Research Article

Semi-Quantitatively Designing Two-Photon High-Performance Fluorescent Probes for Glutathione S-Transferases

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Received 21 December 2019; Accepted 18 February 2020; Published 21 March 2020

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Glutathione S-transferases (GSTs), detoxification enzymes that catalyze the addition of glutathione (GSH) to diverse electrophilic molecules, are often overexpressed in various tumor cells. While fluorescent probes for GSTs have often adopted the 2,4-dinitrobenzenesulfonyl (DNs) group as the receptor unit, they usually suffer from considerable background reaction noise with GSH due to excessive electron deficiency. However, weakening this reactivity is generally accompanied by loss of sensitivity for GSTs, and therefore, finely turning down the reactivity while maintaining certain sensitivity is critical for developing a practical probe. Here, we report a rational semiquantitative strategy for designing such a practical two-photon probe by introducing a parameter adopted from the conceptual density functional theory (CDFT), the local electrophilicity \( \omega_k \), to characterize this reactivity. As expected, kinetic studies established \( \omega_k \) as efficient to predict the reactivity with GSH, and probe NI3 showing the best performance was successfully applied to detecting GST activities in live cells and tissue sections with high sensitivity and signal-to-noise ratio. Photoinduced electron transfer of naphthalimide-based probes, captured by femtosecond transient absorption for the first time and unraveled by theoretical calculations, also contributes to the negligible background noise.

1. Introduction

Glutathione S-transferases (GSTs, EC 2.5.1.18), mainly known as phase II detoxifying enzymes [1], are a family of dimeric enzymes that catalyze the nucleophilic attack of the sulfhydryl of glutathione (GSH) on an electrophilic center of diverse substrates of endogenous or exogenous origin [2]. The expression level of GSTs plays a crucial role in determining the susceptibility to cancer chemotherapy [3]. Among varieties of GST isoenzymes, alpha (GSTA), mu (GSTM), and pi (GSTP) are frequently found overexpressed in various tumor cell lines, particularly in anticancer drug-resistant ones [4–8]. Hence, sensitively and specifically monitoring GST activities in biological systems without background noise, namely, false-positive error usually introduced by GSH, is urgently needed.

Recently, small-molecule fluorescent probes have been rapidly emerging as a powerful tool for enzyme detection in biological samples by virtue of their fast analysis, higher sensitivity, minimal perturbation to living systems, and real-time detection capabilities [9–13]. Indeed, several such probes have been developed for sensitive detection of GST activities with representatives being DNAT-Me [14], DNs-CV [15], and 3,4-DNADCF [16]. However, these probes exhibit either high nonenzymatic background noise or narrow isoenzyme selectivity. Specifically, while the 2,4-dinitrobenzenesulfonyl (DNs) group has often been employed as a receptor unit for GST probes [15, 17], those probes for thiols such as GSH and cysteine mostly just adopt the same group [18–20], demonstrating the nonnegligible background noise due to the nonenzymatic reaction between GSH and this very group. Given the considerable concentration of GSH (ca. 1–10 mM)
in mammalian cells, interferences from this GSH noise with GST detection should not be ignored. However, a probe with higher sensitivity for GSTs is usually accompanied by a higher nonenzymatic background noise due to its chemical reactivity with GSH, which implies that alleviating this noise is also at the expense of sensitivity. Therefore, finely tuning the reactivity with GSH is critical for designing a practical probe for GSTs with both specificity and sensitivity.

