



## ESIPT-based fluorescence probe for the rapid detection of peroxynitrite 'AND' biological thiols†

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An ESIPT-based 'AND' logic fluorescence probe (GSH-ABAH) was developed for the simultaneous detection of ONOO<sup>−</sup> and biological thiols. GSH-ABAH was shown to have good cell permeability and with the addition of just SIN-1 (ONOO<sup>−</sup> donor) or GSH, no fluorescence response was observed in live cells. However, in the presence of both analytes GSH-ABAH could be used to image exogenous ONOO<sup>−</sup> 'AND' GSH added to RAW264.7 cells.

Peroxynitrite (ONOO<sup>−</sup>) is a highly reactive nitrogen species<sup>1</sup> with an incredibly short biological half-life (<10 ms).<sup>2</sup> ONOO<sup>−</sup> is known for its deleterious effects, causing irreversible damage to a range of biological targets such as lipids, proteins and nucleic acids.<sup>3</sup> As a result, abnormal concentrations of ONOO<sup>−</sup> are thought to be associated with inflammation, cancer, atherosclerosis and neurodegenerative diseases.<sup>4–7</sup> In addition, biological thiols such as glutathione (GSH) and cysteine (Cys) are essential in maintaining biological redox homeostasis.<sup>8–10</sup>

GSH is a natural tripeptide (γ-L-glutamyl-cysteinyl-glycine) that exists in the thiol reduced form (GSH) and disulphide-oxidised (GSSG) form.<sup>11</sup> GSH is the predominant form, which exists in mammalian and eukaryotic cells where it functions as an antioxidant.<sup>12–14</sup> More importantly, GSH serves as an ONOO<sup>−</sup> scavenger through its direct oxidation by ONOO<sup>−</sup>.<sup>15</sup>

Therefore, it is common to find elevated levels of GSH when cells are undergoing oxidative stress. Therefore, the susceptibility of a cell towards ONOO<sup>−</sup> largely depends on the concentration of intracellular GSH.<sup>7,16,17</sup>

Within our research groups, we are interested in developing small molecule fluorescent probes for the detection of biological reactive oxygen species as well as biological thiols.<sup>18–21</sup> While many literature reported fluorescent probes have been used to understand the roles of single chemical species, which include metal ions<sup>22</sup> and reactive oxygen species<sup>23,24</sup> in biological systems.<sup>25</sup> Relatively, few probes have been developed to report on the role of two or more analytes in a biological system. In parallel to the development of fluorescent probes, the field of molecular logic gates has developed.<sup>26,27</sup>

Molecular logic gates are molecules that have the ability to bind to multiple analytes and transform the multiple binding events to a measurable output. Recently, we have developed dual activated fluorescent probes. Where, the 'AND' logic operation requires two analytes to produce a positive output signal. These 'AND' logic systems have the ability to detect two different analytes within the same biological sample and hence provide a simple approach for monitoring complex bimolecular events, where two species may be intimately responsible for a particular disease.<sup>28</sup>

Dual fluorescence based probes for monitoring the relationship between ONOO<sup>−</sup> and GSH are uncommon,<sup>29,30</sup> despite numerous fluorescence based probes being developed for the sensing of these analytes separately.<sup>31,32</sup> Recently, we have developed a fluorescein-based 'AND' logic gate, which was capable of detecting ONOO<sup>−</sup> 'AND' GSH in cells (Fig. 1c).<sup>33</sup> 'AND' logic based fluorescence probes for ONOO<sup>−</sup> 'AND' GSH are of particular interest as they could potentially be used to evaluate the therapeutic efficacy of a particular treatment towards Alzheimer's disease.<sup>34</sup>

In this work, we set out to improve on our earlier system by developing an excited state intramolecular proton transfer (ESIPT) 'AND' logic gate for the simultaneous detection of ONOO<sup>−</sup> 'AND' GSH. Owing to the attractive characteristics of

