

Water-Soluble BODIPY Photocages with Tunable Cellular Localization

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Cite This: *J. Am. Chem. Soc.* 2020, 142, 4970–4974



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ABSTRACT: Photoactivation of bioactive molecules allows manipulation of cellular processes with high spatiotemporal precision. The recent emergence of visible-light excitable photoprotecting groups has the potential to further expand the established utility of the photoactivation strategy in biological applications by offering higher tissue penetration, diminished phototoxicity, and compatibility with other light-dependent techniques. Nevertheless, a critical barrier to such applications remains the significant hydrophobicity of most visible-light excitable photocaging groups. Here, we find that applying the conventional 2,6-sulfonation to *meso*-methyl BODIPY photocages is incompatible with their photoreaction due to an increase in the excited state barrier for photorelease. We present a simple, remote sulfonation solution to BODIPY photocages that imparts water solubility and provides control over cellular permeability while retaining their favorable spectroscopic and photoreaction properties. Peripherally disulfonated BODIPY photocages are cell impermeable, making them useful for modulation of cell-surface receptors, while monosulfonated BODIPY retains the ability to cross the cellular membrane and can modulate intracellular targets. This new approach is generalizable for controlling BODIPY localization and was validated by sensitization of mammalian cells and neurons by visible-light photoactivation of signaling molecules.

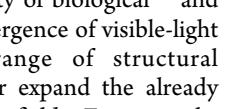
Photoactivation of small bioactive molecules is a powerful approach to manipulate and study cellular events with high spatiotemporal resolution.^{1,2} Photoprotecting groups (PPGs) covalently attached to bioactive molecules mask their biological activity and allow subsequent removal upon exposure to light. Established PPGs, including those based on nitrobenzyl,³ ruthenium⁴ (RuBi), coumarin⁵ and others,⁶ have been used instrumentally in a wide variety of biological^{7,8} and materials^{9,10} applications. The recent emergence of visible-light excitable photocages, spanning a range of structural classes,^{11–15} has the potential to further expand the already significant utility of photocaging in these fields. For example, extension of the excitation wavelength beyond the traditional UV-region⁶ expands the operational window in which uncaging light can be delivered, enabling photoactivation of multiple cues through orthogonally caged molecules.^{16,17} Furthermore, longer wavelength light can penetrate deeper into tissue and is less harmful to biological matter, opening the door to new applications, such as in drug delivery.^{18–20}

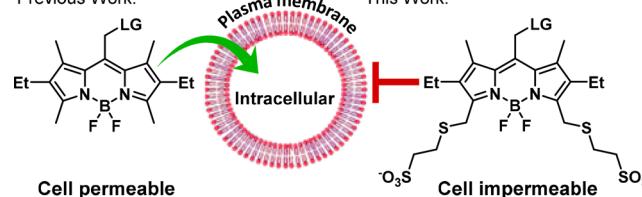
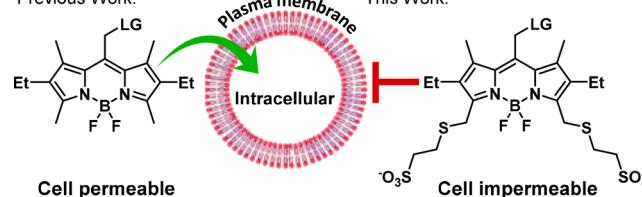
We recently introduced *meso*-methyl BODIPYs as photoprotecting groups in the visible range.^{21,22} The narrow excitation band, adaptable synthetic chemistry, and overall biocompatibility of BODIPYs²³ make them promising candidates for visible-light photocaging. *Meso*-methyl BODIPY PPGs effectively release cargo in living cells, in part because of their large extinction coefficients.^{21,22} Further chemical modification to methyl-BODIPY cages can improve photorelease quantum efficiency,²⁴ extend excitation wavelength into the far-red,²⁵ or allow postsynthetic functionalization for targeting to subcellular locations,²⁶ making them a versatile platform for photorelease.

Nevertheless, all BODIPY PPGs reported to date are inherently highly hydrophobic, which severely limits their potential concentration and thus utility in water-based solutions. Moreover, the hydrophobic nature of BODIPYs makes them highly cell permeable (Scheme 1). While

Scheme 1. Water-Soluble BODIPY Photocages

Previous Work:

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advantageous when specifically pursuing intracellular interventions, this property makes BODIPY PPGs less effective when targeting extracellular proteins or plasma membrane-residing receptors and complicates analysis when the released molecule can act both intra- and extracellularly.

