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Boronate ester cross-linked PVA hydrogels for the capture and H₂O₂-mediated release of active fluorophores†

George T. Williams,^{†ab} Adam C. Sedgwick,^{†c} Sajal Sen,^{†c} Lauren Gwynne,^a Jordan E. Gardiner,^a James T. Brewster II,^c Jennifer R. Hiscock,^{†*b} Tony D. James,^{†*a} A. Toby A. Jenkins^{†*a} and Jonathan L. Sessler^{†*c}

A new set of PVA hydrogels were formed using the boronate ester fluorescent probe PF1 and the novel boronate fluorescent probe PT1 as the covalent crosslinkers. Treatment with aqueous H₂O₂ allowed triggered release of the fluorescent dye accompanied by complete dissolution of the hydrogel.

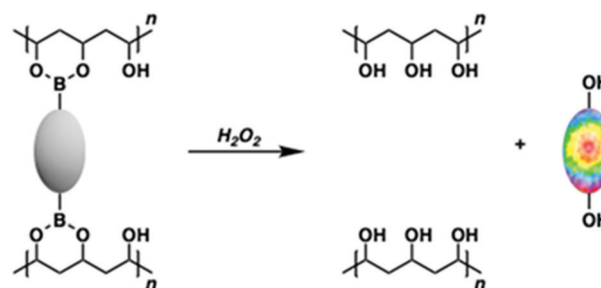
Functional hydrogels have generated widespread interest as so-called intelligent devices wherein a specific stimulus can yield a macroscopic change to the self-supporting material.^{1,2} Such constructs offer promise in the area of drug delivery and design of “smart” wound dressings.^{3–6} In addition, these functional hydrogels have demonstrated great potential as fluorescent probes for live cell imaging, disease diagnosis and sensing applications with the controlled release of a fluorophore.⁷ These constructs have utilised non-covalent interactions such as aromatic–aromatic, hydrogen bonding, and hydrophobic interactions. Unfortunately, these interactions can result in the unwanted leaching of the active molecule from the hydrogel matrix. Next generation systems comprised of a pro-molecule backbone covalently linked to the hydrogel may address these issues by providing a higher local dose and sustained/controlled release of the bioactive molecule.⁸ Here, we demonstrate a new set of controlled release materials wherein hydrogen peroxide (H₂O₂) is used as a stimulus to release fluorophores from polyvinyl alcohol (PVA) boronate hydrogels.

Boronic acid and boronate esters have found widespread application in material-based applications, in part because of their propensity to bind reversibly with 1,2- and 1,3-diols.^{9–19}

Such chemistry has been demonstrated *inter alia* using commercially available PVA and diboronic acid crosslinkers

to afford functional PVA–boronate hydrogels.^{20–25} Boronic acids and boronate esters are well-known to undergo H₂O₂-mediated oxidative transformations to afford their corresponding phenol functionalities.^{26–28} We envisaged that the use of bis-boronate-based pro-molecules as cross-linkers would afford a H₂O₂-responsive hydrogel platform that would allow the controlled and localised release of an active molecule, such as a fluorophore (Scheme 1). It is important to note the boronate functionality is commonly used to mask active therapeutics.^{29,30} Currently, there is considerable interest in functionalized hydrogels wherein a specific stimulus can yield a macroscopic change to the self-supporting material, including for the stimulus-based release of specific payloads.^{31–34} However, new approaches to achieving such overarching objectives are still needed.

To address the above need, we have now prepared a new class of H₂O₂-responsive PVA–boronate hydrogels. These systems rely on covalent cross-linking provided solely by a set of constituent H₂O₂-responsive boronate ester fluorescent probes, namely the known fluorophore **PF1**²⁶ and the novel fluorescent probe, **PT1** (Fig. 1). The resultant hydrogel constructs **Greenment (Gment)** and **Purplement (Pment)** displayed stability over 7 days in both aqueous solution and in the air; however, upon exposure to aqueous H₂O₂ the polymers were oxidised thus releasing their constituent fluorophores, fluorescein²⁶ and thionol³⁵ (Schemes S1 and S2, ESI†).



Scheme 1 Cartoon representation illustrating the boronate pro-fluorophore encapsulated within a PVA hydrogel being activated by H₂O₂ to release the active fluorophore.

^a Department of Chemistry, University of Bath, Bath, BA2 7AY, UK.

E-mail: t.d.james@bath.ac.uk, a.t.a.jenkins@bath.ac.uk

^b School of Physical Sciences, University of Kent, Canterbury, CT2 7NH, UK.

E-mail: J.R.Hiscock@kent.ac.uk

^c Department of Chemistry, University of Texas at Austin, 105 E 24th street A5300, Austin, TX 78712-1224, USA. E-mail: sessler@cm.utexas.edu

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‡ These authors contributed equally.



