Selective photosensitization through an AND logic response: optimization of the pH and glutathione response of activatable photosensitizers†

Sundus Erbas-Cakmak,‡ Fatma Pir Cakmak,⁎ SEDA DEMIREL TOPEL,‡ Taha Bilal Uyar and Engin U. Akkaya⁎

A series of pH and GSH responsive photosensitizers were designed and synthesized. pHN values were optimized by adjusting the inductive contribution of substituents to reach a pH range (6.0–7.4) relevant to the tumour microenvironment. pH-Activatable behaviour and redox mediated release of the quencher from the PS by GSH allow the construction of an AND logic operator for selective photodynamic action in aqueous solutions.

The research in molecular logic gates, which was initiated by the seminal work by de Silva,1 blossomed in the two decades that followed.2 In addition, the limitations and the potential of this approach has become more clear. A particularly promising application of molecular logic gates may be in the field of information processing therapeutic agents. Incorporation of Boolean logic ideas in the function of therapeutic agents would be very valuable, if the same results cannot be achieved by random optimization studies. Previously, our group and others provided the early examples of the work in that direction.3 Our first proof of principle work which linked photodynamic sensitization of a Bodipy based photosensitizer (PS) to the concentrations of sodium ions and the acidity was essentially an AND logic gate, but the system required organic solvents and organic acid to function in the desired manner. While it was considered to be noteworthy for that approach to have practical potential, an AND logic gate based enhanced selectivity should be related to cancer related biological parameters, which can generate significant changes in the photophysical character of the sensitizer in aqueous solutions.

In this work, we took advantage of two characteristics of the tumour microenvironment, lower pH and higher glutathione concentrations. The difference in pH between cancer tissue and healthy tissue is an easily accessible parameter for use in therapeutic activation. A number of pH-responsive polymeric materials, photosensitizers, and nanocarriers were studied to control drug release or activation.5 However, extracellular pH of tumor cells drops to a value not below 6.0.6 Thus, it is challenging to find a smart therapeutic system responsive to pH within the narrow near neutral range and essentially become active at around pH 6.0–6.5 and stay inactive above pH 7.0. Apart from some,7 most related studies in the literature depend on activation at pH below 5.5, which actually requires nonselective lysosomal activation.8 In this work, the properties of the PS are optimized for pH activatability by causing rational chemical modification on the pH responsive moiety with electron donating or withdrawing groups to adjust the pHN to the desired near-neutral value and to get enough spectral shift in acidic aqueous solutions such that protonated PSs are exclusively excited species under the conditions of interest. Thus, the overall design (Scheme 1) involves a pH responsive unit, linked to a quencher, which could be cleaved at elevated GSH concentrations.

Previously, GSH has been used as a PS activator mostly through the cleavage of a disulfide bond9 or through reactions with a dinitrophenyloxy-tethered moiety.10 We used redox mediated cleavage of a disulfide bond with GSH as an additional mode of activation of the photosensitizer, and attached an electronic energy acceptor module to PS, via a disulfide bridge to quench the ¹O₂ production, thus constructing an AND

Scheme 1 Schematic representation of PS activation by acid and GSH. Protonation causes a spectral shift at near neutral pH to enhance PS excitation by light of a specific wavelength, whereas GSH liberates PS from the quencher module by reductive cleavage of the disulfide linker.

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‡ UNAM-National Nanotechnology Research Center, Bilkent University, Ankara, TR-06800, Turkey. E-mail: rsva@fen.bilkent.edu.tr

⁎ Department of Chemistry, Bilkent University, Ankara, TR-06800, Turkey

Akdeniz University, Department of Chemistry, Antalya, TR-07058, Turkey

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molecular logic gate on the PS activation with the other input being acid (Scheme 1).

For both PS and quencher modules, Bodipy derivatives are chosen, since fine-tuning the spectral properties and analyte responsiveness of these Bodipy dyes are straightforward as a result of their versatile chemistry.11

A spectral shift at the wavelength of excitation upon protocation would be ideal for the photosensitizer to be reversibly activated only under the acidic conditions, as we have previously demonstrated.12 In order to optimize the pKₐ values, a series of water soluble PSs have been synthesized. The structures of the compounds are given in Scheme 2, the complete chemical structures can be found in the ESI.†

In order to impart GSH responsiveness, a near-IR absorbing energy acceptor Bodipy dye with an appropriate spectral character for EET is attached to the PS through a bioreducible disulfide linker (Scheme 3, black module). To provide relatively milder reaction conditions, the quenching module and the PS are attached to one another through a disulfide bridge using copper catalysed Huisgen 1,3-dipolar cycloaddition. The Bodipy dye which was employed as an energy sink, was prepared by the Sonogashira coupling at 2,6-positions followed by Knoevenagel condensation.

Water soluble distyryl-BODIPY was synthesized through condensation with appropriate aldehydes (e.g., with 4-pyridine-carboxaldehyde for compound 1). The pKₐ value for 1 was determined to be 3.42 with a protonation-induced bathochromic shift from 594 nm to 615 nm (Table S1 and Fig. S1, ESI†). In addition to an insufficient spectral shift, compound 1 is not basic enough to be protonated in target biological media.