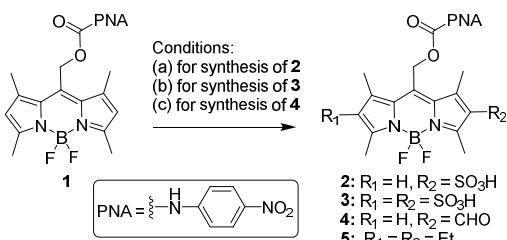
We therefore sought to develop water-soluble BODIPY PPGs with controlled cellular localization, while retaining their

Received: December 8, 2019

Published: February 29, 2020

favorable spectroscopic and photoreaction properties. We initially opted for 2,6-sulfonation²⁷ as a minimal structural modification²⁸ that also provides improved photobleaching resistance.²⁹ 2- and 2,6-sulfo BODIPYs **2** and **3**, bearing *p*-nitroaniline (PNA) as a model leaving group, were synthesized by sulfonation of **1** using a sulfur trioxide–pyridine complex (Scheme 2).³⁰ Surprisingly, both **2** and **3** did not release PNA

Scheme 2. Synthesis/Structures of BODIPYs 1–5^a



^a(a) SO₃–Pyridine, DMF, 60 °C, 24 h; (b) SO₃–Pyridine, DMF, 60 °C, 48 h; (c) DMF, POCl₃, DCM, 0 °C to rt, 3 h.

when irradiated with green light (545/30 nm, 49 mW/cm²). In contrast, **1** is an effective photocage, with $\epsilon \times \Phi_{\text{rel}} = 3$ and $t_{1/2} = 3.8$ min (Figure 1a and Table S1). We hypothesized that the

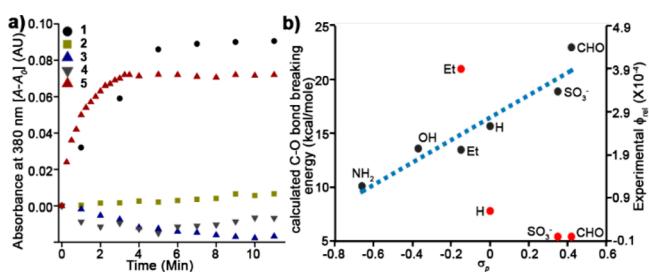


Figure 1. Light-induced release from *meso*-methyl BODIPY PPGs. (a) PNA release from **1–5** (10 μ M in CH_3CN /water 7/3) irradiated with 545/30 nm (49 mW/cm²) light for the indicated times. (b) Observed Φ_{rel} and a DFT calculated C–O bond breaking energy for derivatives **1–5** as plotted versus σ_p Hammett constants.

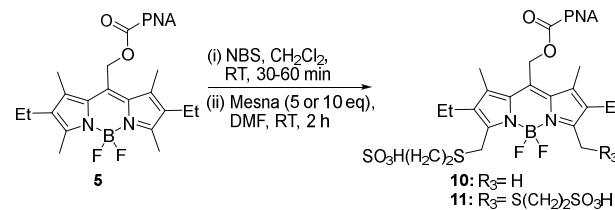
electron-withdrawing effect of sulfonate is responsible for the diminished photoreaction. Indeed, a comparable BODIPY with 2-aldehyde (**4**) also failed to release the leaving group, while 2,6-diethyl BODIPY **5** photolyzed with $\epsilon \times \Phi_{\text{rel}} = 19$ and $t_{1/2} = 31$ s, better than **1** (Table S1).

The observed trend in Φ_{rel} (**5** > **1** > **4** \approx **2** \approx **3**) suggests a strong effect of the 2,6-positions on the photoreaction with a positive influence of electron donation. We therefore modeled the excited state geometries of **1–5** to explore the consequences of 2,6-substitution on photouncaging efficiency (B3LYP/6-31+G(d,p), SMD = H₂O). No fundamental change in the nature of the excited state exists between **1–5**. Neither chromophore planarity nor position of the LUMO (*meso* carbon) differs across compounds **1–5** (Computation S1–S7). However, a relaxed potential energy scan of the C–O bond breaking coordinates (Computation S8–S13) reveals that electron-withdrawing groups (EWGs) at the 2,6-positions substantially raise the barrier for C–O bond heterolysis on the triplet surface compared to electron-donating groups (Figure 1b), consistent with a previous report of these positions' effect on BODIPY photostability.³¹ These computations further support our previous hypothesis regarding photorelease in

meso-methyl BODIPYs, i.e. formation of a *meso* carbocation radical intermediate during the photoreaction.²⁴ Thus, electron-donating groups (EDGs) at the 2,6-positions stabilize the resulting carbocation, lowering the barrier for its formation, and conversely, EWGs increase the barrier to photoreaction.

