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Boronate Oxidation as a Bioorthogonal Reaction Approach for Studying the Chemistry of Hydrogen Peroxide in Living Systems

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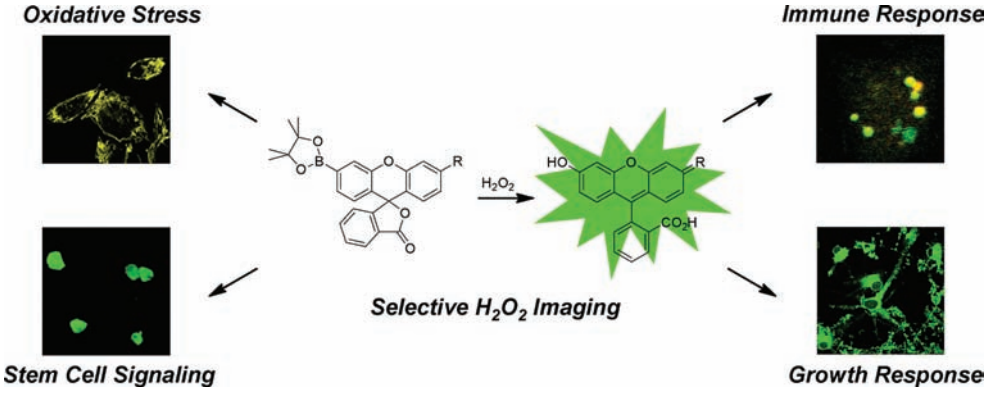

Reactive oxygen species (ROS), such as hydrogen peroxide, are important products of oxygen metabolism that, when misregulated, can accumulate and cause oxidative stress inside cells. Accordingly, organisms have evolved molecular systems, including antioxidant metalloenzymes (such as superoxide dismutase and catalase) and an array of thiol-based redox couples, to neutralize this threat to the cell when it occurs. On the other hand, emerging evidence shows that the controlled generation of ROS, particularly H_2O_2, is necessary to maintain cellular fitness. The identification of NADPH oxidase enzymes, which generate specific ROS and reside in virtually all cell types throughout the body, is a prime example. Indeed, a growing body of work shows that H_2O_2 and other ROS have essential functions in healthy physiological signaling pathways.

The signal–stress dichotomy of H_2O_2 serves as a source of motivation for disentangling its beneficial from its detrimental effects on living systems. Molecular imaging of this oxygen metabolite with reaction-based probes is a powerful approach for real-time, noninvasive monitoring of H_2O_2 chemistry in biological specimens, but two key challenges to studying H_2O_2 in this way are chemoselectivity and bioorthogonality of probe molecules. Chemoselectivity is problematic because traditional methods for ROS detection suffer from nonspecific reactivity with other ROS. Moreover, some methods require enzymatic additives not compatible with live-cell or live-animal specimens. Additionally, bioorthogonality requires that the reactions must not compete with or disturb intrinsic cellular chemistry; this requirement is particularly critical with thiol- or metal-based couples mediating the major redox events within the cell.

Chemoselective bioorthogonal reactions, such as alkyne–azide cycloadditions and related click reactions, the Staudinger–Bertozzi ligation, and the transformations used in various reaction-based molecular probes, have found widespread application in the modification, labeling, and detection of biological molecules and processes. In this Account, we summarize H_2O_2 studies from our laboratory using the H_2O_2-mediated oxidation of aryl boronates to phenols as a bioorthogonal approach to detect fluxes of this important ROS in living systems. We have installed this versatile switch onto organic and inorganic scaffolds to serve as "turn-on" probes for visible and near-infrared (NIR) fluorescence, ratiometric fluorescence, time-gated lanthanide luminescence, and in vivo bioluminescence detection of H_2O_2 in living cells and animals. Further chemical and genetic manipulations target these probes to specific organelles and other subcellular locales and can also allow them to be trapped intracellularly, enhancing their sensitivity. These novel chemical tools have revealed fundamental new biological insights into the production, localization, trafficking, and in vivo roles of H_2O_2 in a wide variety of living systems, including immune, cancer, stem, and neural cell models.

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1. Introduction

Reactive oxygen species (ROS) such as hydrogen peroxide (H_2O_2) play fundamental roles in health and disease but are difficult to study due to their reactive and transient nature (Figure 1).[1−10] In isolated mitochondria, 0.1−2% of all oxygen consumed is estimated to produce ROS,[11] noting that *in vivo* quantitation is challenging[12] and ROS measurements traditionally rely on analysis of downstream chemical products of oxidation.[13] When misregulated, these species can accumulate and cause oxidative damage to cellular protein,[14] nucleic acids,[15] and lipid[16] molecules, thereby contributing to aging[17−19] and age-related disease states ranging from neurodegeneration[20−22] to diabetes[23−25] to cancer.[26−28] Unsurprisingly, organisms have evolved molecular systems, including antioxidant metalloenzymes such as superoxide dismutase[29] and catalase,[30,31] as well as an array of thiol-based redox couples, to scavenge or respond to ROS in order to appropriately neutralize this threat to the cell.[32,33] On the other hand, emerging evidence shows that controlled generation of ROS, particularly H_2O_2, can also be beneficial to cell fitness. A prime example is the presence of active NADPH oxidase enzymes (Nox) that generate specific ROS and reside in virtually all cell types throughout the body.[34] Indeed, a growing body of work points to the fact that H_2O_2 and other ROS play essential functions in healthy physiological signaling pathways spanning growth,[35,36] differentiation,[37,38] migration,[39,40] and immune system function.[41,42]

The signal/stress dichotomy of H_2O_2 provides motivation to disentangle its beneficial from its detrimental effects on living systems, and molecular imaging of this oxygen metabolite is a powerful method for real-time, noninvasive monitoring of H_2O_2 chemistry in biological specimens. Two key challenges to studying H_2O_2 in this context are chemoselectivity, because traditional methods for ROS detection[43] such as 2′-7′-dichlorodihydrofluorescein[44] and the amplex red/peroxidase system[45] suffer from nonspecific reactivity with other ROS or require enzymatic additives that are not compatible with live-cell or live-animal specimens, and bioorthogonality, as not to compete with or disturb intrinsic cellular chemistry, which is particularly critical with thiol- or metal-based couples mediating the major redox events within the cell. In order to study the complex roles of H_2O_2 in living systems and to elucidate its contributions to health, aging, and disease, we have initiated a program aimed at creating and applying new methods for chemoselective, real-time molecular imaging of H_2O_2 in live cells, tissues, and whole organisms. This Account summarizes our efforts to date on the use of H_2O_2-mediated boronate oxidation as a bioorthogonal reaction-based approach to H_2O_2 detection.