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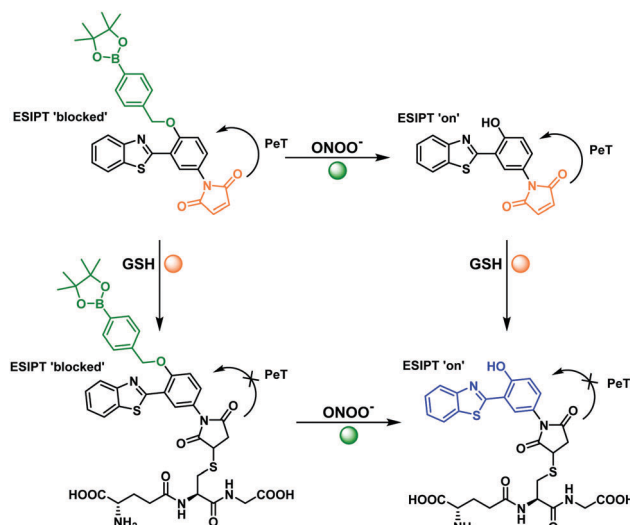
**Fig. 1** (a) ABAH ESIPT fluorophore previously used in the literature (b) this work – ESIPT-based probe **GSH-ABAH** for the detection of  $\text{ONOO}^-$  and biological thiols (c) structure of the **GSH-PF3** probe previously used for the simultaneous detection of  $\text{ONOO}^-$  and GSH.

ESIPT fluorophores, which include: ratiometric sensing, large Stokes shift and environmental sensitivity. Essentially, if a ratiometric system could be developed then this would be a significant advance, potentially allowing for calibration free monitoring.<sup>35–37</sup>

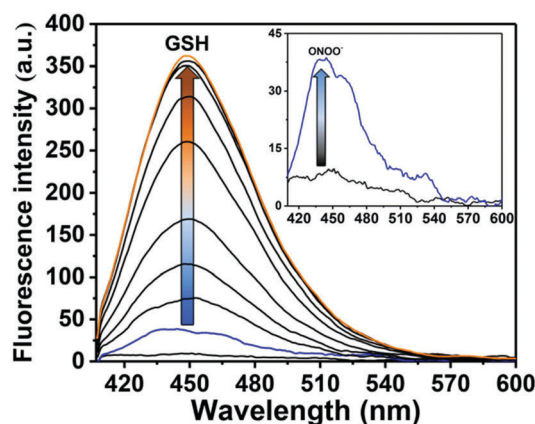
4-Amino-2-(benzo[d]thiazol-2-yl)phenol (**ABAH**) was regarded as an ideal ESIPT fluorophore for the development of an ‘AND’ based fluorescence probe due to having a free phenol and amino group, which can be independently derivatized (Fig. 1 and Scheme S1, ESI†). We believed the functionalization of the free phenolic unit of **ABAH** with a benzyl boronic ester would block the ESIPT process and serve as the reactive unit for  $\text{ONOO}^-$ . Due to aromatic boronates having a greater reactivity towards  $\text{ONOO}^-$  over  $\text{HClO}/\text{ClO}^-$  and  $\text{H}_2\text{O}_2$ .<sup>42</sup> Previously, the functionalization of the amino group of **ABAH** with the thiol-reactive maleimide group resulted in the quenching of the fluorescence intensity due to a PET process. However, in the presence of biological thiols the fluorescence intensity was rapidly restored.<sup>43</sup> Therefore, we thought that the combination of these two reactive units with **ABAH** would result in an effective PET+ESIPT ‘AND’-logic probe for the detection of  $\text{ONOO}^-$  ‘AND’ biological thiols (Fig. 1 and Scheme 1).

To test this hypothesis, we synthesized probe **GSH-ABAH** over three steps (Scheme S2 – see ESI†). **ABAH** was first synthesized in excellent yield (73%) by heating 2-aminothiophenol and 5-aminosalicylic acid in polyphosphoric acid (PPA) at 180 °C. With **ABAH** in hand, maleic anhydride was then added to a solution of **ABAH** in glacial acetic acid. This condensation reaction was performed under reflux for 4 hours to afford the desired intermediate **2** as a yellow solid. **2** was then alkylated using (4-bromomethylphenyl)boronic acid pinacol ester and  $\text{K}_2\text{CO}_3$  in DMF to afford **GSH-ABAH** in 27% yield (Scheme S2, ESI†). The chemical structure of **GSH-ABAH** was fully characterized by  $^1\text{H}$  NMR,  $^{13}\text{C}$  NMR and high resolution mass spectrometry (HRMS).