To circumvent deleterious electronic effects on the BODIPY core when introducing sulfonates, we harnessed our recently reported functionalization method; a one-pot, two-step protocol, to install an unprotected functional group on an *in situ* activated *α*-methyl.²⁶ We synthesized (Figure S1a) tertiary amine (**6**), ether (**7**), and thioether (**8–9**) containing BODIPY PPGs. Although amine substitution gave the highest synthetic yields, tertiary amines could no longer undergo photorelease (**6**, Figure S1d), likely because of a competing electron transfer (PeT) mechanism.^{32–34} Instead, we find thiol nucleophiles best combine high chemical yield with efficient photorelease in BODIPY thioether (Figure S1). Thus, 2-mercaptopropane-sulfonic acid sodium salt (MESNA) was used to introduce sulfonic acid groups, affording BODIPYs **10** and **11** in 42% and 33% yield, respectively (Scheme 3).

Scheme 3. Synthesis of Sulfonated BODIPYs **10 and **11****



As expected, both **10** and **11** show improved water solubility compared to **5**. In mixtures of CH_3CN /water, **5** features absorbance λ_{max} at 545 nm, a shoulder at 511 nm, and an ~ 2.1 peak/shoulder ratio. But, in water, the peak red shifts and broadens (556 nm), and the ratio collapses to 1.1, a nearly 1.9-fold reduction and characteristic of aggregation³⁵ (Figure 2a).

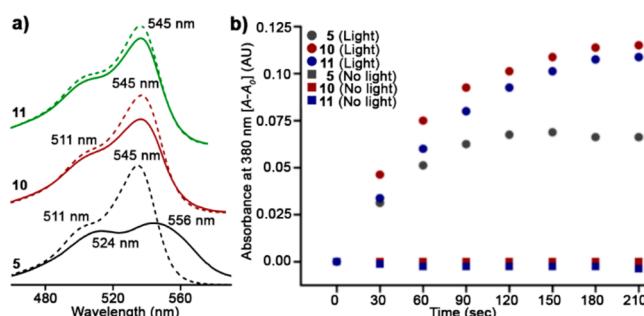


Figure 2. MESNA-BODIPY PPGs. (a) Absorbance spectra of BODIPYs **5**, **10**, and **11** (20 μ M) directly dissolved in CH_3CN /water 7/3 (dashed line) or water (solid line). (b) Light-induced release of PNA from **5**, **10**, and **11** (10 μ M, CH_3CN /water 7/3) following, or not, irradiation with 545/30 nm light (49 mW/cm²) for the indicated times.

In contrast, the absorption spectra of **10** and **11** are nearly identical in either pure water or a mixture of CH_3CN /water, establishing their high water solubility (Figures 2a, S2). Critically, both **10** and **11** retain photoreleasing ability, in stark contrast to core-sulfonated **2** or **3**. Both **10** and **11** possess comparable quantum yield to **5** ($\Phi_{\text{rel}} = (3.6\text{--}5.1) \times 10^{-4}$) (Figures 2b, S3–S5 and Tables S1, S2), but afford

higher photochemical yields (59–60% vs 46%), probably due to their increased solubility. These results establish peripheral MESNA as a small, readily implemented modification to *meso*-methyl BODIPYs that improve solubility while maintaining high photorelease efficiency.

The degree of sulfonation influences the cellular uptake of BODIPY PPGs. HEK 293T cells display intracellular fluorescence, along with bright fluorescent puncta (presumably aggregates), when treated with non-MESNA BODIPY **5** (Figure 3a). In contrast, mono-MESNA **10** shows a higher