2. Application of Oxidative Boronate Cleavage as a Bioorthogonal Reaction for Imaging Hydrogen Peroxide in Living Systems

We considered two main strategies for creating probes to detect molecular entities in biological systems, which we term "recognition" and "reactivity" (Figure 2). Traditional methods for sensing biological analytes largely rely on the former, an approach that has been particularly successful for imaging calcium and other biologically relevant metals using small-molecule fluorescent chemosensors.[46] In this strategy, fluorophores linked to highly specific receptors are designed such that recognition and binding of the analyte of interest provides an observable optical response. However, because H_2O_2 and other ROS are transient in nature and many of these oxygen metabolites are similar in shape and size, building chemoselective hosts for these molecules by a traditional lock-and-key approach is particularly challenging. We reasoned that a reaction-based approach would be a more attractive detection strategy for H_2O_2 in that it offers the opportunity for selective sensing based on the inherent chemical reactivity of a given species instead of its physical shape or size. Moreover, if the reaction is irreversible, this method affords the opportunity to accumulate signal from transient fluxes of reactive species over time.

In order to develop useful probes for H_2O_2, we were particularly motivated to identify chemical reactions that would be selective for H_2O_2 over other biologically relevant ROS including, among others, superoxide ($O_2^{\bullet-}$), hypochlorous acid (HOCl), alkyl peroxides (ROOH), and hydroxyl radical ($^{\bullet}$OH). The key insight to the success of this approach lies in understanding the inherent differences in the reactivity of these species and in designing transformations that take advantage of the unique chemical properties of H_2O_2. In this context, H_2O_2 possesses ambiphilic reactivity; its labile O−O bond allows it to react as a two-electron electrophilic oxidant, whereas H_2O_2 can also be a good nucleophile owing to the α-effect of adjacent nonbonding orbitals on its oxygen atoms.[47,48] To take advantage of these characteristic molecular features, we identified aryl boronates as species with complementary ambiphilic reactivity to H_2O_2 (Figure 2). Upon initially reacting as an electrophile in a reversible manner with nucleophiles to form a negatively charged tetrahedral boronate complex, the C−B bond becomes subsequently capable of reacting as a nucleophile.

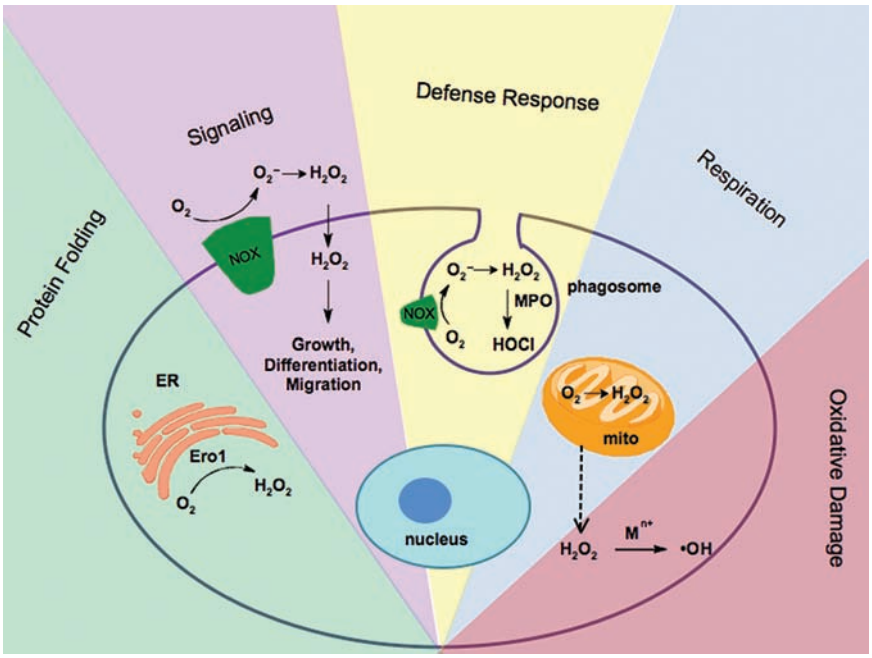

FIGURE 1. Unregulated production of ROS such as H_2O_2 can result in oxidative damage, but these molecules also play central roles in protein folding, signaling, defense response, and respiration and metabolism.

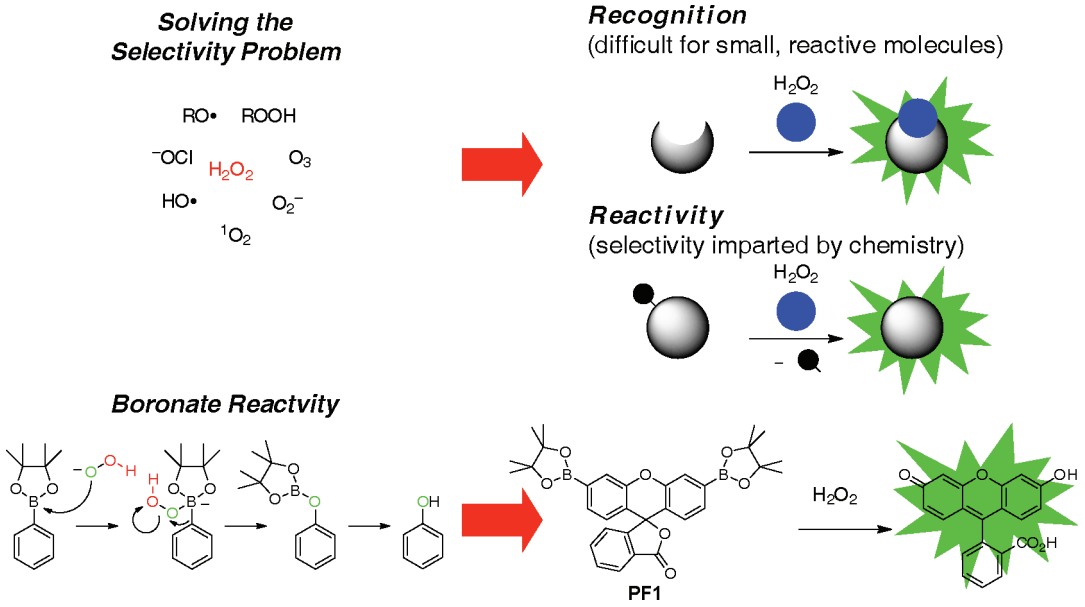

FIGURE 2. Design of a bioorthogonal reactivity approach for selective H_2O_2 detection via boronate oxidation.

