

Unnatural Amino Acid Substitution as a Probe of the Allosteric Coupling Pathway in a Mycobacterial Cu(I) Sensor

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Elucidation of structural and dynamical pathways of communication or coupling between ligand binding sites, that is, classical allostery, is of topical interest and fundamental importance in biological regulation,^{1–3} but remains a challenge to detect and quantify.^{4–6} Metalloregulatory proteins are specialized allosteric proteins that control the intracellular availability of essential transition metal ions by binding a specific metal, which in turn activates or inhibits operator DNA binding, thus programming a defined transcriptional output.^{7,8} In this study, we target the “second coordination shell” of the Cu(I) sensor *Mycobacterium tuberculosis* CsoR and successfully abrogate allosteric coupling of Cu(I) and DNA binding.

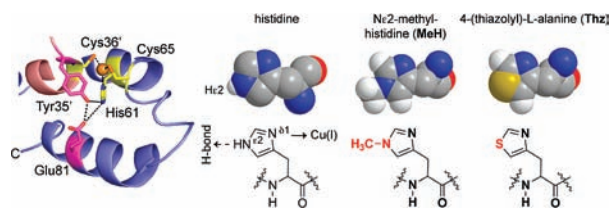


Figure 1. Structure around the Cu(I) binding region of the *Mtb* CsoR dimer interface (protomers shaded slate and salmon)⁹ and space filling and chemical structures of histidine, Nε2-methyl-histidine (MeH) and 4-(thiazolyl)-L-alanine (Thz) used in this study. Note the Nδ1 nitrogen of His61 forms a Cu(I)–N coordination bond while the Nε2 face is within hydrogen bonding distance of Y35' (salmon protomer) and E81.

Mtb CsoR is a Cu(I) regulatory protein distantly related to the Ni(II)/Co(II) sensor *Escherichia coli* RcnR,¹⁰ in which Cu(I)-binding allosterically decreases operator DNA binding affinity. This leads to transcriptional derepression of the copper-sensitive operon (*cso*) in response to Cu(I) stress.⁹ The Cu(I) ion in CsoR occupies a pocket at the protomer interface, where the Sγ atoms of Cys36' and Cys65, and the Nδ1 atom of His61 form a trigonal coordination complex (Figure 1).⁹ The structure further reveals that the Nε2 face of His61 points toward the side chains of two conserved “second coordination shell” residues, Tyr35 and Glu81 (Figure 1). This structure suggests that Tyr35, Glu81, and His61 form a hydrogen bonding network that stabilizes the allosterically inhibited Cu(I) bound state.^{9,11} Substitution of the Cu(I) ligand His61 with Ala changes the Cu(I) coordination number from three to two, resulting in a linear *bis*-thiolato Cu(I) complex.⁹ This substitution also greatly reduces the *cso* operator binding affinity by $\geq 10\,000$ -fold to undetectable levels, despite adopting a folded, α -helical tetrameric assembly state (Figure S1, Supporting Information). Thus, His61

is a multifunctional residue, the distinct physicochemical roles of which cannot be directly probed by conventional mutagenesis.⁹ We therefore employed native chemical ligation to perform an “atom” substitution of His61 by replacement with Nε2-methyl-histidine (MeH) or 4-(thiazolyl)-L-alanine (Thz) to directly test this allosteric coupling model (Figure 1). Both substitutions are expected to preserve the Cu(I) coordination and DNA binding properties of His61 while blocking the ability of the opposite face of His61 to donate hydrogen bonds to Tyr35' and/or Glu81.

The Cu(I) binding affinity ($\log K_{Cu}$) of wild-type *Mtb* CsoR was determined to be 18.0 (± 0.2) from both a conventional titration of Cu(I) into a mixture of CsoR and BCS (Figure S2, Supporting Information), as well as an assay that employs varying BCS concentrations, rather than Cu(I) concentrations (Table 1 and Supplementary Methods).^{9,12,13} The coupling free energy (ΔG_c) was obtained from the ratio of the macroscopic CsoR DNA binding affinities in the presence (A_2^{Cu}) and absence (A_2^{apo}) of bound Cu(I) measured by fluorescence anisotropy⁷ (Supporting Methods and Figures S3–S5, Supporting Information). Cu(I) binding to wild-type CsoR significantly decreases the *cso* operator DNA binding affinity, resulting in a ΔG_c of +3.6 (± 0.2) kcal/mol (pH 7.0, 0.2 M NaCl, 2 mM DTT, 25 °C) (Table 1), with no effect on the assembly state of the CsoR tetramer.¹³