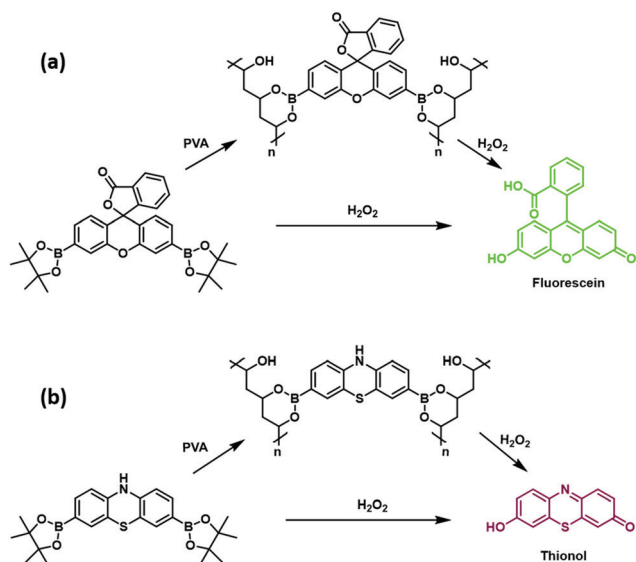


Fig. 1 (a) H₂O₂-responsive fluorescent probe **PF1** and its corresponding H₂O₂-responsive PVA hydrogel **Gment**. (b) H₂O₂-responsive fluorescent probe **PT1** and its corresponding H₂O₂-responsive PVA hydrogel **Pment**.

Complete dissolution of the hydrogel could be effected depending on the specific choice of conditions as detailed below.

PF1 was prepared following literature procedures.²⁶ The novel fluorescent probe **PT1** was synthesized through the dibromination of commercially available phenothiazine (**1**) using Br₂ (5 equiv.) in acetic acid at room temperature, giving the desired product in 74% yield. Subsequent Suzuki–Miyaura borylation using potassium acetate, bis(pinacolato)diboron, and Pd(dppf)Cl₂ afforded **PT1** in 43% yield.

With **PF1** and **PT1** in hand, UV and fluorescence analyses were performed. Upon exposure to aqueous H₂O₂ at concentrations as low as 125 μM, **PF1** exhibited a colour change from clear to green with an increase in absorption at 490 nm and an increase in fluorescence emission at 520 nm, which corresponded to the release of fluorescein (Fig. S1 and S2, ESI†). Whereas, exposure of **PT1** to H₂O₂ in an analogous manner led to a colour change from clear to purple and a concomitant increase in the absorption intensity at 595 nm and an increase in fluorescence emission at 610 nm. These optical changes reflected the release of free thionol as confirmed by high resolution mass spectrometry, Fig. S3–S5 (ESI†). It is important to note that in this work, we have focused on the use of these boronate-based hydrogels as materials whose controlled release may be triggered by H₂O₂. However, previous reports have demonstrated the greater reactivity of boronate-based fluorescent probes towards peroxynitrite (ONOO[−]).^{16,36–39} Therefore, it is likely that if used in cellular applications, both **PF1** and **PT1** could have a role to play in the fluorescence imaging of both ONOO[−] and H₂O₂, albeit not necessarily in a species specific manner.

Next, the **Gment** and **Pment** PVA-hydrogels were prepared by mixing a solution of either **PF1** or **PT1** (100 mM) in dimethylsulfoxide (DMSO) with a DMSO solution of 10% PVA (low molecular weight; purchased commercially) in a 1 : 1 ratio. This solution was then heated to induce gelation, followed by heating at 60 °C overnight in an oven. The resultant gels were washed with hexanes

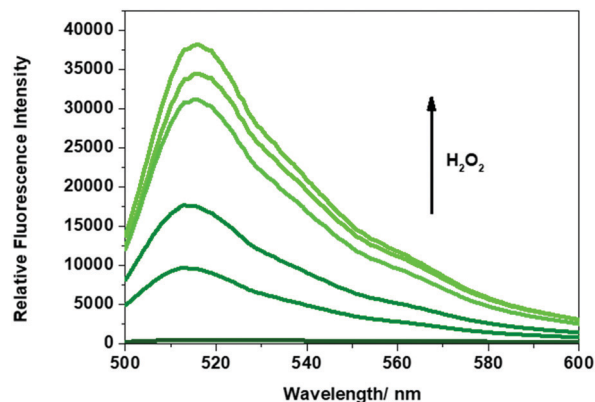


Fig. 2 Fluorescence spectra of the supernatant of **Gment**-based PVA-hydrogels exposed to various concentrations of H₂O₂ (0–1 mM) in PBS, pH 7.4. Measurements were taken after 5 min at 25 °C. λ_{ex} = 472 (bandwidth: 16 nm) on a BMG Labtech CLARIOstar[®] plate reader.

to remove the displaced pinacol and water to remove excess DMSO. These self-supporting gels proved physically robust and stable in air and could be stored in aqueous media (PBS, pH 7.4) without degradation for 7 days until used (Fig. S6–S8 (ESI†)).