It is conceivable that an effective parameter characterizing the reactivity of one GST probe with GSH should be conducive to molecular design for the sake of subtle tuning. It is well documented that GST catalyzes the nucleophilic attack of GSH on the electrophilic center of its substrate via nucleophilic aromatic substitution ($S_{N}Ar$) reaction mechanism [1, 21], so what is desired should be a parameter reflecting the effective electrophilicity of a probe. Therefore, we turned to the local electrophilicity $\omega_k$ [22], a concept quoted from conceptual density functional theory (CDFT), which has been extensively employed to investigate Diels-Alder reactions [23–26]. As shown in Equation (1), $\omega_k$ is equal to the arithmetic product of the global electrophilicity $\omega$ [27] and the electrophilic Parr function $P^+_k$ [22], the latter one being an approximation of the condensed Fukui function $f^+_k$, which characterizes the regioselectivity. With GSH generally accepted as a so-called soft nucleophile and nitrobenzene derivative a soft electrophile [28], it is reasonable to use this parameter to describe the reactivity [29, 30].

$$\omega_k = \omega \cdot P^+_k. \quad (1)$$

Here, we present the first rational semiquantitative strategy for designing practical two-photon fluorescent probes for GSTs with both high sensitivity and negligible background noise. First, based on the $S_{N}Ar$ reaction mechanism, we established that the electrophilic Parr function $P^+_k$ could characterize the regioselectivity of a probe, and therefore, the local electrophilicity $\omega_k$ can be used to represent and predict relative chemical reactivity of different probes. Hence, a series of probe candidates were designed and screened out according to their $\omega_k$ values, which were available by quantum chemical calculations. These probes were synthesized and evaluated in terms of sensitivity and signal-to-noise (S/N) ratio, after which NI3 was selected and successfully applied to the imaging of GST activities in live cells and tissue sections with high sensitivity and S/N ratio. Furthermore, femtosecond transient absorption spectra and time-dependent density functional theory (TD-DFT) calculations revealed the photoinduced electron transfer (PET) mechanism of fluorescence quenching, which also contributed to the considerably low background noise.

2. Results

2.1. Designing and Screening of the Probe Candidates. As stated earlier, the DNs group has often been employed as a receptor unit for GST detection probes; we thus started to design our first two-photon fluorescent probe candidate NI1 by introducing the DNs group to the ring of 4-hydroxy-N-butyl-1,8-naphthalimide (NI1), a well-known fluorophore with two-photon absorptivity [31, 32]. Initially, to examine whether the calculation method introduced here is rational, the electronic spin density distribution and the atomic spin population (namely, the $P^+_k$ values) of the anion radical of NI1 were calculated. The $\alpha$-carbon of the arylsulfonyl group showed the maximum spin density and $P^+_k$ (Figure 1), indicating the most electrophilic center lies on this very carbon, which is to be attacked by GSH, in accord with the regioselectivity revealed by previous experiments [15, 17]. This result indicates that it is the electronic aspects related to electrophilicity rather than other factors such as the leaving ability of the nucleofuge related to nuclear displacement [33, 34] that dominate the regioselectivity herein. Confirming $P^+_k$’s ability to reproduce the real regioselectivity led to the conclusion that the effective reactivity of a probe with GSH could be characterized by the local electrophilicity $\omega_k$ of the $\alpha$-carbon (refer to Equation (1)). It can be envisaged that by altering substitution situations on the nitrobenzene ring and comparing $\omega_k$ of resultant probe candidates, some superior probes will be preliminarily screened out with the criterion: the $\omega_k$ of a practical probe should be modestly lower than that of NI1.

Considering the DNs group is a much too sensitive receptor unit, five approaches were put forward (Figure 2): (1) replace the second nitro group, the one para to the $\alpha$-carbon, with less electron-withdrawing groups to give NI2 and NI3; (2) add an electron-donating group to the position meta to the $\alpha$-carbon to give NI4 and NI5; (3) simply shift the second nitro group to other positions to give NI11, NI12, and NI13; (4) first, shift the second nitro group to the other position ortho to the $\alpha$-carbon, and then, replace it with less electron-withdrawing groups to give NI14 and NI15; and

