Cytosolic Ni(II) Sensor in Cyanobacterium

NICKEL DETECTION FOLLOWS NICKEL AFFINITY ACROSS FOUR FAMILIES OF METAL SENSORS

Received for publication, December 28, 2011, and in revised form, February 20, 2012. Published, JBC Papers in Press, February 22, 2012, DOI 10.1074/jbc.M111.338301

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Background: The function of CsoR/RcnR-like protein InrS was unknown.

Results: InrS and CsoR metal complexes have similar spectra, but InrS senses nickel not copper.

Conclusion: InrS detects cytosolic nickel with tighter $K_D$ than the other metal sensors of the cell.

Significance: InrS might be exploited to optimize hydrogenase Ni(II) supply, and this study shows how metal specificity can be a shared function of a set of metal sensors.

Efflux of surplus Ni(II) across the outer and inner membranes of Synechocystis PCC 6803 is mediated by the Nrs system under the control of a sensor of periplasmic Ni(II), NrsS. Here, we show that the product of ORF sll0176, which encodes a CsoR/RcnR-like protein now designated InrS (for internal nickel-responsive sensor), represses nrsD (NrsD is deduced to efflux Ni(II) across the inner membrane) from a cryptic promoter between the final two ORFs in the nrs operon. Transcripts initiated from the newly identified nrsD promoter accumulate in response to nickel or cobalt but not copper, and recombinant InrS forms specific, Ni(II)-inhibited complexes with the nrsD promoter region. Metal-dependent difference spectra of Ni(II)- and Cu(I)-InrS are similar to Cu(I)-sensing CsoR and dissimilar to Ni(II)/Co(II)-sensing RcnR, consistent with factors beyond the primary coordination sphere switching metal selectivity. Competition with chelators mag-fura-2, nitrilotriacetic acid, EDTA, and EGTA estimate $K_D$ for the tightest site of InrS as 2.05 (±1.5) × 10^{-14} M, and weaker $K_D$ Ni(II) for the cells’ metal sensors of other types: Zn(II) co-repressor Zur, Co(II) activator CoaR, and Zn(II) derepressor ZiaR. Ni(II) transfer to InrS occurs upon addition to Ni(II) forms of each other sensor. InrS binds Ni(II) sufficiently tightly to derepress Ni(II) export at concentrations below $K_D$, Ni(II) of the other sensors.

The photosynthetic machinery generates special demands for metals in cyanobacteria such as Synechocystis PCC 6803 (hereafter referred to as Synechocystis): manganese for the oxygen evolving water-splitting enzyme, 22 atoms of iron/pair of photosystems (1), copper for plastocyanin, zinc in carbonic anhydrase to liberate CO$_2$ for fixation in carboxysomes (2), as examples, and cobalt is needed for cyancobalamin (whereas higher plants contain no B$_12$-requiring enzymes) (3). Nickel is used by the bidirectional hydrogenase which can generate dihydrogen gas to remove surplus reducing potential from the light reactions of photosynthesis (4). The prospect of engineering cyanobacteria to transduce light into usable bioenergy, for example dihydrogen, has attracted attention (5). The optimization of cofactor supply for critical metalloenzymes may become important for such efforts (6, 7). There is interest in discovering and understanding the action of metal sensors from these bacteria because they modulate metal availability for metalloenzymes.