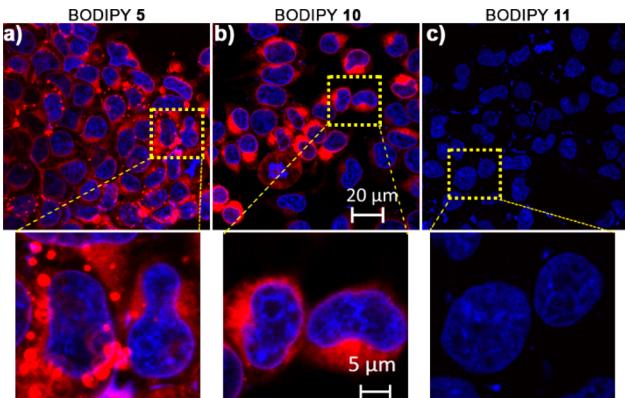
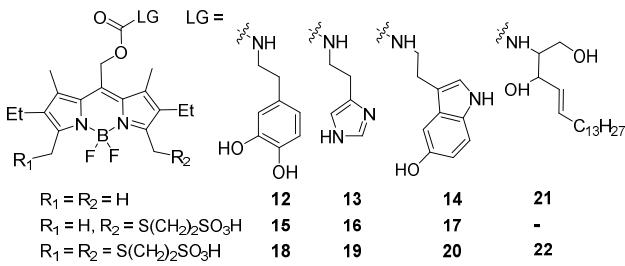


Figure 3. Confocal fluorescence microscopy of HEK 293T cells treated with BODIPY **5**, **10**, or **11** (2 μ M) for 30 min and costained with Hoechst dye. Cells were washed thrice and imaged.

degree of cellular fluorescence (2-fold higher than **5**, Figure S6), but without any observable puncta (Figure 3b). The higher intracellular fluorescence may be a result of better water solubility of **10** compared to **5**, leading to higher effective concentration in the buffer. Di-MESNA **11**, with two sulfonates, was completely cell impermeable and showed no intracellular or membrane-associated fluorescence (Figure 3c). These results are in line with previous observations of sulfonated coumarin photocages.³⁶ No toxicity or phototoxicity was observed for compound **5**, **10**, or **11** (Figure S7).

To evaluate the dependence of sulfonated BODIPY PPG cellular permeability on the nature of the leaving group, we compared sets of non-, mono-, and di-MESNA BODIPYs bearing three caged biogenic amines: serotonin, dopamine, and histamine (compounds **12–20**, Scheme 4), forming a series of

Scheme 4. Structures of BODIPYs **12–20**



leaving groups with decreased hydrophobicity. The cellular permeability of non- and mono-MESNA-BODIPYs was highly dependent on the polarity of the leaving group while di-MESNA-BODIPY was completely cell impermeable, irrespective of the leaving group polarity (Figure S6).

Collectively, these data establish that the solubility of BODIPY photocages can be significantly improved by sulfonation without compromising photoreaction properties and that their cellular permeability can be predetermined by tuning the number of sulfonates.

To highlight the ability to tune the cellular accessibility of caged biomolecules with BODIPY compounds, we synthesized two sphingosine-caged BODIPY derivatives, **21** and **22** (Scheme 4). **21** is based on the traditional, nonsulfonated BODIPY photocage, while **22** utilizes the di-MESNA-BODIPY scaffold. Our hypothesis was that **21** could pass through plasma membrane to effect localized uncaging of sphingosine intracellularly, triggering Ca^{2+} release, while **22** would be retained externally and would be incompetent to trigger internal Ca^{2+} release.³⁷ Consistent with this hypothesis, treatment of HeLa cells with **21**, followed by green uncaging light, results in large Ca^{2+} transients detected by the fluorescent Ca^{2+} indicator, fura-2 (Figure S8a–c). Induction of Ca^{2+} transients requires uncaging light: we observed no Ca^{2+} oscillations in the absence of light (Figure S8d). In contrast, the uncaging of extracellularly targeted **22** results in no Ca^{2+} -associated transient (Figure S8e). Together, these data show that di-MESNA-BODIPY cages can retain even lipophilic bioactive molecules in the extracellular space.

The enhanced solubility of MESNA-BODIPYs makes them promising candidates to modulate cell surface receptors. We utilized them to control the availability of the neuromodulator dopamine. We examined the localization of BODIPY-caged dopamine compounds in cultured neurons. While BODIPY-dopamine **12** shows significant cytosolic accumulation (Figure S9a,d), both mono- (**15**) and di-MESNA-BODIPY-dopamine **18** display little to no cellular uptake (Figure S9b,e and S9c,f), consistent with the localization of di-MESNA-BODIPY cages in HEK cells (Figures 3, S6).