The ability of **Gment** or **Pment**-based PVA-hydrogel to release the corresponding dye in the presence of H₂O₂ was then evaluated. This was done by submerging the chosen hydrogel (200 ± 10 mg) in aqueous solutions containing different concentrations of H₂O₂. As shown in Fig. 2, exposure of **Gment** gels to H₂O₂ (0–1 mM) led to a dose-dependent increase in the fluorescence emission intensity. The colorimetric nature of **Gment** was then tested by placing the hydrogel (200 ± 10 mg samples) in an aqueous solution of H₂O₂ (1 mL, 1 mM). A change in colour from colourless to green ensued. Analysis of the UV-Vis absorption revealed an increase in two absorption peaks at 450 nm and 490 nm (Fig. S9, ESI†). The absorption peak at ~450 nm is tentatively assigned to the release of monoboronate **PF3**⁴⁰, while the absorption peak at 490 nm corresponds to the release of fluorescein. Based on this result, we believe that oxidation of only one boronate linkage is required to release the fluorescent cargo from the PVA-hydrogel system (Scheme S3, ESI†).

As shown in Fig. 3, **Pment** PVA-hydrogels exposed to various concentrations of H₂O₂ (0–1 mM) also led to a dose-dependent increase in the fluorescence intensity at the emission maximum of 610 nm. The colorimetric nature of **Pment** was then tested by placing the hydrogel (200 ± 10 mg samples) in an aqueous solution of H₂O₂ (1 mL, 1 mM). A readily discernible change in colour was observed from colourless to purple with an increase in the absorption intensity at 595 nm (see ESI† – Fig. S9–S11). In comparison to one another, **Gment** was found to be more sensitive to H₂O₂ than **Pment** (Fig. S12 and S13, ESI†). This finding is reflected in **Gment** having a lower Limit of Detection ((LoD) – **Gment** = 0.12 mM, LoD **Pment** = 0.33 mM). However, it is important to note, these calculated LoD values are dependent upon incubation times.

Notably, subjecting the hydrogels to an aqueous solution of H₂O₂ (100 mM) resulted in the complete dissolution of the hydrogels into solution, as shown in Fig. 4. Of note is that



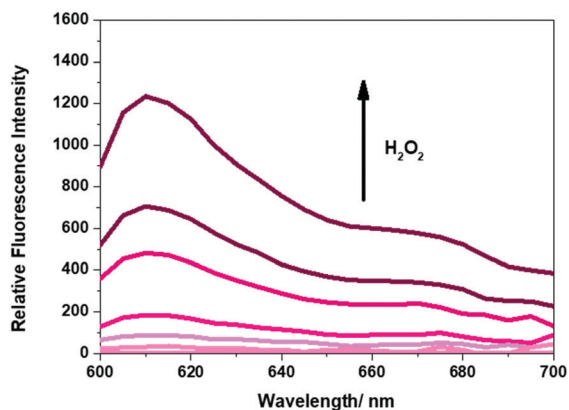


Fig. 3 Fluorescence spectra of the supernatant of **Pment**-based PVA-hydrogels exposed to various concentrations of H_2O_2 (0–1 mM) in PBS, pH 7.4. Measurements were taken after 5 min at 25 °C. $\lambda_{\text{ex}} = 570$ (bandwidth: 16 nm) on a BMG Labtech CLARIOstar[®] plate reader.

commercially available 3% H_2O_2 sold for consumer use is approximately 980 mM. The present work thus demonstrates the potential utility of boronate-based PVA polymers as a smart material for the masking and facile release of easy-to-visualise fluorophores using a readily accessible trigger. Lastly, an MTT assay with A549 cells was carried out using the **Gment** gel. At concentrations up to $50 \mu\text{g mL}^{-1}$ (note – PVA mw 13 000 – 23 000 kDa), A549 cells displayed at least 80% viability, thus demonstrating minimal acute cytotoxicity in this well-studied cell line (Fig. S14, ESI[†]). We believe these findings provide further support for the suggestion that the present approach may prove useful in achieving the controlled delivery of fluorescence-based diagnostics and active pharmacophores.²⁹

In conclusion, we report here the synthesis of a new H_2O_2 -responsive bis-boronate fluorescent probe, **PT1**, and the synthesis of the previously reported H_2O_2 -responsive fluorescent probe **PF1**. Both **PT1** and **PF1** were successfully used as diboronate acid crosslinkers to form air and aqueous stable PVA-based hydrogels. Exposure of these initially colourless and non-fluorescent systems to aqueous solutions of H_2O_2 allowed for the controlled release and activation of the encapsulated fluorophore. We believe these systems serve to illustrate a masking and delivery

strategy that has the potential to achieve the controlled and localised release of boronic acid-based sensors and pro-drugs.²⁹

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Conflicts of interest

There are no conflicts to declare.

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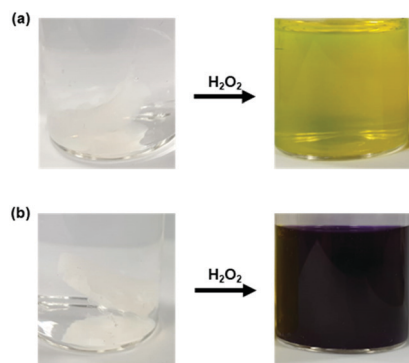


Fig. 4 (a) **Gment** and (b) **Pment** PVA-hydrogels before and after 1.5 h exposure to 100 mM H_2O_2 in PBS, pH 7.4.



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