The Synechocystis genome encodes one nickel, but unstudied, representative of the CsoR/RcnR family of DNA-binding metal-responsive transcriptional regulators. CsoR and RcnR sense Cu(I), or Ni(II) and Co(II), in Mycobacterium tuberculosis and Escherichia coli, respectively (8–10). CsoR-like Cu(I) sensors have also been described in Bacillus subtilis (11, 12), Listeria monocytogenes (13), Thermus thermophilus (14), and Staphylococcus aureus (15, 16), plus a second CsoR-like Cu(I) sensor (RicR) has been discovered in Mycobacterium tuberculosis (17). S. aureus also contains a paralogue of CsoR, CstR, but this regulates inorganic sulfur metabolism in response to oxidation of its Cys residues by an intermediate in assimilatory sulfate reduction (15). One additional RcnR-like Ni(II) sensor has been characterized (NcrB) from Leptospirillum ferrophilum (18). Effort has been directed toward understanding the molecular mechanisms of metal selectivity of CsoR, RcnR, and indeed other types of DNA-binding metal-responsive transcriptional regulators. CsoR has a trinodal Cu(I) site composed of two Cys (residues XZ below) and one His (residue Y below) whereas a combination of x-ray absorption spectroscopy and mutagenesis indicates the presence of a pseudo-octahedral Ni(II) or Co(II) site in RcnR which includes the N-terminal plus one defined Cys and two (or three for Co(II)) deduced His (including residue W below) (8, 10). The allosteric mechanism of CsoR also relies on a Tyr residue (residue A below) which in Cu(I)-CsoR forms a hydrogen bond with the noncoordinating imidazole nitrogen of a Cu(I)-binding His plus a second coordination sphere Glu (residue B below) (8, 19). Together, these
residues define the WXYZ(AB) motif of CsoR/RcnR sensors (10, 20) (supplemental Fig. S1).

Cytosolic sensors of Ni(II) or of Cu(I) have not been described in Synechocystis. The carrier that shuttles electrons between the two photosystems within the thylakoid lumen undergoes a copper-dependent switch. When copper is limiting, heme iron is used in cytochrome c55, but this is replaced by copper in plastocyanin under copper sufficiency, and the switch occurs at the transcriptional level (21). Such a switch was first described in Chlamydomonas reinhardtii (22, 23) where it is controlled by Crr1 (24). The functionally equivalent cyanobacterial Cu(I) sensor remains to be discovered. Expression of the pacS gene encoding a Cu(I)-transporting P1-type ATPase that supplies copper to plastocyanin is also Cu(I)-regulated, but again the Cu(I) sensor remains to be discovered. The periplasmic Ni(II) sensor NrsS modulates the nrsBACD Ni(II) efflux operon via the DNA-binding transcriptional regulator NrsR (25, 26), but there is no known cytosolic Ni(II) sensor in Synechocystis. Moreover, when the Ni(II)/Co(II) sensor NmtR from Mycobacterium tuberculosis was introduced into a related cyanobacterium, Synechococcus PCC 7942, Co(I) sensing was retained, but Ni(II) sensing was lost, suggesting that the buffered concentration of Ni(II) in the cyanobacterial cytosol may be maintained at a lower level than in M. tuberculosis, too low for NmtR to gain access to Ni(II) in the heterologous host (27). Supplementation of growth medium with additional Ni(II) increases hydrogenase activity (which can either consume or generate dihydrogen depending upon the enzyme type and environmental conditions) in a range of cyanobacteria (28–32), which is again consistent with a low and limiting buffered concentration of Ni(II) in the cyanobacterial cytosol, but the Ni(II) sensor that maintains this concentration was not known previously.

Known cytosolic metal sensors in Synechocystis include cobalt-dependent activator of expression of cobalt efflux, CoaR (33), zinc-dependent derepressor of expression of zinc efflux, ZiaR (34), and zinc-dependent co-repressor of expression of zinc influx, Zur (35, 36). The primary and secondary metal coordination spheres of these sensors must somehow confer different metal selectivities. One untested hypothesis is that selectivity is partly a function of the relative metal affinities of the complement of metal sensors in a cell, regardless of their protein families (6). In this work we characterize the CsoR/RcnR sensor of Synechocystis, herein referred to as InrS (internal nickel-responsive sensor) and compare its nickel affinity with cytosolic sensors of other metals including one sensor from each family represented in the Synechocystis genome.

**EXPERIMENTAL METHODS**

Protein Expression Plasmids—sll0176 (Cyanobase annotation) was amplified from Synechocystis genomic DNA using primers 1 and 2 (supplemental Table S1) and the resulting fragment cloned (Ndel and BamHI) into pET29a (Novagen) to create pETInrS. pEToCoaR was produced in an analogous manner using primers 3 and 4 (supplemental Table S1) to amplify sll0794 and the resulting fragment cloned (Ndel and EcoRV) into pET29a. The production of pETZiaR (37) and pETZur (36) has been described previously.