Di-MESNA BODIPY-dopamine **18** delivers dopamine in a light-dependent fashion to neurons. Ca^{2+} imaging in hippocampal neurons treated with dopamine (5 μ M) results in fluorescence oscillations (Figure 4a,b).^{22,38} Hippocampal neurons treated with di-MESNA-BODIPY-dopamine **18** (5 μ M) and irradiated with green light also show Ca^{2+} oscillations (Figure 4c), with 34% of neurons responding compared to 46% with dopamine alone (Figure S10). In the absence of green light, **18** has little effect on the activity of hippocampal neurons (Figure 4d), and green light alone, when **18** is not present, does not evoke a similar Ca^{2+} response (Figure 4e). Finally, preincubation with the dopamine receptor antagonist butaclamol (100 μ M) prior to green light uncaging in the presence of **18** results in a substantial reduction in the number of Ca^{2+} transients (Figures 4f, S10).

Complementary experiments using the cell-impermeable mono-MESNA-BODIPY caged histamine **16** reveal that this caged compound can also effectively modulate neuronal physiology and Ca^{2+} signaling in a light-dependent fashion (Figure S11). We further show that the spatial resolution of uncaging can be controlled (Figure S12).

In summary, we introduce biocompatible BODIPY PPGs with substantially improved water-solubility, user-designed control over cellular localization and high photorelease efficiency. Initial efforts to directly sulfonate the BODIPY core improved solubility but abolished photorelease. A combination of computation and *in vitro* characterization suggests that EWGs at the 2,6-positions destabilize the carbocation formed during the photoreaction. We circum-

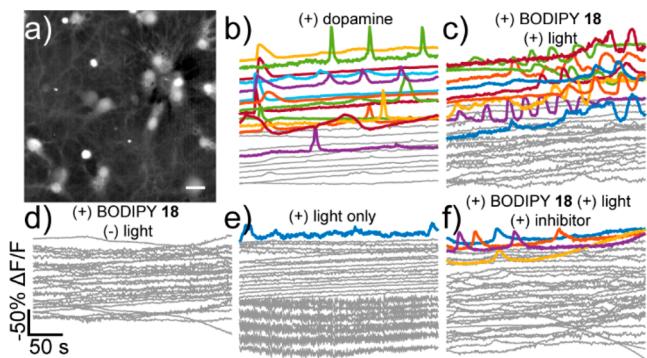


Figure 4. Dopamine uncaging in neurons. (a) Widefield fluorescence image from neurons stained with fura-2. Scale bar is 20 μ m. (b–f) Uncaging of dopamine from 18 causes Ca^{2+} oscillations in cultured rat hippocampal neurons. Ca^{2+} imaging in neurons treated with (b) dopamine (5 μ M), (c) 18 (5 μ M) and uncaging light, (d) 18 (5 μ M) without light, or (e) only with uncaging light and (f) 18 (5 μ M) and light in the presence of the dopamine receptor antagonist butaclamol (100 μ M). Plots represent $\Delta F/F_{\max}$ for representative cells vs time and are inverted. A decrease in fluorescence represents a rise in cellular Ca^{2+} . Uncaging light was provided for 10 s at 90 mW/mm². Gray traces are neurons which did not show < -20% $\Delta F/F$. Colored traces did show < -20% $\Delta F/F$ response.

vented this barrier by introducing remote sulfonation, resulting in an increase in water solubility and the ability to regulate cellular localization through the degree of sulfonation. The cellular impermeability of peripherally disulfonated BODIPYs makes them promising candidates for use in modulation of extracellular proteins and cell-surface receptors, while monosulfonated BODIPYs retain the ability to cross the cellular membrane and can modulate intracellular targets. Moreover, the peripheral sulfonation strategy presented herein should be applicable to BODIPY fluorophores at large, providing a convenient route to confer water solubility and control cellular permeability.

ASSOCIATED CONTENT

Supporting Information

The Supporting Information is available free of charge at <https://pubs.acs.org/doi/10.1021/jacs.9b13219>.

¹H and ¹³C NMR spectra (PDF)

Supplementary data, including supporting figures, procedures, and analysis (PDF)

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Notes

The authors declare no competing financial interest.

ACKNOWLEDGMENTS

R.W. and E.W.M. acknowledge generous support from the Binational Science Foundation (2016060) and from the Rosalinde and Arthur Gilbert Foundation. R.W. acknowledges support from the European Research Council (GAtransport). A.H.W. acknowledges support from the National Science Foundation (CHE-1464956). D.F.M. acknowledges support from the Israel Science Foundation (1310/15). P.L. was supported by an A*STAR graduate fellowship, and M.X.N. was supported in part by the NIH (T32GM066698). D.K. was supported in part by the Planning and Budgeting Committee (PBC) of the Israeli Council for Higher Education.

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