Table 1. Cu(I) Affinities and Allosteric Coupling Free Energies for Various *Mtb* CsoRs^a

<i>Mtb</i> CsoR	$\log K_{Cu}^b$	ΔG_c (kcal/mol) ^d
Wild-type	18.0 (± 0.2)	3.6 (± 0.2)
WT 1–106	17.3 (± 0.4)	3.0 (± 0.3)
L58C 1–106	17.3 (± 0.3)	3.0 (± 0.4)
H61MeH	18.4 (± 0.2)	0 (± 0.4)
H61Thz	16.7 (± 0.1)	0.5 (± 0.2)
H61A	14.5 (± 0.3)	n.d. ^e
E81A	14.9 (± 0.4) ^c	
E81Q	17.7 (± 0.4)	0.6 (± 0.3)
E81D	17.6 (± 0.5)	1.9 (± 0.3)
E81I	17.8 (± 0.4)	1.5 (± 0.3)
E81N	17.3 (± 0.4)	1.6 (± 0.4)
Y35F	16.7 (± 0.4)	2.4 (± 0.2)
Y35F/E81Q	17.6 (± 0.3)	0.8 (± 0.3) ^f

^a Conditions: 10 mM HEPES, 0.2 M NaCl, pH 7.0, 25 °C, with 2 mM DTT present only in the DNA binding experiments. ^b Determined by competition with the chromophoric complex Cu^I(BCS)₂ ($\log \beta_2 = 19.8$) or ^c Cu^I(BCA)₂ ($\log \beta_2 = 17.2$) as described in Supplementary Methods (Supporting Information). ^d Determined using fluorescence anisotropy-based titrations like those shown in Figure S5 (Supporting Information), with detailed fitting parameters compiled in Table S1 (Supporting Information). ^e n.d., not detected, $A_2 \leq 10^{10} M^{-1}$ under these conditions. ^f $\delta = \Delta \Delta G_c^{Y35F/E81Q} - (\Delta \Delta G_c^{Y35F} + \Delta \Delta G_c^{E81Q}) = +0.1$ kcal/mol where $\Delta \Delta G_c^{mutant} = \Delta G_c^{mutant} - \Delta G_c^{WT}$.

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A semisynthetic route using an intein fusion strategy was used to introduce MeH and Thz analogs of His61 (Figure 1 and Supplementary Methods, Supporting Information). To increase the efficiency of such a strategy, L58C CsoR 1–106 was chosen as the parent molecule to incorporate both H61MeH and H61Thz substitutions by chemical ligation, since it showed no significant differences from wild-type CsoR in Cu(I) binding affinity (Table 1), Cu(I) coordination geometry (Figure 2 and Table S2, Supporting Information), DNA binding affinity and negative allosteric regulation by Cu(I) (Table 1 and Figure S5, Supporting Information). The integrity of the resulting H61MeH and H61Thz *Mtb* CsoRs was confirmed by trypsin digestion and tandem LC–MS/MS sequencing (Figure S6, Supporting Information).