![Figure 1: Spin density distribution of the anion radical of NI1.](image-url)
(5) first, shift the second nitro group to the other position ortho to the α-carbon, and then, add an electron-donating group to the position meta to the α-carbon to give NI16 and NI17. Subsequently, these compounds were evaluated in terms of spin density distribution, \( P_k \) and \( \omega_k \) values, and the results showed that all probe candidates except those in the third approach displayed a valid regioselectivity and reasonably lower \( \omega_k \) values with NI15, NI3, and NI14 among the most moderate ones, suggestive of their potential as practical probes (Figure S1 and Table S1). It should be noted that similar \( \omega_k \) values appear in NI1 and NI13, NI10 and NI14, NI12 and NI15, or NI4 and NI16, respectively, indicating that there is no significant difference in the electron-withdrawing group’s locating para or ortho to the α-carbon, which is in line with the chemical intuition. As for NI11 and NI12, the most electrophilic center lies on the alternative β-carbon rather than on the α-carbon (Figure S1), indicative of their inappropriateness as GST detection probes. Actually, one tries synthesizing NI11 but only to find that apart from the fluorine atom, one nitro group was substituted competitively and comparably by the sulfonic group just via the SNAr reaction mechanism (Figure S2; refer to the synthesis section below and in Supplementary Materials; for more evidence for the alternative method calling for poisonous gas SO2. Compounds NI1–NI10 and relevant intermediate products were fully characterized using NMR spectroscopy (Figures S20–S57) and mass spectrometry.

With these probe candidates in hand, we investigated whether they were amenable to GST detection in vitro. On the whole, upon encounter with GST’s from the equine liver, all these probe candidates gained a drastic enhancement in fluorescence intensity from a virtually nonluminescence state, despite their different S/N ratios (Figure S5). For instance, NI9 showed beyond 35-fold fluorescence increase at 560 nm in less than 30 minutes (Figure 3(a)). To confirm the probe was lightened by no other than GST activities, a full set of control experiments were conducted. As shown in Figure 3(b), hardly any fluorescence was triggered without either of GST and GSH or both, using deactivated GSTs or replacing the GSH with other sulphur-bearing analogues, namely, oxidized glutathione, N-acetylcysteine, L-cysteine, and L-homocysteine. In addition, if ethacrynic acid (EA), a well-known inhibitor for various GSTs [37], was added 30 min prior to GSH and NI9, the rising of fluorescence was substantially suppressed (Figure 3(b)). These results demonstrate that GST and GSH are both indispensable to the fluorescence enhancement. Further, with both of the resultant organic products being captured and tracked, the UPLC-MS analysis (Figure S6) as well as the spectra comparison (Figure S7) provided a more explicit and solid evidence that the detection mechanism is exactly the one illustrated in Figure 3(c). As designed, under the catalysis of GST, the attack of GSH on the α-carbon releases glutathione conjugate, SO2, and NI, enabling the detection of GST activities.

Although every single probe did display measurable response towards GSTs, they differed greatly from one
another in terms of sensitivity and nonenzymatic noise. For example, with rapid response to either GSTs or GSH, NI1 is regarded as an oversensitive probe, whereas NI6 belongs to undersensitive probes due to slow response towards GSTs, along with no background noise at all (Figures S5a, f and S8). In order to inspect the relationship between chemical structures of the probes and their performances quantitatively, an elaborate kinetic study on both nonenzymatic and enzymatic reactions was implemented, and the kinetic parameters were plotted as the function of $\omega_k$ values of the $\alpha$-carbon (Figure 4 and Tables S4–S6). With all the probes whose nonenzymatic reactions with GSH are detectable falling into the quasilinear plot of $\ln k_{\text{nonc}}$ and $\ln \omega_k$ (the goodness of fit $R^2 = 0.991$), the local electrophilicity $\omega_k$ proved itself an excellent parameter to describe the $S_N^1$Ar reactivity with GSH, namely, the nonenzymatic noise for GST detection. Remarkably, the order of $k_{\text{nonc}}$ for different probes (NI2 < NI4 < NI3 < NI5 < NI1) agrees quite well with the order of fluorescence rising rate in preceding nonenzymatic tests (Figure S8b), thus corroborating the conclusions drawn here. To our knowledge, this is the first time the

