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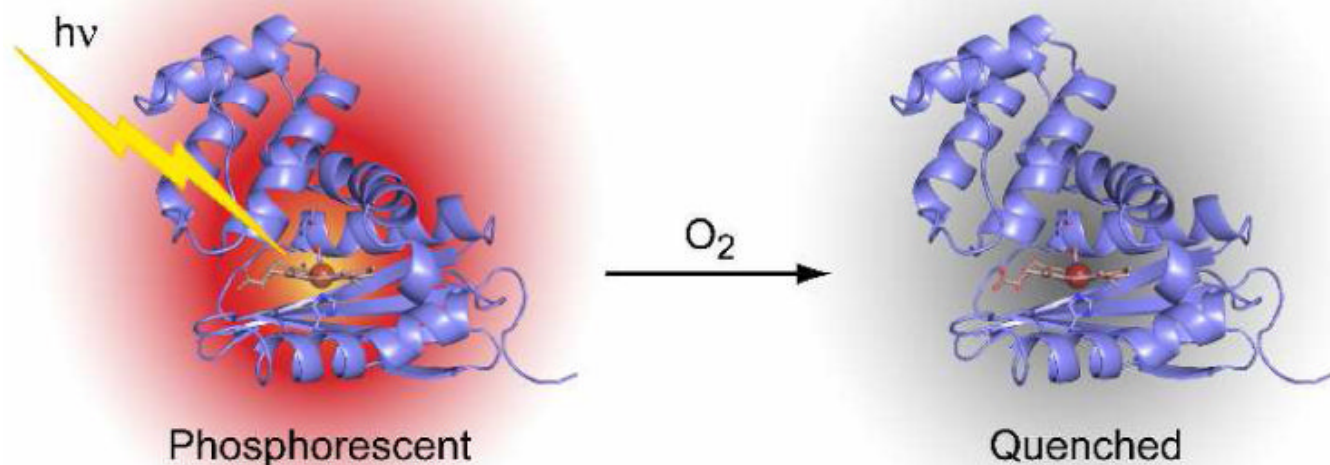
Ru-Porphyrin Protein Scaffolds for Sensing O₂

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Abstract



Hemoprotein-based scaffolds containing phosphorescent ruthenium(II) CO mesoporphyrin IX (RuMP) are reported here for oxygen (O₂) sensing in biological contexts. RuMP was incorporated into the protein scaffolds during protein expression utilizing a novel method that we have described previously. A high-resolution (2.00 Å) crystal structure revealed that the unnatural porphyrin binds to the proteins in a manner similar to the native heme and does not perturb the protein fold. The protein scaffolds were found to provide unique coordination environments for RuMP and modulate the porphyrin emission properties. Emission lifetime measurements

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Supporting Information Available: Synthetic details, porphyrin stoichiometry, further photophysical characterization of the RuMP proteins, structural alignments, and x-ray diffraction data.

demonstrate a linear O₂ response within the physiological range and precision comparable to commercial O₂ sensors. The RuMP proteins are robust, readily-modifiable platforms and display promising O₂ sensing properties for future *in vivo* applications.

Proteins that natively bind heme are under-utilized scaffolds for porphyrin-based tools in biology.^{1,2} Porphyrins have broad applications, ranging from dyes in solar cells³ to sensitizers for radiotherapy⁴ to frameworks for catalysis.⁵ Traditional methods for unnatural porphyrin incorporation into hemoproteins have limited their utility as biological tools. Harsh, denaturing conditions are typically required to remove native heme from proteins,^{6,7} dramatically decreasing the number of viable protein constructs. We recently reported a novel method for incorporation of unnatural porphyrins into hemoproteins during protein expression.⁸ Here we demonstrate the versatility of this expression-based method through the development of protein-based sensors, in which the native heme cofactor of different hemoprotein scaffolds has been substituted with an unnatural porphyrin for oxygen (O₂) sensing within biological contexts.

O₂ is a key metabolic indicator for profiling the physiology of tissues and cells.⁹ Quenching of small molecule luminescence by O₂ is a simple, non-invasive method for imaging *in vivo* O₂ levels.¹⁰ However, the utility of small molecules for this application is hampered by lack of targetable delivery, non-specific binding, self-aggregation, and limitations in photophysical properties.^{11,12} Incorporation of luminescent porphyrins into hemoprotein scaffolds provides a novel platform to address these issues.