We reasoned that we could capitalize on this dual-mode reactivity of H_2O_2 with boronates to achieve selectivity over other biologically relevant ROS, because most of the other oxygen metabolites operate by one-electron transfers or purely electrophilic oxidation pathways. In addition, H_2O_2 should react with boronates faster than the corresponding alkyl peroxides because water is a better leaving group than alcohols, giving specificity for free H_2O_2 over lipid-derived peroxides. The reaction is accelerated at higher pH values so caution is required in quantitating ROS bursts accompanied by large local pH changes. Having identified phenols as functional groups that could be released from masked boronates by the action of H_2O_2, we have exploited this single reaction to devise a wide array of fluorogenic and luminescent molecules that detect H_2O_2 through boronate oxidation (Figure 2). We note that this approach offers

TABLE 1. Boronate Probes for the Detection of Biological H_2O_2

probe	probe $\lambda_{abs}/\lambda_{em}$ (nm)	product $\lambda_{abs}/\lambda_{em}$ (nm)	turn-on	comments
peroxyfluor 1 (PF1)	NA/NA	494/521	>1000-fold	exogenous H_2O_2 detection in cells
peroxyresorufin 1 (PR1)	NA/NA	530/584	>1000-fold	exogenous H_2O_2 detection in cells
peroxyxanthone 1 (PX1)	350/400	350/450	52-fold	two-photon excitation
ratio peroxyfluor 1 (RPF1)	420/464	420/517,461	8-fold[a]	ratiometric *in vitro* H_2O_2 detection
peroxy green 1 (PG1)	460/510	460/510	10-fold	detection of H_2O_2 in cell signaling
peroxy crimson 1 (PC1)	480/584	530/584	40-fold	detection of H_2O_2 in cell signaling
peroxy lucifer 1 (PL1)	375/475	435/540	12-fold[a]	ratiometric H_2O_2 detection in cells
mitochondria peroxy yellow 1 (MitoPY1)	489, 510/540	510/528	4.5-fold	mitochondrially targeted
naphtho peroxyfluor 1 (NPF1)	345/NA	598/660	25-fold	far-red excitation and emission
SNAP peroxy green 1 and 2 (SPG1 and SPG2)	465/515	495/513	32-fold	can localize dye to various cellular compartments
peroxyfluor 2 (PF2)	NA/NA	475/511	50-fold	multiple colors
peroxyfluor 3 (PF3)	454/521	492/515	10-fold	multiple colors
peroxy emerald 1 (PE1)	480/519	491/514	3-fold	multiple colors
peroxy yellow 1 (PY1)	494/558	519/548	12-fold	multiple colors
peroxy orange 1 (PO1)	507/574	540/565	8-fold	multiple colors
peroxy yellow 1 methyl ester (PY1-ME)	489, 510/548	515/540	10-fold	increased dye retention in cells
peroxyfluor 6 acetoxymethyl ester (PF6-AM)	460/530	492/517	7-fold	increased dye retention in cells
terbium peroxy reporter 1 (TPR1)	226/545	226/545	6-fold	utilizes lanthanide luminescence
terbium peroxy reporter 2 (TPR2)	240/545	240/545	6-fold	utilizes lanthanide luminescence
peroxy caged luciferin 1 (PCL-1)	NA/NA	NA/612	7-fold	*in vivo* imaging

[a]Change in the ratio of the major peaks.

generality for monitoring any molecular species of interest in living systems if appropriate combinations of reactivity and bioorthogonality can be suitably balanced.

3. First-Generation Boronate Probes for Detecting Hydrogen Peroxide at Oxidative Stress Levels in Living Cells

Fluorescein is a widely used dye for cellular imaging applications owing to its high fluorescence quantum yield, good water solubility, nontoxic nature, and established use in live and fixed cell specimens. We therefore synthesized the boronate masked fluorescein peroxyfluor 1 (PF1)[49] as a first-generation H_2O_2 probe prototype through a 3′,6′-diiodoxanthenone intermediate followed by a palladium-mediated boronate transmetalation (Table 1, Figure 3). Installation of boronates at the 3′ and 6′ positions drives the molecule into a closed lactone form, effectively eliminating its absorptive and emissive properties in the visible wavelength region. Reaction of PF1 with H_2O_2 transforms the boronates into phenols with concomitant lactone opening resulting in a >1000-fold increase in fluorescence intensity upon generation of the green-fluorescent fluorescein product. Importantly, this response is selective toward H_2O_2 over other biologically relevant ROS (Figure 4). Moreover, this first-generation probe could effectively image changes in high micromolar concentrations of H_2O_2, a concentration range that is relevant to states of oxidative stress, in both live HEK293T cells and primary hippocampal neural cell cultures (Figure 5).[50] We further demonstrated the generality of this reaction-based approach for H_2O_2 detection through the development of peroxyxanthone 1 (PX1) and peroxyresorufin 1 (PR1) probes, which are based on blue xanthone and red resorufin scaffolds, respectively. The success of these probes for visualizing changes in H_2O_2 levels under oxidative stress conditions establishes that bioorthogonal boronate chemistry is a suitable approach for detection of this ROS in live biological samples.

4. Second-Generation Boronate Probes for Studying Endogenous Peroxide Bursts Produced during Growth Factor and Immune Response Signaling

Although the first-generation family of PF1/PR1/PX1 probes were capable of imaging exogenously added H_2O_2 in a variety cell types at oxidative stress levels, attempts to use these reagents for visualizing endogenous production of H_2O_2 were frustrated by their relatively low H_2O_2 sensitivity. In order to address this challenge, we reasoned that switching from bis-boronate masked dyes to monoboronate caged fluorophores would result in enhanced sensitivity by requiring reaction of only a single equivalent of H_2O_2 to yield the fluorescent product. To this end, we synthesized peroxy green 1 (PG1) based on Nagano's Tokyo Green scaffold.[51] Owing to its boronate cage, PG1 retains high selectivity for H_2O_2, and we therefore moved on to apply this probe toward endogenous H_2O_2 detection.