![Figure 3: In vitro GST detection with NI9 and the detection mechanism for NI-series probes.](image)

(a) Time-dependent fluorescence spectra of NI9 (20 $\mu$M) in HEPES buffer (20 mM, 0.5% DMSO, pH 7.4) upon addition of GSTs (12.5 $\mu$g/mL) over the course of 25 min at 37°C in the presence of GSH (2 mM). $\lambda_{\text{ex}} = 445$ nm. (b) A full set of control experiments on examining the cause of fluorescence enhancement. EA = ethacrynic acid (GSTs were preincubated with 200 $\mu$M EA for 30 min before addition of GSH and NI9 sequentially); deac-GST = deactivated GSTs (12.5 $\mu$g/mL) by pretreatment at 100°C for 10 min; GSSG = oxidized glutathione (2 mM); NAC = N-acetylcysteine (2 mM); Cys = L-cysteine (2 mM); Hcy = L-homocysteine (2 mM). $\lambda_{\text{ex/em}} = 445/560$ nm. (c) Schematic for the proposed GST activity detection mechanism of NI-series probes.
nonenzymatic noises of probes for GST detection have been depicted and predicted by a single parameter (see Figure S9 for more evidence). Furthermore, to some extent, this parameter can also reflect the probe’s sensitivity to GSTs (Figures 4(b)–4(d)). Remarkably, the data of NI8 and NI10 deviate from the description by $\omega_k$, demonstrating the $\omega$-NO$_2$ is indispensable to GST catalysis, in agreement with the previous literature [1, 15]. In general, a smaller $\omega_k$ means a lower background noise and yet probably a lower sensitivity meanwhile. Then, to what extent do these two aspects depend on the chemical structure, namely, $\omega_k^2$?

Notably, the preexponential factor (2.08) and exponential term (8.72) of the fitting formula for the nonenzymatic reaction are both larger than the ones for enzymatic reactions (0.94 and 4.75 for GSTA1-1; 1.29 and 4.57 for GSTM1-1; and 0.04 and 7.43 for GSTP1-1, respectively (Figure 4), implying that improving the sensitivity (here depicted by $k_{cat}$) by enlarging the $\omega_k$ would be monotonically accompanied by the loss of S/N ratio (here depicted by $k_{cat}/k_{nonc}$), in good agreement with preceding results (Figures S5 and S8). Thus, there is a trade-off between sensitivity and S/N ratio, and reaching a balance point between them was critical for a superb probe. Fortunately, the relationships above can also be reviewed from the other side: starting from an oversensitive probe such as NI1, a tiny decrease of $\omega_k$ would probably afford a drastic reduction in nonenzymatic

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**Figure 4**: Structure-activity relationships between nonenzymatic or enzymatic kinetic parameters and the local electrophilicity $\omega_k$ of the $\alpha$-carbon. (a) Regarding the second-order rate constant $k_{nonc}$ of the nonenzymatic reaction between GSH and probes. Data for other probes are unavailable due to extremely low reactivity. (b–d) Regarding the catalytic constant $k_{cat}$ of (b) GSTA1-1, (c) GSTM1-1, and (d) GSTP1-1, respectively, towards different probes. Linear fittings were based on mean values. Error bars represent SD.
noise while leaving the sensitivity almost unchanged (cf. **NI1** and **NI3** in Figures 4(a) and 4(c); see also Figure S8b), thus obtaining a probe with both high sensitivity and high S/N ratio, self-supporting the design strategy here quantitatively. Therefore, it is unsurprising that after an overall consideration of sensitivity, S/N ratio, and broad isoenzyme selectivity (Table S7), **NI3**, one of the two probes whose \( \omega_k \) are modestly lower than that of **NI1** (Table S1), was found to be the best one. It was thus used for more practical and rigorous applications such as bioimaging in the next section.

