. Gardiner, L. R. Peacock, G. Kim, J. Yoon, S. D. Bull and T. D. James, *Chem. Commun.*, 2017, **53**, 10441–10443.
- A. C. Sedgwick, H. H. Han, J. E. Gardiner, S. D. Bull, X. P. He and T. D. James, *Chem. Commun.*, 2017, **53**, 12822–12825.
- A. C. Sedgwick, H. H. Han, J. E. Gardiner, S. D. Bull, X. P. He and T. D. James, *Chem. Sci.*, 2018, **9**, 3672–3676.
- A. C. Sedgwick, W. T. Dou, J. B. Jiao, L. L. Wu, G. T. Williams, A. T. A. Jenkins, S. D. Bull, J. L. Sessler, X. P. He and T. D. James, *J. Am. Chem. Soc.*, 2018, **140**, 14267–14271.
- L. L. Wu, H. H. Han, L. Y. Liu, J. E. Gardiner, A. C. Sedgwick, C. S. Huang, S. D. Bull, X. P. He and T. D. James, *Chem. Commun.*, 2018, **54**, 11336–11339.
- A. C. Sedgwick, J. E. Gardiner, G. Kim, M. Yevglevskis, M. D. Lloyd, A. T. A. Jenkins, S. D. Bull, J. Yoon and T. D. James, *Chem. Commun.*, 2018, **54**, 4786–4789.
- L. L. Wu, A. C. Sedgwick, X. L. Sun, S. D. Bull, X. P. He and T. D. James, *Acc. Chem. Res.*, 2019, **52**, 2582–2597.
- B. C. Dickinson, C. Huynh and C. J. Chang, *J. Am. Chem. Soc.*, 2010, **132**, 5906–5915.
- E. W. Miller, A. E. Albers, A. Pralle, E. Y. Isacoff and C. J. Chang, *J. Am. Chem. Soc.*, 2005, **127**, 16652–16659.
- A. Sikora, J. Zielonka, M. Lopez, J. Joseph and B. Kalyanaraman, *Free Radical Biol. Med.*, 2009, **47**, 1401–1407.
- M. Weber, A. B. Mackenzie, S. D. Bull and T. D. James, *Anal. Chem.*, 2018, **90**, 10621–10627.
- M. L. Odyneic, A. C. Sedgwick, A. H. Swan, M. Weber, T. M. S. Tang, J. E. Gardiner, M. Zhang, Y. B. Jiang, G. Kociok-Kohn, R. B. P. Elmes, S. D. Bull, X. P. He and T. D. James, *Chem. Commun.*, 2018, **54**, 8466–8469.
- A. Marrocchi, A. Facchetti, D. Lanari, S. Santoro and L. Vaccaro, *Chem. Sci.*, 2016, **7**, 6298–6308.
- Y. P. Chen, Y. L. Xianyu, J. Wu, B. F. Yin and X. Y. Jiang, *Theranostics*, 2016, **6**, 969–985.
- H. C. Kolb, M. G. Finn and K. B. Sharpless, *Angew. Chem., Int. Ed.*, 2001, **40**, 2004–2021.
- D. C. Hooper, S. Spitsin, R. B. Kean, J. M. Champion, G. M. Dickson, I. Chaudhry and H. Koprowski, *Proc. Natl. Acad. Sci. U. S. A.*, 1998, **95**, 675–680.
- D. Lee, S. Khaja, J. C. Velasquez-Castano, M. Dasari, C. Sun, J. Petros, W. R. Taylor and N. Murthy, *Nat. Mater.*, 2007, **6**, 765–769.
- M. L. Odyneic, H. H. Han, J. E. Gardiner, A. C. Sedgwick, X. P. He, S. D. Bull and T. D. James, *Front. Chem.*, 2019, **7**, 775.
- M. J. Reese, D. W. Knapp, K. M. Anderson, J. A. Mund, J. Case, D. R. Jones and R. A. Packer, *PLoS One*, 2018, **13**, e0203517.
- K. Seibert, Y. Zhang, K. Leahy, S. Hauser, J. Masferrer and P. Isakson, in *Eicosanoids and Other Bioactive Lipids in Cancer, Inflammation, and Radiation Injury 2, Pts A and B*, ed. K. V. Honn, S. Nigam and L. J. Marnett, 1997, vol. 400, pp. 167–170.
- A. A. Onischuk, T. G. Tolstikova, I. V. Sorokina, N. A. Zhukova, A. M. Baklanov, V. V. Karasev, G. G. Dultseva, V. V. Boldyrev and V. M. Fomin, *J. Aerosol Med. Pulm. Drug Delivery*, 2008, **21**, 231–243.
- C. Chen, *Nat. Chem. Biol.*, 2010, **6**, 401–402.
- M. Kawashima, N. Ogura, M. Akutsu, K. Ito and T. Kondoh, *J. Oral Pathol. Med.*, 2013, **42**, 499–506.