In this context, ROS are produced upon stimulations of cells with extracellular ligands such as epidermal growth factor (EGF) or platelet-derived growth factor (PDGF), which then in turn can mediate intracellular kinase signaling.[52,53]

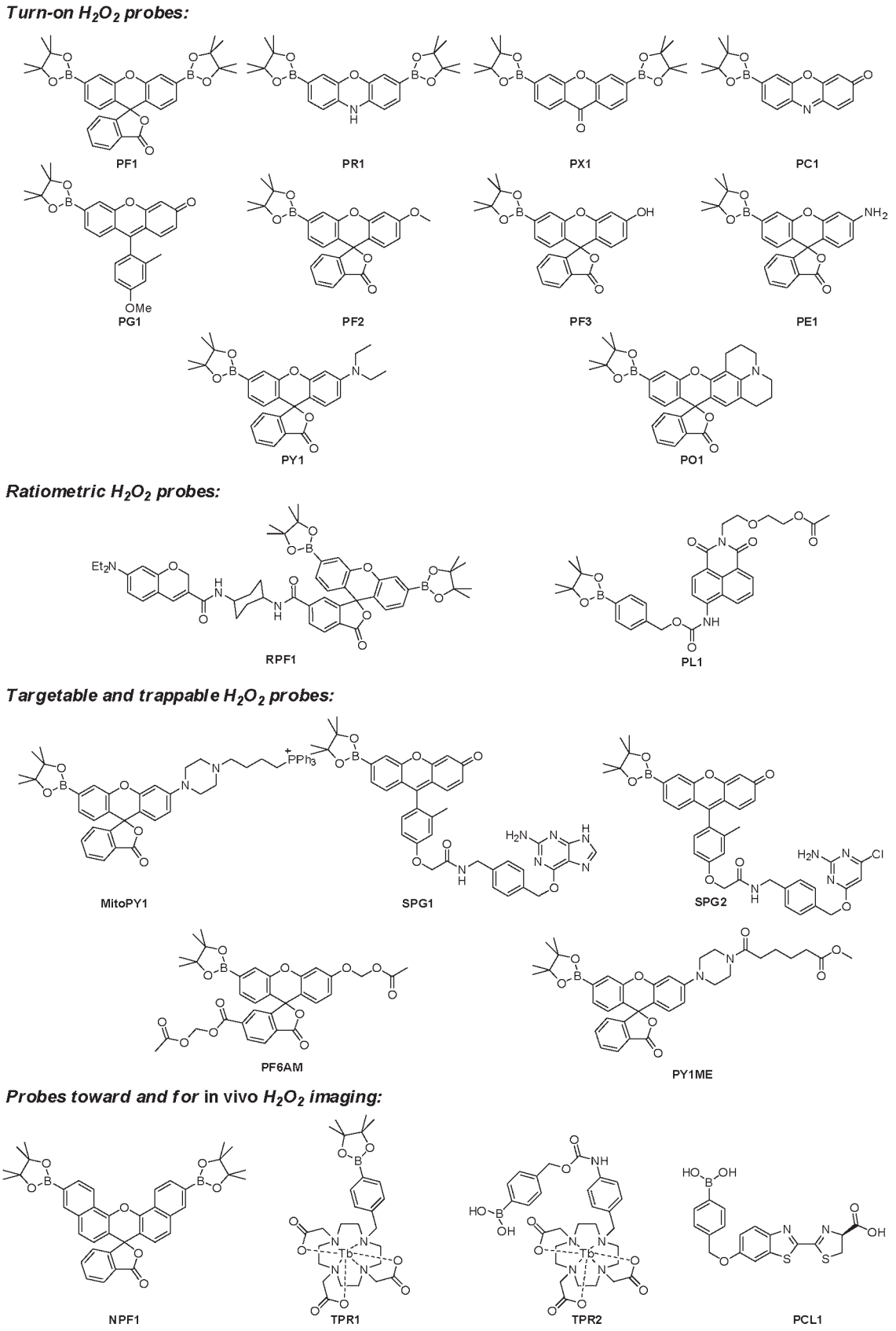

FIGURE 3. Boronate-based probes for H_2O_2 detection and imaging.

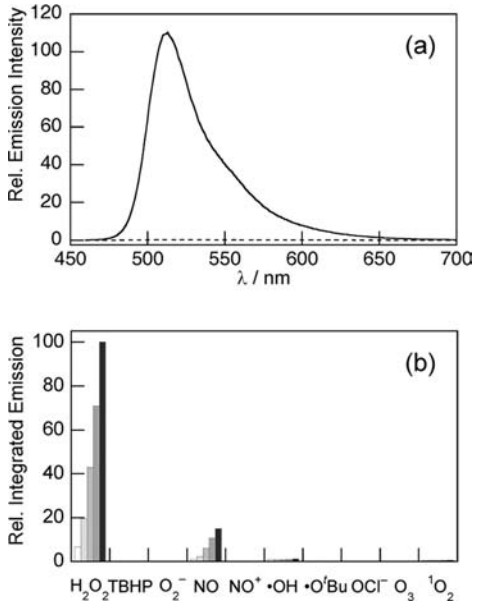

FIGURE 4. (a) Fluorescence response of peroxyfluor 1 (PF1) to H_2O_2. The dashed and solid spectra were recorded before and after H_2O_2 addition, respectively. (b) Fluorescence responses of PF1 to various ROS. Bars represent relative responses after 5, 15, 30, 45, and 60 min after addition of the given ROS.