**Protein Expression and Purification—**E. coli strain BL21(DE3) was transformed to kanamycin resistance with pETInrS. Exponentially growing cells were induced with 1 mM isopropyl 1-thio-

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2 The abbreviations used are: ICP-MS, inductively coupled plasma mass spectrometry; CAT, chloramphenicol acetyltransferase; LMCT, ligand to metal charge transfer; mf2, mag-fura-2; NTA, nitrilotriacetic acid; RLM-RACE, RNA ligase-mediated rapid amplification of complementary ends.
InrS and Ni(II) Specificity

mutagenesis (Stratagene). Primers 9 and 10 followed by 11 and 12 (supplemental Table S1) were used to introduce NdeI restriction sites toward both ends of sl0176. Following excision of the bulk of sl0176 from the plasmid using NdeI the chloramphenicol acetyltransferase gene (CAT) was ligated in its place to create pGEMSl0176::CAT. SacII and PstI were used to excise the CAT cassette disrupted sl0176 fragment which was incubated with Synecocystis to transform the cells to chloramphenicol resistance. Transformants were selected on BG11 plates (40 μg ml⁻¹ chloramphenicol) prior to growth in BG11 (7.5 μg ml⁻¹ chloramphenicol). Deletion of inrS by insertion of the CAT cassette and segregation to all chromosomal copies were confirmed by PCR using primers 13 and 14 (supplemental Table S1) to identify a diagnostic 4.9-kb fragment (wild type (WT) gives a 4.3-kb fragment).

Isolation of RNA and Reverse Transcription PCR—Logarithmically growing cells were inoculated to A₆₀₀ nm = 0.1 in standard BG11 or BG11 supplemented with maximum noninhibitory concentrations of NiSO₄ (0.5 μM), ZnSO₄ (12 μM), CoCl₂ (2.0 μM), or CuSO₄ (1.0 μM) (concentrations confirmed in a series of growth yield experiments to give <10% inhibition) and cultured for 48 h. Total RNA was extracted as described previously (40), and following DNaseI treatment, cDNA was produced using an ImPromII kit (Promega). Reverse transcriptase was omitted from negative controls. Transcript abundance was assessed by PCR with primers 15 and 16 (supplemental Table S1) (nrsB, control) (supplemental Table S1) along with primers included in the kit (specific to the 5’-adapter). Fragments were cloned in pGEM-T for sequencing.

Phenotypic Assays—Strains (WT and ∆inrS) were inoculated to OD₈₀₀ nm = 0.075 and cultured with or without 0.5 μM NiSO₄ for 24 h. Cell numbers were recorded using a Casyl Cell Counter TT (Innovatis) before harvesting 20 ml of each culture at 3,900 × g. Cell pellets were washed with 50 mM Tris, pH 7.5, 0.5 mM sorbitol, and 100 μM EDTA (3 × 10 ml) then suspended in ultrapure 65% v/v HNO₃ (1 ml) and left to digest prior to metal analysis by ICP-MS. Visible absorption spectra of logarithmically growing cells inoculated to OD₈₀₀ nm ~0.3 were recorded using a Multiskan GO microplate reader and spectrophotometer (Thermo Scientific). Fluorescence emission spectra were recorded using a Cary Eclipse Fluorescence Spectrophotometer (Varian) (which contain established formulas (42) [Carotenoids] (μg ml⁻¹) = (A₄₆₁ nm - 0.046 × OD₆₆₄ nm) × 4, [Chl a] (μg ml⁻¹) = 1.21 × OD₆₆₄ nm - 0.17 × A₆₂₅ nm).

Protein Chelator-Nickel Competition—Experiments were carried out in Chelex-treated and Ni(II)-purged 10 mM HEPES, pH 7.8, 100 mM NaCl, 400 mM KCl under anaerobic conditions. Chelators (NTA, EGTA, and EDTA) were incubated with Ni(II) for 10 min before adding InrS. A₃₃₃ nm was monitored every 30 s (Perkin Elmer A35 spectrophotometer) to equilibrium and used in conjunction with calibration curves produced by titration of InrS with Ni(II) to calculate affinity constants (detailed in supplemental Fig. S8). The nickel affinities of ZiaR, Zur, and CoaR were determined by competition with the fluorescent chelator mf2 (quantified via ε = 22,000 M⁻¹ cm⁻¹ at 369 nm) (43) and NTA for CoaR. mf2 was incubated with Ni(II) for 10 min before adding protein. Fluorescence emission of mf2 was monitored every 30 s (λₑₓ = 380 nm, λₑᵐ = 505 nm) to equilibrium, and affinity constants were calculated in conjunction with a concurrently produced standard curve of mf2 fluorescence emission upon titration with Ni(II) (for details, see supplemental Fig. S8). Ni(II) or Ni(II)-NTA was added to CoaR and intrinsic fluorescence emission of CoaR recorded (λₑₓ = 280 nm, λₑᵐ = 300–400 nm).

