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

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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.

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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

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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 H_2O_2 *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** (H_2O_2 “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 μM 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 μM 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



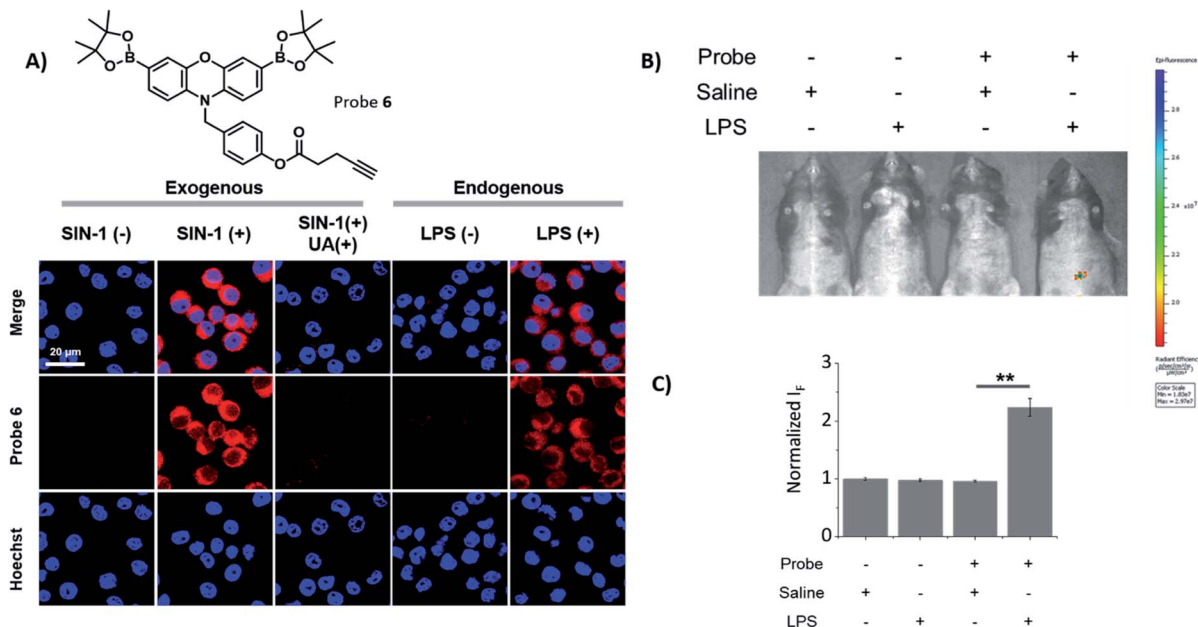


Fig. 2 (A) Confocal imaging of RAW 264.7 macrophages treated with probe 6 (20 μ M, 30 min) in the presence and absence of SIN-1 (500 μ M, 30 min) and uric acid (100 μ M, 2 h) or LPS (1 μ g mL⁻¹, 24 h) as indicated. Fluorescence data was collected using λ_{ex} = 559 nm and λ_{em} = 580–650 nm, respectively. The cell nuclei was stained using Hoechst 33342 and fluorescence collected at λ_{ex} = 405 nm and λ_{em} = 450–480 nm. Scale bar = 20 μ m. N = 3. (B) Intraperitoneal injection of male C57BL/6J mice with probe 6 (200 μ M) or saline in the absence and presence of LPS (2 mg mL⁻¹ in saline) with λ_{ex} = 535 nm and λ_{em} = 600 nm. N = 3. (C) Quantification of (B) C57BL/6J male mice treated with probe 6 (200 μ M) or saline in the absence and presence of LPS (2 mg mL⁻¹ in saline) with λ_{ex} = 550 nm and λ_{em} = 580–620 nm. Error bars represent s. d. with ** p \leq 0.01. N = 3. Normalised fluorescence intensities were calculated using the saline solution fluorescence intensities.

ONOO⁻ and their suitability for use as fluorescence-based probes. The SIN-1 generated fluorescence signal was then evaluated with the ONOO⁻ scavenger, uric acid.³⁰ As expected, uric acid attenuated the fluorescent increase that was induced by SIN-1 for all probes, thus confirming the ONOO⁻ mediated increase in fluorescence intensity. Next, we evaluated the capability of 2, 5 and 6 to detect endogenous ONOO⁻ in LPS primed RAW 264.7 macrophages. All three probes were shown to detect endogenous ONOO⁻ in LPS primed RAW 264.7 macrophages (Fig. 2A and S11[†]), confirming their promise for the imaging of LPS-induced inflammatory responses. In addition, HeLa and A549 cell lines treated with or without SIN-1 were used to illustrate the versatility of the **Pinkment** probes (Fig. S12 and S13[†]).

Encouraged by these cell imaging results, we used a known LPS-induced inflammation mouse model³¹ for the *in vivo* detection of ONOO⁻ (Fig. 2B). The injection of LPS (2 mg mL⁻¹ in saline) to the abdominal region of mice followed by the injection of 6 (200 μ M) led to its fluorescence activation. The quantified fluorescence intensity in the probe(+)/LPS(+) group was significantly larger than that in the probe(+)/LPS(-) group (Fig. 1C), demonstrating the potential of using 6 for the monitoring of ONOO⁻ *in situ* during acute inflammation.

In order to follow our current interest in theranostics,³² we then turned our attention towards the potential of **Pinkment-OH** for the design of fluorescence-based drug releasing probes. Therefore, we used the drugs chlorambucil and indomethacin to afford two distinct theranostic probes 7 and 8, respectively

(Fig. 1A). Chlorambucil is used to treat chronic lymphatic leukemia³³ and indomethacin is used as a non-steroidal anti-inflammatory drug (NSAID).^{34,35} Both 7 and 8 were easily accessible from **Pinkment-OH** (Scheme S7 and S8[†]).

Mass spectrometry confirmed and validated the simultaneous release of each drug and fluorescent resorufin dye (Fig. S14 and S15[†]). Therefore, the enhancement in the fluorescence intensity over time indicates the release of each drug. As such, time-dependent fluorescence experiments with 7 and 8 in the presence of ONOO⁻ were performed to illustrate the time dependence of the drug release. These experiments revealed a maximum fluorescence response after \sim 10 min (Fig. S16[†]).

Fluorescence studies were carried out including ROS selectivity, H₂O₂ titration and ONOO⁻ titration studies (Fig. S17–S21[†]) and demonstrated high sensitivity towards these inflammation-based biomarkers. Following these initial studies, we evaluated both 7 and 8 in RAW 264.7 macrophages towards exogenous ONOO⁻ detection (Fig. S22[†]). The presence of SIN-1 significantly enhanced the intracellular fluorescence of 7 and 8, confirming the applicability of the probes *in vitro*. Despite 7 displaying significant promise, the creation of an appropriate model system to differentiate between cancerous and healthy cells would require a significant amount of development and as such was beyond the scope of this current research. Therefore, only 8 was further evaluated, since its cellular behaviour was easier to monitor. Endogenous ONOO⁻ was also detected by 8 in RAW 264.7 macrophages (Fig. 3A). Indomethacin, a NSAID, is an effective and non-selective





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** ($20 \mu\text{M}$, 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 = $100 \mu\text{m}$. $N = 3$. (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** ($50 \mu\text{M}$) 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.

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