We then evaluated the changes in the UV-Vis absorption of **GSH-ABAH** in the presence of both GSH and  $\text{ONOO}^-$ . The maximum absorption of **GSH-ABAH** at 326 nm shifted to 370 nm with the addition of  $\text{ONOO}^-$  while the absorption peak



**Scheme 1** Fluorescence turn ‘on’ mechanism of **GSH-ABAH** in the presence of  $\text{ONOO}^-$  and GSH.



**Fig. 2** Fluorescence spectra of **GSH-ABAH** (2 μM) with addition of  $\text{ONOO}^-$  (4 μM) (inset) followed by the addition of GSH (0–2 μM), and 1 min wait in buffer solution [8% DMSO, 1 mM CTAB] (pH = 8.20 at 25 °C) fluorescence intensities were measured with  $\lambda_{\text{ex}} = 390 \text{ nm}/\lambda_{\text{em}} = 451 \text{ nm}$  with slit widths ex slit: 4 nm and em slit: 4 nm.

does not change with addition of GSH, which is consistent with the PET process (Fig. S1 and S2, ESI†). Fluorescence experiments with  $\text{ONOO}^-$  were then carried out. As shown in Fig. 2 and Fig. S3 (ESI†), **GSH-ABAH** was initially non-fluorescent, however upon the addition of  $\text{ONOO}^-$  (4 μM), a small fluorescence increase was observed. However, a large increase in fluorescence intensity (>10-fold, see Fig. 2 and Fig. S4, ESI†) was then observed following the subsequent addition of GSH (0–2 μM). This observation demonstrated the requirement of both  $\text{ONOO}^-$  ‘AND’ GSH to obtain a significant turn ‘on’ fluorescence response.

The addition of both analytes was then carried out in reverse order. Similarly, the addition of GSH (5 μM) only resulted in a small increase in fluorescence intensity (Fig. 3 and Fig. S5, ESI†). However, as expected a large fluorescence increase was observed after the subsequent addition of  $\text{ONOO}^-$  (0–14 μM) (Fig. 3 and Fig. S6, ESI†).



Fig. 3 Fluorescence spectra of **GSH-ABAH** (2  $\mu$ M) with addition of GSH (5  $\mu$ M), 1 min wait (inset), then addition of  $\text{ONOO}^-$  (0–14  $\mu$ M) in buffer solution [8% DMSO, 1 mM CTAB] (pH = 8.20 at 25  $^\circ\text{C}$ ) fluorescence intensities were measured with  $\lambda_{\text{ex}}$  = 390 nm/ $\lambda_{\text{em}}$  = 451 nm with slit widths ex slit: 4 nm and em slit: 4 nm.

Next, we evaluated the selectivity of probe **GSH-ABAH** towards a number of biologically relevant amino acids including serine, lysine and methionine (Fig. S7, ESI $^\dagger$ ). The amino acids without a thiol (S–H) group led to no change in fluorescence intensity of **GSH-ABAH**. However, as predicted, thiol (S–H) containing biological analytes (glutathione, cystine and homocystine) induced an enhancement in fluorescence intensity. While **GSH-ABAH** demonstrated an excellent selectivity for  $\text{ONOO}^-$  over reactive oxygen/nitrogen species including  $\text{H}_2\text{O}_2$  (Fig. S8, ESI $^\dagger$ ).