A list of spectral shifts (on protonation) for all compounds and the summary of the data obtained with calculated pKₐ values are given in Fig. S1 and Table S1 (ESI†). Since the desired pH-responsive behaviour cannot be reached with pyridine or quinolone derivatives we turned our attention to phenolic groups. In the literature, monostyryl-Bodipy with a 3-chloro-4-hydroxyphenyl substituent was reported to have a pKₐ of 7.6.13 As a final attempt, with the same strategy to adjust pKₐ through changing inductive/resonance effects, another variation of this phenolic substituent with a stronger electron withdrawing group was targeted with an expectation of decreased pKₐ. Compound 5, BOD 1 and PS with a nitro group in place of chloro are synthesized with these considerations (Scheme 1 and Scheme S1, ESI†).

PS is the non-water soluble module of the photosensitizer part of BOD 1, the exact chemical structure of which is given in the ESI† (Scheme S1, the green-blue module in Scheme 2). The pH response of PS is investigated within a micelle in aqueous solutions, since this compound and the final AND logic gate construct is not soluble in water. Fortunately, in accordance with our expectations, the compound was determined to have a pKₐ of 6.92 in Cremophor EL micelles, with a very large spectral change (+81 nm) in absorbance from 649 nm to 730 nm as a result of deprotonation (Fig. 1 and Fig. S2, ESI†). The spectral data clearly show that, at the wavelength of light used for PDT measurements (625 nm, indicated with a blue dashed line in Fig. S2, ESI†), deprotonated compounds have substantially decreased absorbance at the selected wavelength of excitation (625 nm), which ensures selective activation of the PDT agent only in acidic solutions.

In order to investigate if the pH response is preserved in the non-micellar system, a water soluble version (compound 5) is made and titrated in 40% THF in water. The pKₐ was determined to be 6.62 (Table S1, ESI†). 0.30 unit difference may result from the fact that a relatively more hydrophobic microenvironment within the micelle may alter the deprotonation due to the fact that the charged species cannot solvate easily in the micelle microenvironment. The absorption spectrum of a deprotonated compound is essentially the same as it is in
micelles, except the minor broadening of the peaks. The absorption spectra of these two compounds are given in Fig. 1, Fig. S2, S4 and Table S2 (ESI†). With the promising pKa value obtained, the pH dependent component of the molecular AND logic gate is built with distyryl-BODIPYs generated through Knoevenagel condensation reaction with 4-hydroxy-3-nitrobenzaldehyde (Scheme 3).

The electronic absorption spectrum of micellar BOD 1 in water is given in Fig. S5a (ESI†). Two peaks corresponding to two chromophore modules converge to give an essentially single peak at a higher wavelength upon deprotonation, since PS shows a bathochromatic shift under the conditions applied, whereas the quencher module remains the same. For equal concentrations of compounds PS and BOD 1, emission spectra show a decrease in the emission of the photosensitizer part of BOD 1 compared to the free photosensitizer PS, which is an indication of energy transfer (Fig. S5b, ESI†). Since the deprotonated form of free PS is non-emissive, the same spectral analysis cannot be performed for this form. The cleavage of the disulfide bond is analyzed by incubating the micellar BOD 1 for 12 hours at room temperature with 2.5 equivalents of GSH and comparing it with the GSH-free BOD 1 both via spectroscopic analysis and High Resolution Mass Spectra (HRMS). The thiol form, GSH-conjugate of the free photosensitizer and both reduced and disulfide forms of the quencher are detected by HRMS after 12 h of incubation (Fig. S6, ESI†).

After resolving the reduction of the disulfide linker by GSH through HRMS analysis, spectral examination was also performed to demonstrate excitation energy transfer (EET). Since the EET efficiency is expected to decrease upon release of the energy donor part, the emission of this part is predicted to increase. An increase in emission of the PS part is clearly observed in fluorescence spectra after GSH treatment (Fig. S7, ESI†), which indicates that the EET is less effective in the free form.

O2 generation experiments were performed using a water soluble O2 trap (ESI†) and a decrease in the absorption at 378 nm was followed as a measure of the O2 production rate. First, to show that the trap molecule does not decompose in the absence of a photosensitizer, control experiments under dark and 625 nm irradiation were performed under similar conditions using PS-free solutions. The trap is stable under experimental conditions (Fig. S9, ESI†). On the other hand, the photosensitizer free from the quencher shows a greater extent of O2 generation in the presence of slightly acidic media, Fig. 2. Although BOD 1 produces O2 to some extent in the absence of GSH, still this is less efficient compared to free PS. The results are depicted as relative initial O2 generation rate in Fig. 3 as determined by percent decrease of trap absorption at 378 nm for each experimental condition. The threshold value of O2 generation efficiency for the AND logic gate was set as 0.30 and 0.55 for initial 5 min irradiation and 1 h irradiation respectively. Thus, the PS produces O2 only in the presence of both inputs, acid and GSH.

In this work, a viable alternative for enhanced selectivity for photodynamic action was provided. The designed PS is responsive to acidity comparably found in the tumor regions and higher GSH. The acid induced change in the absorption of the PS allows an increase of the extinction coefficient at the wavelength of excitation and thus prepares it for activation. However, an energy acceptor conjugated to the PS via a reducible disulfide bond still quenches the excited state through energy transfer. Singlet oxygen generation activity of the PS was thus shown to be significantly enhanced only when both cancer
related inputs are available at above threshold values. Such 
AND logic constructs based on cancer related parameters as inputs 
should be expected to yield more selective therapeutic agents.

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