Ruthenium(II) CO mesoporphyrin IX (RuMP) (Figure S1) is an ideal cofactor for protein-based sensors because it exhibits O₂-sensitive phosphorescence¹³ and presents a proximal axial ligation site¹⁴ to facilitate binding to the protein scaffold. Myoglobin (Mb) and the H-NOX (Heme Nitric oxide / OXygen binding) domain from the thermophilic bacterium *Thermoanaerobacter tengcongensis* (*Tt* H-NOX) are robust proteins for RuMP sensors, as they can be readily modified with genetically-encoded affinity tags and site-directed mutagenesis.^{1,15} In addition, *Tt* H-NOX is stable under extreme temperatures (>70 °C).¹⁵

Experimental details for preparation and characterization of RuMP-substituted Mb (Ru Mb) and *Tt* H-NOX (Ru *Tt* H-NOX) are described in Supporting Information. Briefly, RuMP was synthesized in a manner similar to published methods¹⁴ and incorporated into Mb and *Tt* H-NOX during anaerobic protein expression. The RuMP-substituted proteins were isolated containing a stoichiometric amount of porphyrin (Table S1). Indeed, further evaluation of the stability of Ru *Tt* H-NOX indicated no detectible porphyrin loss for >24 hours under biological conditions (mouse plasma at 37 °C, Figure S2).

Purified Ru *Tt* H-NOX was crystallized to verify proper porphyrin insertion and preservation of the protein fold. The high-resolution (2.00 Å) structure of Ru *Tt* H-NOX (Figure 1, Table S2) is the first crystal structure of a Ru porphyrin bound to a protein and demonstrates that the unnatural porphyrin maintains key contacts with surrounding heme pocket residues. These contacts include coordination of the proximal histidine to Ru and hydrogen bonding between the distal porphyrin ligand and a tyrosine residue (Figure 1, Figure S3). In fact, comparison of heme-bound *Tt* H-NOX with its Ru analogue indicates little perturbation of the protein fold (overall rmsd 1.3 Å, Figure S4).

Steady-state and time-resolved spectroscopies were employed to examine the spectral properties of RuMP bound to the protein scaffolds. UV-visible spectra for Ru *Tt* H-NOX and Ru Mb show similar Soret band features at 400 nm and 397 nm, respectively (Figure 2, Table 1). However, the α band at ~550 nm for Ru Mb is split, as observed previously.¹⁴ Steady-state emission spectra reveal a blue-shifted emission band and decreased emission

quantum yield for Ru Mb as compared to Ru *Tt* H-NOX (Table 1). Time-resolved emission spectroscopy conducted to further probe the spectral features of the porphyrin-protein complexes yielded single-exponential emission decays (following 550 nm laser excitation) under anaerobic conditions that vary widely between the two proteins ($\tau_0 = 7.7 \mu\text{s}$ for Ru *Tt* H-NOX vs. $37.3 \mu\text{s}$ for Ru Mb, respectively). Taken together, these data indicate a substantially different conformation and/or chemical environment for RuMP in Mb and *Tt* H-NOX. Indeed, the crystal structure of Mb reveals that the heme is partially exposed to solvent,¹ whereas the heme in *Tt* H-NOX is buried within the protein matrix (Figure 1).

The ability of phosphorescent molecules to sense O₂ is determined by the degree of emission quenching in the presence of O₂. Comparison of the steady-state emission spectra of Ru *Tt* H-NOX and Ru Mb measured under aerobic and anaerobic conditions reveals that O₂ appreciably quenches the emission of both proteins (Figure 2). To further evaluate the highly stable Ru *Tt* H-NOX protein as an O₂ sensor, its excited state lifetime was measured at several O₂ concentrations (Figure 3). The data were analyzed according to the Stern-Volmer (SV) equation for O₂ quenching (Supporting Information) and yielded a bimolecular quenching constant, k_q , of $1350 \text{ mmHg}^{-1}\text{s}^{-1}$ ($8.2 \times 10^8 \text{ M}^{-1}\text{s}^{-1}$). In addition to intrinsic emission properties, the precision of lifetime-based O₂ sensors is governed by the instrument error associated with the lifetime measurement. Taking our instrument error of 2.5% into account, Ru *Tt* H-NOX can be used to determine O₂ concentrations to within $\pm 2.5 \text{ mmHg}$ ($4.2 \mu\text{M}$) in spite of its low quantum yield. This precision is comparable to that reported for commercial O₂ sensors (Table 2) and is ideally suited for determining O₂ concentrations in biology. Indeed, emission quenching was observed to be linear across the biologically relevant range of O₂ concentrations (Figure 3).⁹