We then carried out kinetic studies for **GSH-ABAH** with both  $\text{ONOO}^-$  and GSH (Fig. S9 and S10, ESI $^\dagger$ ). After initial addition of GSH or  $\text{ONOO}^-$ , followed by the subsequent addition of the second analyte a significant increase in fluorescence within 30 s was observed. HRMS experiments were performed, in order to confirm the reaction mechanism. When 2 eq. of  $\text{ONOO}^-$  (in water) was added to a solution of **GSH-ABAH** (HRMS in acetonitrile Fig. S11, ESI $^\dagger$ ) the mass spectra was consistent with deprotection of the phenol (Fig. S12 (ESI $^\dagger$ ) and Scheme 1). Subsequently, 1 eq. GSH (in water) was added a mass peak at 630.1354 was observed confirming the reaction of GSH with the maleic anhydride group *via* electrophilic addition (Fig. S13 (ESI $^\dagger$ ) and Scheme 1). These results clearly demonstrate the ability of **GSH-ABAH** to perform 'AND' logic with  $\text{ONOO}^-$  'AND' GSH.

Due to these results, **GSH-ABAH** was then evaluated for cellular imaging of GSH and  $\text{ONOO}^-$ . RAW264.7 cells were pre-treated with *N*-ethylmaleimide (NEM, GSH scavenger) before incubation with **GSH-ABAH**. Subsequently, GSH or SIN-1 (a peroxynitrite donor)<sup>15</sup> were added to produce intracellular GSH or  $\text{ONOO}^-$ . As shown in Fig. 4 and Fig. S14 (ESI $^\dagger$ ), the addition of GSH or  $\text{ONOO}^-$  led to no fluorescence response in cells. However, treatment with both GSH and SIN-1 resulted in a significant increase in the fluorescence intensity enabling the visualisation of both species in living cells.

In summary, we have developed an ESIPT-based 'AND' logic fluorescence probe (**GSH-ABAH**) for the detection of  $\text{ONOO}^-$  and biological thiols. **GSH-ABAH** was shown to have high sensitivity and selectivity towards  $\text{ONOO}^-$  and biothiols. More importantly,

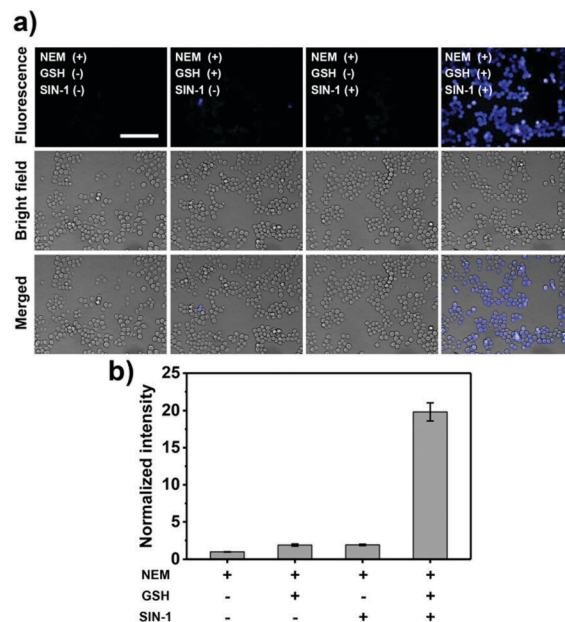


Fig. 4 Fluorescence imaging (a) and quantification (b) of RAW264.7 cells with **GSH-ABAH** (20  $\mu$ M) in the presence of exogenously added GSH (300  $\mu$ M) and/or SIN-1 (500  $\mu$ M) with 1% DMSO. Excitation channel 360–400 nm, emission channel filtered = 410–480 nm. Scale bar = 100  $\mu$ m. Error bars represent SD. Note: the cells were pre-incubated with *N*-ethylmaleimide (NEM, GSH scavenger).

**GSH-ABAH** was able to visualise exogenous  $\text{ONOO}^-$  and GSH in RAW264.7 cells. This simple novel 'AND' logic-based system provides a scaffold for the further development of a multi-analyte probes. We are now turning our attention to the development of longer wavelength ESIPT-based probes for multi-analyte *in vivo* imaging.

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## Conflicts of interest

No conflicts of interest.



## Notes and references

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