Interprotein Nickel Exchange—Proteins (ZiaR, Zur, and CoaR) were preincubated with Ni(II) in 10 mM HEPES, pH 7.8, 100 mM NaCl, 400 mM KCl for Zur, with 0.1% w/v n-dodecyl β-D-maltoside (Chelex-treated) for CoaR, and 10 mM HEPES,
InrS and Ni(II) Specificity

InrS Binds Cu(I) or One Equivalent of Ni(II) with UV-Visible Difference Spectra Similar to CsoR—The metal binding properties of InrS were analyzed with a view to identifying candidate metal effectors. Recombinant InrS (molecular mass 11,887 Da) contains two Cys. The feature at 333 nm saturates at 1 eq of Ni(II) (Fig. 1B inset) but is otherwise similar to that of Cu(I)-CsoR from several bacteria (8, 12, 15). Ni(II)-InrS shows an intense feature at 333 nm (ε_{333 nm} \approx 17,200 \text{ M}^{-1} \text{ cm}^{-1}, Fig. 1B) reminiscent of Ni(II)-CsoR (B. subtilis) (ε_{330 nm} \approx 11,500 \text{ M}^{-1} \text{ cm}^{-1}) (12), assigned as ligand to metal charge transfers (LMCT) due to nickel-thiolate bonds. The feature at 333 nm saturates at 1 eq of Ni(II) (Fig. 1B, inset), and a ~1:1 Ni(II)-InrS complex co-migrates in size exclusion chromatography (supplemental Fig. S3). The Ni(II) coordination environment of RcnR is distinct from InrS with features below 300 nm and not between 330 and 340 nm (10). Co(II)-InrS LMCTs differ from RcnR and CsoR with multiple features between 290 nm and 400 nm (Fig. 1C and supplemental Fig. S4). The intensities of Co(II)-dependent LMCTs in the 290 to 400 nm region (within the range of 2,000–3,000 \text{ M}^{-1} \text{ cm}^{-1}) are indicative of two Co(II)-thiolate bonds/monomer (ε_{318 nm} in the range 900–1,200 \text{ M}^{-1} \text{ cm}^{-1} reporting on each Co(II)-thiolate bond in other proteins) (44), and recombinant InrS contains two Cys. The d-d transition envelope centered at 600 nm (ε \approx 200 \text{ M}^{-1} \text{ cm}^{-1} using a sample incubated with 1 eq of Co(II)) (supplemental Fig. S4) is sufficiently intense to suggest a tetrahedral Co(II)-InrS complex, similar to Co(II)-CsoR but unlike Co(II)-RcnR (10, 12). The Co(II)-dependent spectral features saturate between 1.5 and 2 eq (supplemental Fig. S4). Ni(II)-InrS exhibits d-d transitions at λ_{max} \approx 480 nm (supplemental Fig. S4) consistent with Ni(II) coordinated in a square planar or distorted square planar environment but too intense for an octahedral environment (12, 45).

InrS Represses Final Open Reading Frame in nrs Operon—The spectral properties of InrS-metal complexes are more similar to CsoR than RcnR, and the ability to form InrS-DNA complexes was therefore tested with (i) the upstream regions of known copper-responsive genes pacS and petE (plastocyanin) and (ii) upstream gene regions that contain nucleotide sequences with some similarity to the B. subtilis CsoR DNA binding site and additionally with connection to copper (moeA, involved in copper to molybdenum substitution in molybdoenzyme biosynthesis, and coxB, cytochrome c oxidase subunit II). No specific retardation was detected in assays with upstream regions of pacS or petE, but some specific binding, with an apparent DNA binding affinity K_{DNA} weaker than 8 \text{ μM}, was detected with moeA and coxB giving solely large InrS-DNA complexes (supplemental Fig. S5).