The RuMP proteins described here represent a new class of sensors for detection of dissolved O₂. The sensors are readily expressed in *E. coli*, exceptionally robust, and able to detect O₂ levels in the biologically relevant range. The photophysical properties may be further modulated with the choice of emissive porphyrin or through modification of the protein scaffold (e.g. via site-directed mutagenesis). In addition, the proteins may be expressed with genetically-encoded tags for targeted delivery in biology and derivatized for enhancing biocompatibility. We anticipate that this new class of sensors will prove useful for monitoring O₂ levels in biological contexts. One area of particular interest for sensing O₂ is in tumor microenvironments wherein detailed knowledge of local O₂ concentrations is key to improving cancer diagnosis and treatment.⁹

Supplementary Material

Refer to Web version on PubMed Central for supplementary material.

Acknowledgments

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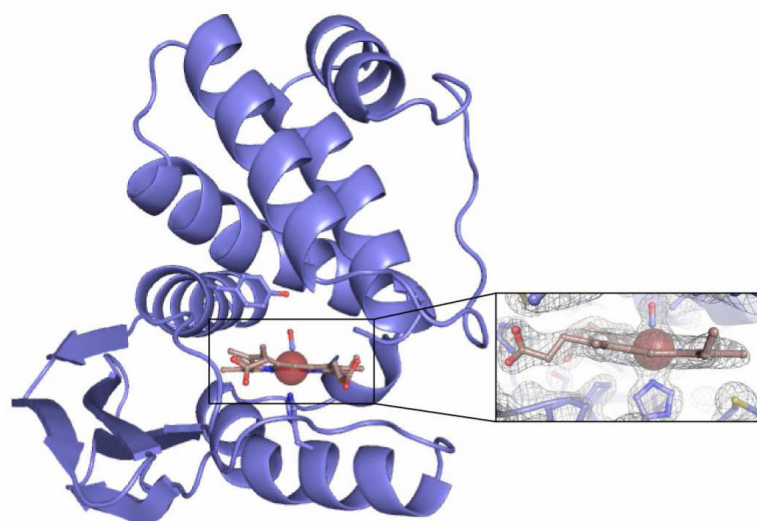


Figure 1. Crystal structure of *Tt* H-NOX containing RuMP solved at 2.00 Å resolution. Inset: $2(F_o - F_c)$ electron density map calculated by omitting RuMP and the proximal histidine side chain.