However, the precise nature of the contributing ROS, the enzymatic source(s) of its generation, its trafficking, and cellular targets remain incompletely understood. With a sensitive and selective H_2O_2 probe in our possession, we turned our attention to EGF signaling in A431 cells because this epidermoid carcinoma line possesses an unusually high copy number of the requisite EGF receptor.[54] After confirming the ability of PG1 to detect exogenously applied H_2O_2 in the A431 line, we discovered that EGF stimulation of these cells also leads to a marked increase in PG1 fluorescence, directly establishing H_2O_2 production in EGF signaling.[51] Furthermore, we utilized PG1 imaging in combination with a panel of pharmacological inhibitors to establish that a Nox enzyme was responsible for H_2O_2 production and that the initial signal is dependent on phosphatidylinositol-3-OH kinase (PI3K) activity (Figure 6). In this same study, we also demonstrated that this growth factor signaling pathway is present in primary hippocampal cell cultures. Taken together, this work provides the first direct imaging evidence that H_2O_2 is endogenously generated during cell signaling and establishes that the boronate reactivity approach can be used for elucidating the roles of H_2O_2 in biological systems.

Encouraged by these results, we synthesized a panel of monoboronate probes for H_2O_2 at physiological signaling levels with excitation and emission profiles that span the visible region.[55] We utilized three of these reagents, peroxyfluor

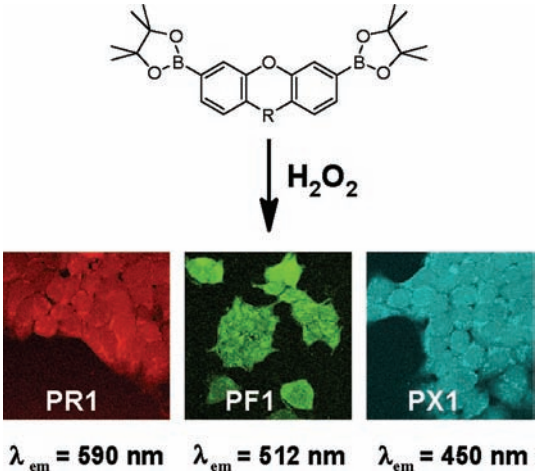

FIGURE 5. Images of peroxyresorufin 1 (PR1), peroxyfluor 1 (PF1), and peroxyxanthone 1 (PX1) detecting H_2O_2 fluxes in living cells.

3 (PF3), peroxy yellow 1 (PY1), and peroxy orange 1 (PO1), for chemoselective monitoring of H_2O_2 signaling after growth factor stimulation as well as during phagocytic immune response. Moreover, we established the utility of this expanded color palette by performing two-color, dual-ROS imaging experiments with PO1 in combination with APF,[56] a probe for highly reactive oxygen species (hROS) that responds to hypopchlorite (HOCl), hydroxyl radical (•OH), and peroxynitrite ($ONOO^-$). Interestingly, we discovered three different types of phagosomes as characterized by the distinct types of ROS produced, those that produce predominately H_2O_2, those that produce predominately hROS, and those that produce both (Figure 7). This work highlights the advantage of using multiple bioorthogonal probes to disentangle which discrete types of ROS molecules contribute to a given biological process, enabling studies of the distinct chemical reactivity of each particular oxygen metabolite within a complex environment.

5. Dual-Wavelength Boronate Probes for Ratiometric Peroxide Imaging in Living Cells

Intensity-based turn-on fluorescent probes are of practical utility for many applications and can be employed for comparative discovery studies, but their use for precise quantitation of analytes is complicated by variations in sample thickness, cellular microenvironments, and local probe concentrations. To address these issues, we have explored ratiometric approaches in which one can simultaneously monitor two signals that change differentially with analyte concentration, such that the ratio of the signals will be independent of the probe concentration and environment and allow for more accurate and quantitative measurements.[57] Our first probe for ratiometric H_2O_2 detection, ratio

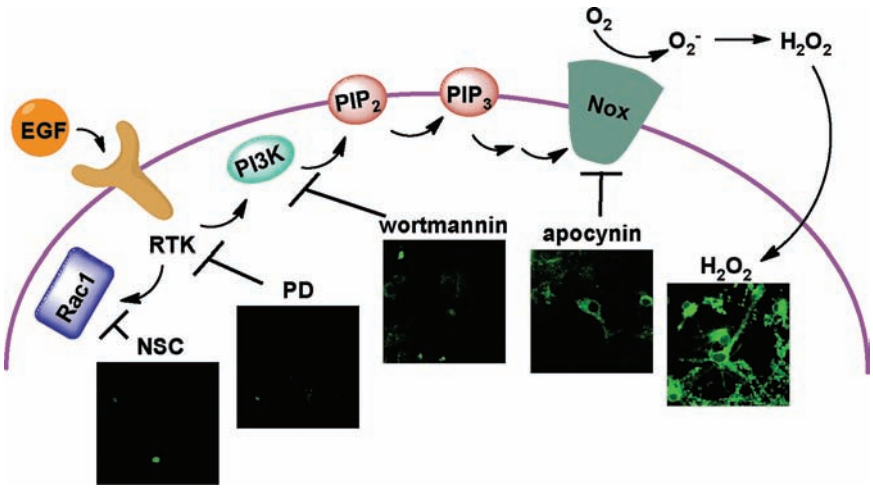

FIGURE 6. H_2O_2 and growth factor signaling in living neurons. EGF stimulation produces an increase in the fluorescence response of peroxy green 1 (PG1). This response is attenuated by apocynin, a Nox inhibitor; wortmannin, an inhibitor of PI3K; PD153035, an inhibitor of the receptor tyrosine kinase domain of the EGF receptor; and NSC23766, a Rac1 inhibitor.

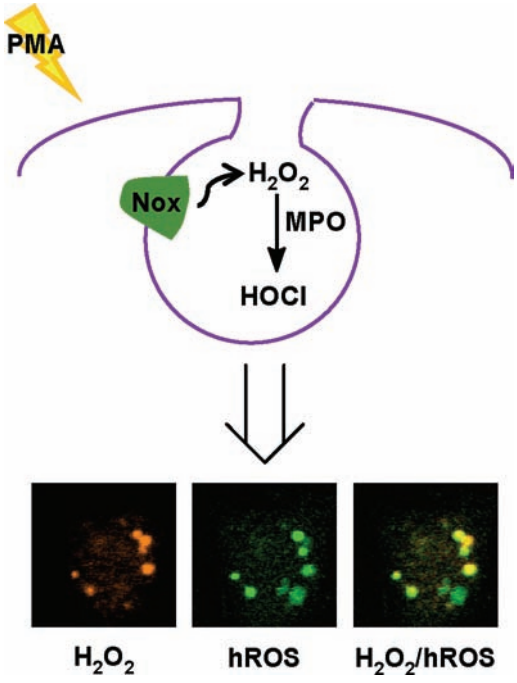

FIGURE 7. Confocal fluorescence images of H_2O_2-producing phagosomes, hROS-producing phagosomes, and dual H_2O_2 and hROS-producing phagosomes in live RAW264.7 macrophages as distinguished by simultaneous imaging with peroxy orange 1 (PO1) and aminophenyl fluorescein (APF).