2.3. Fluorescence Imaging of Live Cells and Tissue Sections. It is often desirable to be able to detect very low levels of enzymatic activities in live cells, cell extracts, or tissues. Hence, **NI3** was examined whether it was capable of reporting GST activities by cellular fluorescence imaging. First, HepG2 was selected as an appropriate cell line for GST monitoring according to the Western blotting results (Figure S10). Incubation with 20 \( \mu \)M **NI3** in HEPES buffer (pH 7.4) for just one minute could afford a discernible fluorescence image derived from a completely dark one when no probe was added, and then, the cells gradually became brighter in the following ca. 30 min (Figure S11 and Video 1), demonstrating the probe was ignited by the intracellular substances. To ascertain the fluorescence arose from GST activities, cells were pretreated with the GST inhibitor EA and the GSH-depleting agent N-ethylmaleimide (NEM), respectively, before the addition of **NI3**. The results showed a substantial loss of fluorescence for both cases (Figures 5(a)–5(c)), proving that it was the attack of GSH on the probe by virtue of GST catalysis that lighted the cells up. A similar consequence was obtained from the flow cytometric analysis (Figure 5(d) and Table S8). Furthermore, an analogous assay in cell lysate samples revealed that the fluorescence intensity of cell lysate pretreated with EA was still obviously higher than that of the control group which represented the nonenzymatic reaction of **NI3** with GSH (Figure 5(e)). This finding implies the remaining fluorescence that appeared in cellular imaging or flow cytometry came from the residual GST activities other than the GSH itself (Figures 5(b) and 5(d)) and thus highlights the remarkably high sensitivity and S/N ratio of **NI3**. Actually, the limit of detection \( (3\sigma) \) was calculated to be 3.7 nM. Moreover, to further verify that the nonenzymatic reaction produces little noise, we selected MHCC97L cells as a negative control and HepG2 together with A549 and HeLa cells as positive controls based on the Western blotting results (Figures S10). After being subjected to **NI3** incubation and fluorescence imaging, MHCC97L cells displayed little fluorescence, whereas other cells exhibited strong emission under the same conditions (Figures 5(f)–5(i)). With almost no GST in the MHCC97L cell line and varied GST isoenzymes in each individual positive cell line, this result manifested the probe’s specificity for GSTs with negligible nonenzymatic noise again and broad isoenzyme selectivity as well. Incidentally, when incubated with **NI3**, all cells kept a normal and fine morphology during the whole imaging course, indicating its low cytotoxicity and favorable biocompatibility. In addition, to investigate the source of the GST activities, the colocalization experiment was performed and the results showed the fluorescence spread all over the cytoplasm homogeneously rather than focusing on any organelles (Figures S12–S14), consistent with the GSTs’ coming from the whole cytosol. Notably, when HepG2 cells were incubated with 20 \( \mu \)M **NI3** or **NI2** for 30 min, respectively, both cellular imaging and flow cytometry tests exhibited a weaker fluorescence for the latter (Figure S15). Additionally, when pretreated with EA and then incubated with **NI1**, HepG2 cells showed almost the same fluorescence intensity as incubated with only **NI1** (Figure S16), highlighting **NI1**’s nonnegligible background noise. All these consequences were in agreement with previous in vitro results, demonstrating the local electrophilicity \( \omega_k \) does affect a probe’s effective performances.