During the course of this work a consensus nucleotide binding sequence was reported for CsoR-like proteins (15) (Fig. 2A), and this was used to search regions (300 bp) upstream of Synechocystis ORFs. The best match also has a diagnostic (of CsoR/RcnR DNA binding sites) CG-rich sequence (46) but lies within the nrs polycistronic transcript (25) (Fig. 2A). Because the deduced binding site is upstream of nrsD, whose product is predicted to export Ni(II) across the plasma membrane, this raised the intriguing possibility that a cytosolic metal sensor might additionally regulate the final gene in the nrs operon independently via a cryptic promoter in the nrsC-nrsD intergenic region (Fig. 2A).
InrS and Ni(II) Specificity

A mutant deficient in InrS was generated by homologous recombination-mediated insertion of the CAT gene within ORF sll0176 (inrS). Insertion and segregation were confirmed via PCR with genomic DNA recovered from the mutant demonstrating loss of all WT sll0176 product (−4.3 kb) and appearance of a larger fragment (−4.9 kb) diagnostic of CAT gene insertion, and the strain was designated ΔinrS (Fig. 2B). Increased abundance of nrsD, but crucially not nrsB, transcripts were detected in total RNA from ΔinrS relative to WT by RT-PCR (Fig. 2B). Although there was not an equivalent increase in abundance of coxB or moeA transcripts in the mutant, moeA transcripts did show some elevation in ΔinrS cells, but moeA was not responsive to exogenous nickel or copper (supplemental Fig. S6). Taken together, data presented here imply the pacS, petE, moeA, and coxB promoters are not targets for metallo-regulation by InrS.

InrS specifically retards a DNA fragment containing part of the nrsC-nrsD intergenic region generating low molecular mass complexes in addition to high molecular mass complexes (Fig. 2C). Binding to this DNA fragment is tighter than to other fragments tested in supplemental Fig. S5. The effects of Ni(II) on DNA binding were examined under equilibrium conditions by fluorescence anisotropy (Fig. 2, D and E). Titration of hexachlorofluorescein-labeled 33-bp nrsD operator-promoter (nrsD-ProFA) with apo-InrS showed an increase in anisotropy reporting on the formation of InrS-DNA complexes with apparent $K_{DNA} \sim 100 \text{ nm}$ (Fig. 2D). Crucially, the apparent $K_{DNA}$ is at least 1 order of magnitude weaker for Ni(II)-InrS than for apo-InrS (Fig. 2D); moreover, addition of Ni(II) to preformed InrS-DNA complexes leads to loss of DNA binding (Fig. 2E). Thus, InrS represses expression of the last gene in the nrs operon (nrsD) and binds specifically to a hypothetical nrsD operator-promoter as an inverse function of [Ni(II)].

Identification of Ni(II)-regulated Transcription Start Sites between nrsC and nrsD—The possibility that expression of nrsD is also driven in response to metal from a cryptic promoter in the nrsC-nrsD intergenic region was examined. RT-PCR confirmed an accumulation of nrsD transcripts in response to maximum noninhibitory concentrations of nickel and cobalt, but not copper or zinc salts (Fig. 3A). It is possible that these transcripts could be solely products of expression from the two-component NrsS-NrsR-regulated nrs promoter. The abundance of nrsD transcripts in response to nickel and cobalt-responsive short nrsD products of a diagnostic size (~400 bp) for initiation within the nrsC-nrsD intergenic region were identified by 5′-RLM-RACE (Fig. 3B). Short products of other sizes were detected with varying relative abundance in replicate experiments, but only the ~400-bp product was dependent upon tobacco acid pyrophosphatase treatment, diagnostic of a triphosphate-capped mRNA as opposed to degraded mRNA (Fig. 3C). Cloning and sequence analysis of the ~400-bp products revealed two transcription start sites upstream of the nrsD initiation codon (Fig. 3D), 10 and 14 bp downstream of the mid-point of a candidate Pribnow box (5′-TAGAAT-3′), which overlaps the deduced InrS binding site (Fig. 2A).
InrS and Ni(II) Specificity