peroxyfluor 1 (RPF1), utilizes a two-dye cassette that undergoes changes in the ratio of fluorescence resonance energy transfer (FRET) between donor and acceptor fluorophores upon reaction with H_2O_2.[58] Whereas most FRET probes operate by a physical change in donor–acceptor distances and orientations to sense analytes, we opted to modulate FRET properties in an electronic fashion by triggering

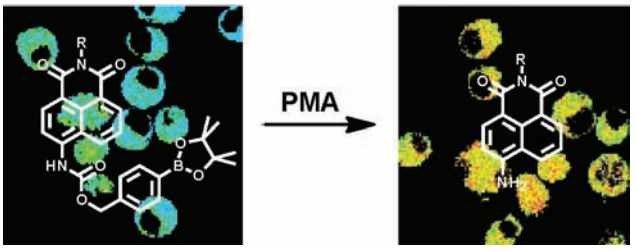

FIGURE 8. Ratiometric confocal fluorescence images of H_2O_2 in stimulated live RAW 264.7 macrophages as visualized with peroxy lucifer 1 (PL1).

changes the donor–acceptor spectral overlap before and after reaction with H_2O_2. In the absence of H_2O_2, the FRET acceptor is a PF1 derivative that has negligible visible absorption, leading to poor FRET from the coumarin donor. However, upon reaction with H_2O_2, generation of the colored fluorescein product creates an efficient FRET acceptor for the coumarin donor. Experiments in isolated mitochondria from *Saccharomyces cerevisiae* show that RPF1 can detect H_2O_2 generated by antimycin A inhibition of the electron transport chain (ETC). We have extended this ratiometric imaging approach to live-cell imaging by tuning the internal charge transfer (ICT) properties of a single dye to cause a shift in the observed emission maxima upon reaction with H_2O_2. Peroxy lucifer 1 (PL1)[59] masks a pendant electron-rich amine as an electron-poor carbamate by using a *para*-boronate group that undergoes a selective H_2O_2-triggered self-immolative release.[60] PL1 can readily visualize localized increases in H_2O_2 in the phagosomes of PMA-stimuated macrophages by ratiometric imaging (Figure 8).

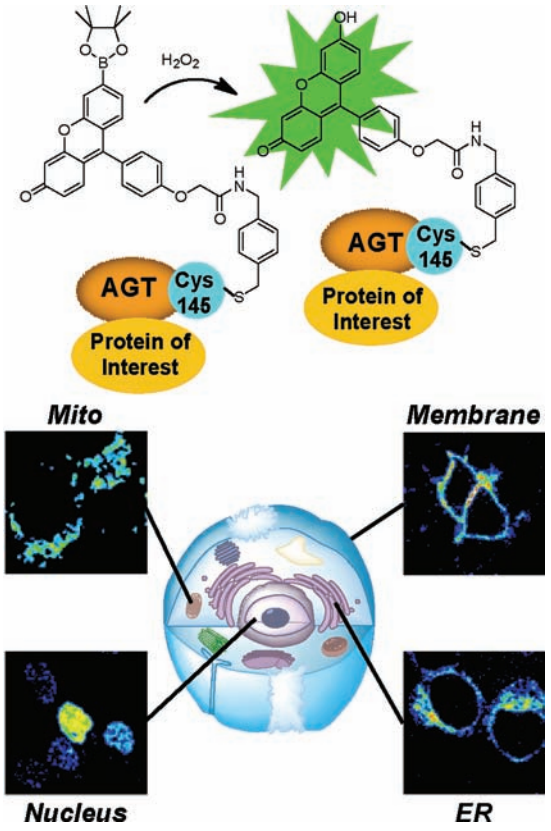

FIGURE 9. Images of SNAP peroxy green 2 (SPG2) localized to the plasma membrane, mitochondria, endoplasmic reticulum, and nucleus.

6. Targetable and Trappable Boronate Probes for Understanding Peroxide Trafficking and Stem Cell Function

In addition to events at the whole single cell level, controlling the subcellular localization and trafficking of H_2O_2 is a vital mechanism that the cell employs to attenuate its toxicity and off-target function, allowing it to mediate beneficial physiological processes. For example, organelles such as the mitochondria are equipped with numerous enzymes aimed at reducing levels of oxidative stress,[12] whereas the endoplasmic reticulum (ER) maintains a higher level of oxidative species in order to ensure proper protein folding.[61,62] To better study the contributions of subcellular localization and trafficking of H_2O_2 in physiological and pathological processes, we developed a family of boronate probes equipped with functional groups that are capable of targeting these tools to specific subcellular spaces. For example, mitochondrial peroxy yellow 1 (MitoPY1) combines a monoboronate-masked fluorophore with Murphy's phosphonium cation for mitochondrial localization.[63] This probe can operate in a wide variety of cell types (HEK293T, HeLa, Cos7, and CHO.K1, etc.) and can visualize discrete oxidative

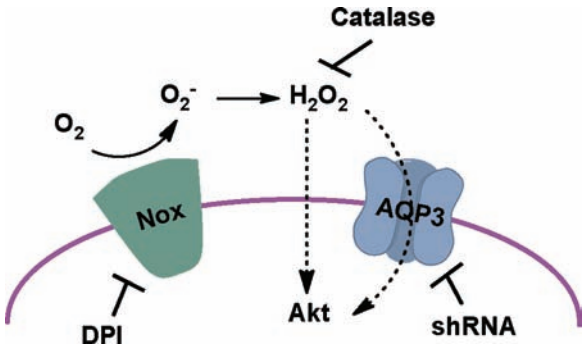

FIGURE 10. Aquaporins facilitate H_2O_2 trafficking in growth factor signaling, as shown by the aquaglyceroporin family isoform aquaporin 3 (AQP3).

stress changes confined to this organelle, including those generated in a chemically induced Parkinson's disease model.[64]

We have also recently explored a more general protein-based labeling approach that enables us to tag many parts of the cell[65] by exploiting Johnsson's elegant SNAP tag methodology.[66−68] In this approach, any protein of interest can be fused with a mutant human O^6-alkylguanine-DNA alkyltransferase (hAGT) protein that can be selectively tagged with benzyl guanine or benzyl-2-chloro-6-aminopyrimidin-4-amine containing dyes, allowing one to target a probe to any subcellular compartment of interest. Indeed, SNAP peroxy green 1 and 2 (SPG1 and SPG2) are two first-generation PG1 derivatives with linkages to benzyl guanine or benzyl-2-chloro-6-aminopyrimidin-4-amine, respectively, that afford a general method for directing H_2O_2-responsive dyes to the plasma membrane, mitochondria, ER, and nucleus (Figure 9).