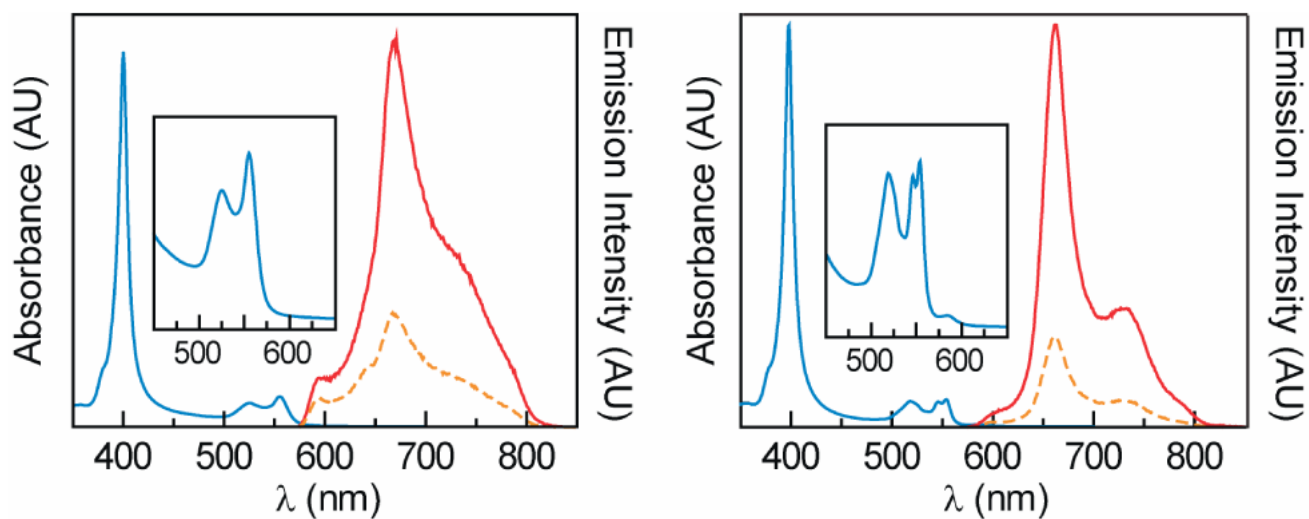


Figure 2. Steady-state absorbance (—) and emission spectra of Ru Tt H-NOX (left) and Ru Mb (right) in aqueous HEPES/NaCl buffer. Emission spectra were acquired following excitation at 550 nm in the presence (----, 256 μ M) and absence (—) of O₂.

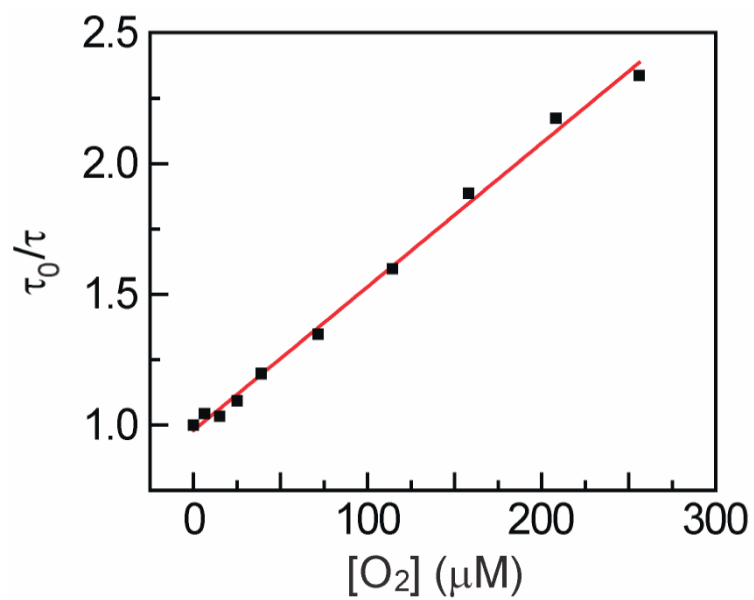


Figure 3. Stern-Volmer plot of the excited state lifetime of Ru Tt H-NOX vs. $[O_2]$ showing linear phosphorescence quenching by O_2 from 0 to 256 μM O_2 ($R^2 = 0.9957$).

Table 1

Spectroscopic and photophysical properties of Ru proteins

Ru Protein	λ_{abs} (nm) / (ϵ)	λ_{em}^a (nm)	Φ_{em}^c	τ_{em}^d (μs)
Tr H-NOX	400 (173)	668	1.7×10^{-4}	7.7 ($-\text{O}_2$)
	524 (10.7)	$\sim 734^b$		2.9 ($+\text{O}_2$)
	555 (13.9)			
Mb	397 (197)	663	4.8×10^{-5}	37.3 ($-\text{O}_2$)
	518 (12.2)	$\sim 733^b$		12.2 ($+\text{O}_2$)
	553 (13.2)			

^a $\lambda_{\text{ex}} = 550$ nm.

^b shoulder.

^c $\lambda_{\text{ex}} = 550$ nm, no O_2 .

^d $\lambda_{\text{ex}} = 550$ nm, $\lambda_{\text{det}} = 640$ nm, no O_2 and 256 μM O_2 .

Table 2Comparison of Ru *Tt* H-NOX with select O₂ sensors

Complex	k_q (mmHg ⁻¹ s ⁻¹)	τ_0 (μ s)	Precision ^a (mmHg)	Ref.
Ru <i>Tt</i> H-NOX	1350	7.7	5.0	<i>this work</i>
Ru ^{II} (bpy) ₃ ²⁺	4300	0.58	21	16
Oxyphor	293	707	0.25	17
PtP-C343	150	60	5.9	12

^aDetermined assuming an error of 2.5% in τ_0 measurement