With its ability to detect GST activities certified by single-photon confocal fluorescence imaging, we next tested if **NI3** was amenable to two-photon imaging of more complicated biological samples. Initially, identical consequences were obtained by two-photon cell imaging upon irradiation at 810 nm with a femtosecond pulse laser (Figure S17), establishing the probe’s capacity for applications based on two-photon microscopy. Subsequently, **NI3** was interrogated as to whether it could afford clear images of tissue sections containing plenty of GSTs. Hence, the tissues of the liver and lung from female BALB/c mice were cut into 100 \( \mu \)m slices with a frozen slicer and then soaked into the HEPES buffer containing 40 \( \mu \)M **NI3** for 1 h before two-photon microimaging. As shown in Figures 6(b) and 6(d), both liver and lung tissues displayed bright fluorescence, albeit with different GST isoenzymes in them [38, 39], whereas completely dark images were acquired in the absence of **NI3** (Figures 6(a) and 6(c)), with the negligible background autofluorescence benefiting from the near-infrared excitation wavelength implied by the two-photon absorptivity of the probe. Furthermore, fluorescence images of the liver tissue sections at different depths were collected in the Z-scan mode (Figure S18 and Video 2), and the results indicate **NI3** is able to realize tissue imaging as deep as ca. 100 \( \mu \)m, which enables the 3D reconstruction of the tissue images (Figure S19). To sum up, these results exhibited the excellent two-photon staining and tissue-penetrating capabilities of **NI3**.

2.4. Fluorescence Quenching Mechanism of Intact NI-Series Probes. The establishment of **NI3**’s outstanding performances is unavailable without the low background noise, which is intimately related not only to the appropriate nonenzymatic reactivity but also to the remarkable “off” state of the intact probe. Thus, it is high time to review the fluorescence quenching mechanism. As not merely **NI3** but all the other intact NI-series probes showed well-quenched fluorescence (Figure S5), the nitro group was considered to bring about this property, and thus, **NI9** was selected as the representative subjected to the subsequent exploration. We used femtosecond transient absorption (TA) spectroscopy to monitor spectral changes induced by excitation at 370 nm. Almost the moment the
pump light was administrated (<120 fs), a photoinduced absorption band centered at around 484 nm was observed (Figures 7(a) and 7(b)), which is attributed to the formation of the locally excited (LE) state. Subsequently, the absorption of the LE state decreased gradually, accompanied by the emergence of a new absorption band centered at around 429 nm, indicative of the formation of a new state. It is remarkable that the timescales of the decay of the LE state...
and the formation of the new state are both 1 ps according to their respective fits, suggesting the new state was derived from the LE state, which caused the fluorescence quenching.

To elucidate this phenomenon and gain more insight, calculations on the electronic transitions of NI9 and NI were implemented based on the TD-DFT method. As shown in

Figure 6: Two-photon confocal fluorescence imaging of mouse (a, b) liver and (c, d) lung tissue sections incubated with or without 40 μM NI3 at a depth of 60 μm with a 60x objective. Scale bar = 40 μm. λ_{ex} = 810 nm. λ_{em} = 520–560 nm.

Figure 7: Experimental and theoretical studies on the fluorescence quenching mechanism. (a) Pseudocolor femtosecond transient absorption (TA) spectral plot of NI9 in DMSO. (b) Kinetic traces at different wavelengths following the 370 nm laser pulse excitation and the respective fit with three exponential functions. (c) TD-DFT calculations on the electronic transitions of NI9 and NI in DMSO at the B3LYP/aug-cc-pVDZ level.
Table S9, for NI9, a small oscillator strength of $S_0 \rightarrow S_1$ transition ($f = 0.009$) suggests a forbidden transition, demonstrating the $S_1$ state of NI9 is not accessible directly from the $S_0$ state. However, it might be populated via internal conversion from the $S_2$ state, which arises from a considerable oscillator strength of $S_0 \rightarrow S_2$ transition ($f = 0.382$). This result is corroborated by the agreement between experimental (360 nm) and calculated (356 nm) maximum absorption wavelengths. The $S_0 \rightarrow S_2$ transition is dominated by the transition of HOMO to LUMO+1, both of which are located on the NI moiety, exhibiting a LE characteristic; the $S_0 \rightarrow S_1$ transition is dominated by the transition of HOMO to LUMO, the latter being located on the nitrobenzene moiety, exhibiting a charge-transfer (CT) characteristic (Figure 7(c), left). Hence, a donor-excited photoinduced electron transfer (d-PET) process occurred from the NI moiety to the nitrobenzene moiety upon excitation owing to the driven force derived from the energy (~2.7 and ~3.1 eV for LUMO+1 and LUMO, respectively) gap, quenching the fluorescence, and the new state formed in Figures 7(a) and 7(b) corresponds to NI9’s $S_1$ state, a dark state, also known as the CT state. To our knowledge, this is the first time the actual PET process of NI-based probes has been observed experimentally. As a comparison, for NI, the maximum oscillator strength appears in $S_0 \rightarrow S_1$ transition ($f = 0.200$), which is mainly contributed by the transition of HOMO to LUMO (Table S9). With both molecular orbitals settled on the NI moiety and no other state between $S_0$ and $S_1$ (LE state), its fluorescence shines out unrestrictedly (Figure 7(c), right), ensuring the excellent applications in bioimaging with NI-based probes. Taken together, the existence of a nitro group in the intact probe induces a d-PET process caging the fluorescence, avoiding a background noise arising from the probe itself.