Finally, we have developed two new types of probes, peroxy yellow 1 methyl ester (PY1-ME)[69] and peroxyfluor 6 acetoxymethyl ester (PF6-AM),[70] that take advantage of multiple masked carboxylates to increase cellular retention and hence sensitivity to low levels of peroxide. In their ester-protected forms, the PY1-ME and PF6-AM dyes are more lipophilic than their carboxylate counterparts and can readily enter cells. Once inside cells, the protecting groups are rapidly cleaved by intracellular esterases to produce their anionic carboxylate forms, which are effectively trapped within cells because they cannot pass back through the plasma membrane. The increased retention of PY1-ME and PF6-AM leads to their enhanced sensitivity to H_2O_2 by greater buildup of signal through irreversible boronate oxidation events. In particular, we utilized PY1-ME to interrogate the cellular mechanisms involved in the trafficking of H_2O_2 during growth factor signaling (Figure 10) and

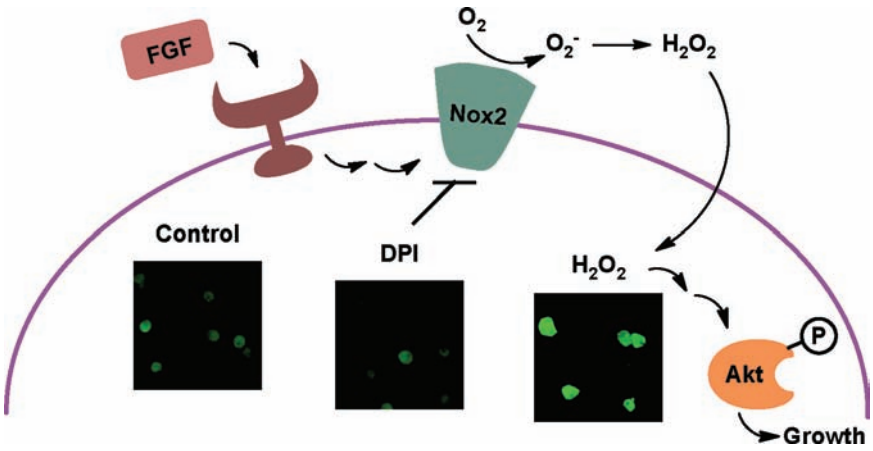

FIGURE 11. FGF stimulation induces a Nox2-dependent increase in intracellular H_2O_2 levels as imaged by peroxyfluor 6 (PF6).

discovered that certain classes of aquaporin water channels, the aquaglyceroporins and unorthodox aquaporins but not classic aquaporins, can enhance the uptake of extracellularly produced H_2O_2 and regulate intracellular signal transduction. This work represents the first study revealing that aquaporins can mediate both H_2O_2 transport and signaling in mammalian cells and has broad implications for H_2O_2 biology in processes ranging from cell migration[39] to wound repair.[40] In parallel work using PF6-AM imaging, we have explored the roles of H_2O_2 in the self-renewal of neural stem cells. Specifically, we discovered that adult hippocampal progenitor cells (AHPs) require basal generation of H_2O_2 for their normal growth and proliferation in cell culture and *in vivo* and determined that the Nox2 enzyme and phosphatase PTEN are molecular sources and targets of H_2O_2, respectively (Figure 11). This study provides primary evidence that H_2O_2 is a physiological regulator in living organisms and a molecular model for how H_2O_2 can mediate beneficial events.

7. Boronate Reporters for Imaging Hydrogen Peroxide in Live Tissue and Animals

In addition to creating boronate probes for imaging in dissociated cell culture samples, we have also initiated several parallel approaches to expand H_2O_2 imaging technologies to thicker tissue and whole animal specimens. In particular, we have explored optical H_2O_2 detection in the near-infrared spectroscopic window, where the absorption and autofluorescence of biological tissues is at a minimum, using naphtho peroxyfluor 1 (NPF1),[71] as well as lanthanide luminescence, which allows the use of time-gated imaging to decrease autofluorescence from native, short-lived organic species in biological specimens, through the synthesis and evaluation of terbium peroxy reporters 1 and 2 (TPR1 and TPR2).[72]

Finally, we have recently succeeded in establishing boronate oxidation as a bioorthogonal reaction approach for imaging H_2O_2 in living animals through the creation of the bioluminescent probe peroxy caged luciferin 1 (PCL1).[73] Bioluminescence is a modality that drastically increases sensitivity for *in vivo* imaging owing to the absence of any autofluorescence background endemic to fluorescence techniques. By caging luciferin with a self-immolative boronic acid, we can use this reaction-based approach to selectively detect H_2O_2 in living luciferase-expressing mice (FVB-luc$^+$) through H_2O_2-dependent luciferin generation (Figure 12). Moreover, PCL1 can visualize H_2O_2 generated by a luciferase-expressing prostate cancer cell line (LNCaP-luc) as well as in an LNCap-luc tumor xenograft model in immunodeficient SCID hairless outbred (SHO) mice following testosterone stimulation. By expanding the scope of boronate oxidation to living animals, these results offer a significant technical advance for exploring H_2O_2 chemistry in complex biological settings, particularly for models of disease and aging that occur on the whole organism scale.