Both H61MeH and H61Thz *Mtb* CsoRs bind Cu(I) with an affinity comparable to the parent L58C CsoR 1–106 ($\log K_{\text{Cu}} = 17.3$) (Table 1) and 100–1000-fold higher affinity than that of H61A CsoR, which forms a digonal S_2 complex.⁹ This suggests that H61MeH and H61Thz CsoRs form trigonal coordination complexes with Cu(I), a result confirmed by the Cu(I) near-edge region of the X-ray absorption spectrum (Figure 2, Table S2 and Figure S7, Supporting Information). Quantitative analysis of the EXAFS spectrum of H61MeH CsoR reveals a coordination geometry that is identical to wild-type CsoR (Table S2, Supporting Information).⁹ Both H61MeH and H61Thz CsoRs bind the *cso* operator with near wild-type affinity in their apo-forms which reveals the semisynthetic proteins are folded correctly and likely form stable tetramers (Figure S5 and Table S1, Supporting Information).¹³ Strikingly, the DNA binding affinities of both H61MeH and H61Thz CsoRs are not strongly regulated by Cu(I), with $\Delta G_c = 0 (\pm 0.4)$ and $0.5 (\pm 0.2)$ kcal mol⁻¹, respectively (Table 1). These findings clearly establish that the N ϵ 2 face of His61 is specifically required to link thermodynamically and functionally Cu(I) binding to DNA binding, with no significant influence on the magnitude of the Cu(I) binding affinity or coordination geometry.

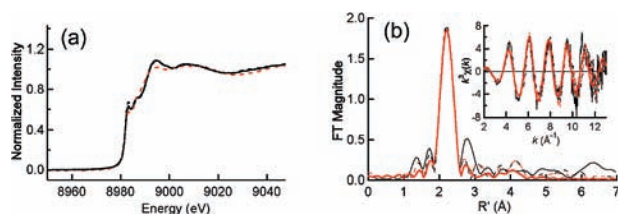


Figure 2. Cu X-ray absorption edge (a), EXAFS (b, inset), and FT (b; $k = 2\text{--}13 \text{ \AA}^{-1}$, k^3 weighting) for WT 1–106 (black dashed), L58C (black solid), and H61MeH (red dashed) CsoRs. The best fit of H61MeH CsoR based on a $\text{CuS}_2(\text{imid})_1$ model is shown in bold red in (b). Fitting parameters are compiled in Table S2, Supporting Information.

To further test this structural linkage model (Figure 1), we targeted the other “second coordination shell” residues, Tyr35 and Glu81, using conventional site-directed mutagenesis. Y35F and all E81 mutant CsoRs retained wild-type Cu(I) binding affinity and trigonal S_2N Cu(I) coordination geometries by X-ray absorption spectroscopy (Table 1, Table S3 and Figure S8, Supporting Information). Y35F CsoR is characterized by a 33% decrease in ΔG_c , while *cso* operator DNA binding by E81A CsoR is nearly refractory to Cu(I) regulation ($\Delta G_c = 0.6 \text{ kcal mol}^{-1}$) (Table 1 and Figure S9, Supporting Information). More conservative substitutions of Glu81, that is, with Gln, Asp, or Asn, also give rise to

significant decreases in ΔG_c , to about 50% of wild-type CsoR, while Cu(I) binding affinities remain unaffected (Table 1). Inspection of the magnitude of ΔG_c for a double mutant, Y35F/E81Q CsoR, reveals a near additivity of ΔG_c measured for the component single mutants (Table 1). Thus, these residues play important roles, but only weakly interact energetically with one another to drive allosteric negative regulation of CsoR by Cu(I). This suggests that hydrogen bonds from Tyr35 and Glu81 to His61, and not to each other (Figure 1), are most critical for metalloregulation in this system.

We propose that the heteroaromatic character of His61 contacts the DNA in a way that does not require the N ϵ 2 atom of the imidazole ring. Cu(I) coordination to the N δ 1 atom is necessary but not sufficient to drive allosteric switching, but critically, initiates formation of a hydrogen-bonding network involving the N ϵ 2 face of the same histidine, and the side chains of Y35 and E81, that ultimately leads to dissociation of the CsoR tetramer from the DNA. It is remarkable that opposite N δ 1 and N ϵ 2 faces of a key metal coordinating histidine residue, albeit one far from the DNA binding site,¹⁴ are proposed to play exactly analogous roles in the arsenic repressor (ArsR) family zinc sensor CzcA, despite the completely unrelated protein fold and different metal that is sensed.^{14–16} This speaks to the evolutionary generality of a mechanism of allosteric regulation that exploits the unique physicochemical features of a key histidine side chain to orchestrate cellular metal homeostasis.

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Supporting Information Available: Supplementary Methods, Tables (S1–S3), and Figures (S1–S9). This material is available free of charge via the Internet at <http://pubs.acs.org>.

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