3. Discussion

Finely turning down the nonenzymatic reactivity with GSH plays a pivotal role in reducing the background noise of a GST detection probe while maintaining a considerable sensitivity. We have adopted and established the local electrophilicity index $\omega_k$ as efficient to characterize this reactivity and thus developed a rational semiquantitative strategy to design a two-photon fluorescent probe for GSTs with high sensitivity and S/N ratio by evaluating its $\omega_k$. In this way, NI3 has been selected, and both examinations in vitro and bioimaging in live cells or tissue sections verify its outstanding performances, demonstrating the feasibility of this strategy. Moreover, besides the modestly lower $\omega_k$, the success of achieving a low background noise depends on the caged fluorescence of intact probes by PET mechanism as well, which is observed for the first time by femtosecond TA spectra for NI-based probes, and a theoretical study based on TD-DFT calculations has explained how PET, and thus, fluorescence quenching happens.

In summary, this work highlights the start of introducing a parameter from CDFT to GST probe design. Theoretically speaking, the $\omega_k$ adopted here is not only limited to GST probe design but can be widely used for any probes based on $S_0$–Ar reactions between soft nucleophile and soft electrophile. Overall, we anticipate our strategy will inspire more high-performance probes like NI3 to be applied to biomedical research in the future.

Data Availability

All data needed to evaluate the conclusions in the paper are present in the paper and/or the Supplementary Materials. Any additional datasets, analysis details, and material recipes are available upon request.

Conflicts of Interest

The authors declare no conflicts of interest.

Authors’ Contributions

X. X. Zhang wrote the manuscript. H. Qi performed the biological experiments. X. X. Zhang and M. H. Lu conducted the computational work. S. Q. Yang and P. Li contributed materials/analysis tools. K. L. Han and H. L. Piao planned and initiated the project, designed experiments, and supervised the entire project. Xue-Xiang Zhang and Huan Qi contributed equally to this work.

Acknowledgments

This paper is dedicated to the 70th anniversary of the Dalian Institute of Chemical Physics, Chinese Academy of Sciences. The authors thank Pramod Pandey for meritorious suggestions on exploring the cause of problems in analytical chemistry, Han Liao for constructive advice on biochemistry, Run-Ze Liu for theoretical guidance, Qi-Chao Yao for preparation of tissue slices, Ning-Jiu Zhao for guidance on TA experiment, and Guang-Hua Ren for dedicated review of the manuscript. This work was supported by the Scientific Instrument Developing Project of the Chinese Academy of Sciences (Grant No. YJKYYQ20190003), the Liao Ning Revitalization Talents Program (XLYC1802126), the Dalian City Foundation for Science and Technology Innovation (2019J12GX031), and the National Natural Science Foundation of China (Grant Nos. 21673237 and 21503224).

Supplementary Materials

Detailed experimental and computational methods, material preparations, characterizations, fluorescence imaging videos, and supplementary figures and tables are available in Supplementary Materials. (Supplementary Materials)

References


tissues during photodynamic therapy,” *Chemical Communications*, vol. 52, no. 83, pp. 12330–12333, 2016.