8. Concluding Remarks

In this Account, we have described the identification and application of H_2O_2-mediated boronate oxidation as a chemoselective reaction-based approach for studying the chemistry of H_2O_2 in complex biological systems. This switch has been installed onto a diverse array of scaffolds for bioorthogonal optical detection of H_2O_2 in living cells and animals. Monoboronate-bearing fluorophores have proved to be the most effective chemical tools for live-cell microscopy experiments and methods for reaction-based trapping inside cells have yielded probes useful for interrogating the production, trafficking, and targets of H_2O_2 in growth factor signaling, immune response, and stem cell

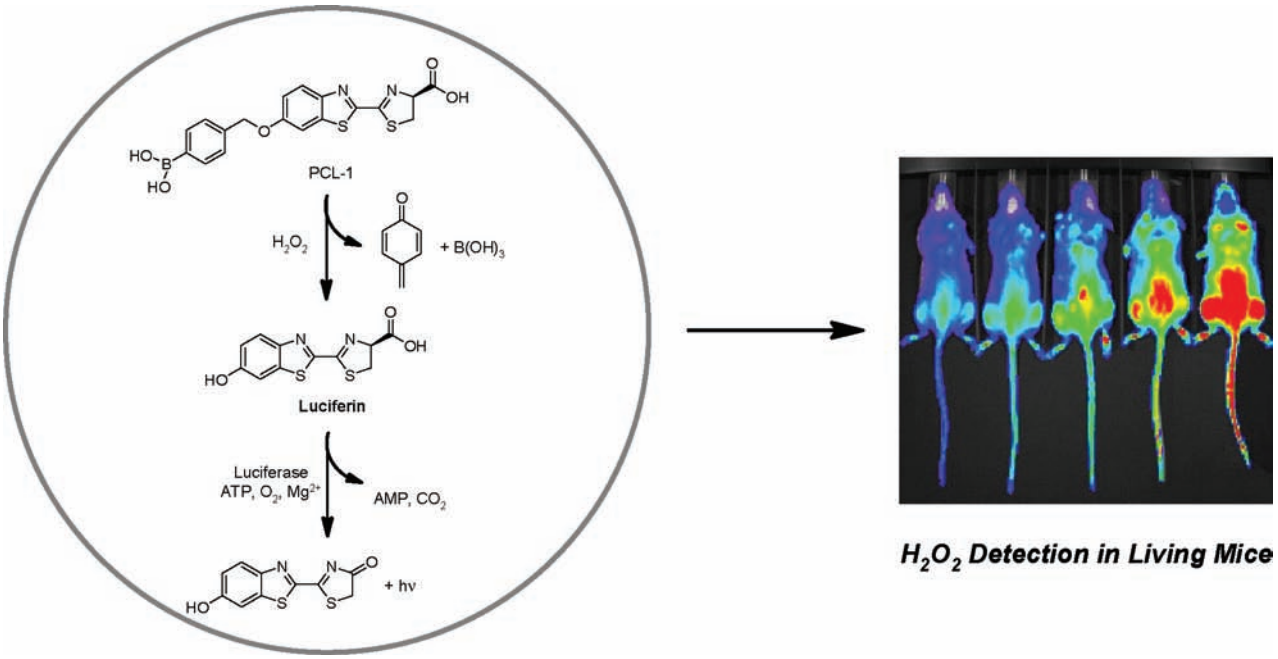

FIGURE 12. Peroxy caged luciferin 1 (PCL-1) detects H_2O_2 *in vivo* using bioluminescence.

function. Both chemical and biological strategies have been successful in targeting probes to subcellular domains, providing a means to study the roles of H_2O_2 in specific organelles, and continued efforts in the development of ratiometric, targetable, near-IR, and lanthanide-based luminescent probes are expected to provide new opportunities for the precise imaging of subcellular domains as well as the study of thicker biological specimens. Finally, the development of a boronate-caged luciferin has enabled the bioluminescent imaging of H_2O_2 *in vivo* and opens up many new avenues for studying H_2O_2 in animal models of health and disease.

In addition to these aforementioned studies, a growing number of methods exploiting boronate oxidation show the broader utility of this switch for probing and manipulating peroxide biology. Innovative examples include alternative H_2O_2 indicators bearing blue-fluorescent,[74,75] dendrimer,[76,77] and near-infrared[78] scaffolds, as well as mass spectrometry tags for tracking peroxide biology in whole organisms.[79] Oxidatively sensitive therapeutics such as masked metal chelators[80,81] and inhibitors[82] have also been devised using the boronate switch. As well, recent data suggest that certain boronate derivatives may also find utility in probing peroxynitrite.[83] Finally, this boronate chemistry has inspired work into alternative bioorthogonal reactions for H_2O_2, including the oxidative decarboxylations of α-ketoacids[84] and Baeyer–Villiger benzil oxidations.[85] The rapidly expanding toolbox for probing and manipulating H_2O_2 in living systems presages new frontiers for discovering and understanding its fundamental roles in signaling and stress processes and highlights the synergy between bioorthogonal chemistry and biology.

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Genevieve C. Van de Bittner was born and raised in Moraga, CA. She graduated with Honors in Chemistry (B.S. 2007) from Chapman University, where she performed research in the laboratories of Prof. Daniel Wellman and Prof. Kenneth Sumida. As an undergraduate, Genevieve also spent a summer at Cornell University working under the guidance of Prof. Dotsevi Sogah. She is currently completing her doctoral research in the laboratory of Prof. Chris Chang and was recently awarded a Klaus and Mary Ann

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Christopher J. Chang is an Associate Professor of Chemistry and HHMI Investigator at UC Berkeley. He received his B.S. and M.S. degrees from Caltech in 1997, working with Prof. Harry Gray. After spending a year as a Fulbright scholar in Strasbourg, France, with Dr. Jean-Pierre Sauvage, Chris received his Ph.D. from MIT in 2002 under the supervision of Prof. Dan Nocera. He stayed at MIT as a postdoctoral fellow with Prof. Steve Lippard and then began his independent career at UC Berkeley in Fall 2004. Research in the Chang lab is focused on chemical biology and inorganic chemistry, with particular interests in molecular imaging and catalysis applied to neuroscience, stem cells, cancer, infectious diseases, renewable energy, and green chemistry. His group's work has been honored by awards from the Dreyfus, Beckman, Sloan, and Packard Foundations, Amgen, Astra Zeneca, and Novartis, AFAR, Technology Review, the ACS Cope Scholar Fund, and the Society for Biological Inorganic Chemistry.

FOOTNOTES

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