Ni(II)-related Phenotypes of ΔinrS Cells—The connection between InrS and Ni(II) homeostasis was further supported by assays of metal content of the deletion mutant. Cells missing InrS are expected to show constitutive Ni(II) export to the periplasm, and this is consistent with a reduction in Ni(II) content from 1.0 to 0.64 million atoms cell⁻¹ when grown in medium supplemented with the maximum noninhibitory [nickel] for WT and 0.13–0.091 million atoms cell⁻¹ in standard medium (Fig. 4A). In contrast, the copper content of ΔinrS shows negligible change (supplemental Fig. S7). There was a slight, but reproducible, increase in nickel tolerance in ΔinrS (680 nm; note inset) or exposed to maximum noninhibitory [Ni(II)] (supplemental Fig. S8, estimate 

Synechocystis Sensors of Other Metals from Other Families Bind Ni(II) More Weakly—What are the relative (to 2 \times 10^{-14} M) Ni(II) affinities of the tightest exchangeable binding site of sensors that detect other metals in the cytosol of Synechocystis? In addition to InrS, Synechocystis contains genes encoding deduced proteins with sequence similarity to four other families of metal sensors, MerR-like (e.g. CoaR) (33), Fur-like (e.g. Zur) (35, 36), ArsR-SmtB-like (e.g. ZiaR) (34,) and CopY-like (50), however the deduced CopY homologue (Slr0240) is conspicuously truncated and missing candidate C-terminal metal-sensing residues (51) (Fig. 6 inset). A sensor from each family has a sampling of every tenth data point which reports on Ni(II)-InrS formation (Fig. 5). In a similar experiment with equimolar EDTA, again Ni(II) partitions to InrS whereas in contrast a 2-fold molar excess of EDTA fully outcompetes InrS placing the Ni(II) affinity of InrS in the tightest site (per tetramer) was determined. Apo-InrS was added to a Ni(II)-NTA mix (using equimolar InrS and NTA), and the formation of Ni(II)-InrS was monitored via absorbance at 333 nm, establishing that at equilibrium Ni(II) partially partitions to InrS (Fig. 5).

InrS Outcompetes NTA and EDTA but Not EDTA for Ni(II)—To explore metal selectivity, the affinity of InrS for Ni(II) at the tightest site (per tetramer) was determined. Apo-InrS was added to a Ni(II)-NTA mix (using equimolar InrS and NTA), and the formation of Ni(II)-InrS was monitored via absorbance at 333 nm, establishing that at equilibrium Ni(II) partially partitions to InrS (Fig. 5).

FIGURE 4. Nickel-homeostasis and pigments are altered in ΔinrS mutants. A, whole cell nickel content of WT and ΔinrS cells cultured in standard media (left and inset) or exposed to maximum noninhibitory [Ni(II)] (right). B, absorption spectra of WT (red) and ΔinrS (black) cells normalized to OD600 nm = 0.3. Inset, cultures of both genotypes. C, absorption spectra of N,N-dimethylformamide-extracted pigments from WT (red) and ΔinrS (black) cells with mean concentration (± S.D.) of carotenoids derived from absorbance at 461 nm and chlorophyll a derived from absorbance at 664 nm for WT (red) and ΔinrS (black). Arrows indicate wavelengths used to calculate concentrations of carotenoids (461 nm) and chlorophyll a (664 nm). D, chlorophyll a fluorescence emission of cultures used in B.
flourescent metal chelator mf2 resulted in partial Ni(II) occupancy of sensor and chelator at equilibrium, enabling estimation of $K_D$, Ni(II) of the tightest site (per dimer) as 3.07 (± 0.81) × 10^{-8} M (Fig. 6F and supplemental Fig. S9). Even with a ~4-fold excess of chelator, CoaR outcompeted mf2, implying $K_D$ Ni(II) numerically ~ 10^{-9} M (Fig. 6G). Conversely, equimolar NTA fully outcompeted CoaR such that quenching of CoaR autofluorescence was only detected after saturation of the Ni(II) sites of NTA, implying $K_D$ Ni(II) numerically ≥ 10^{-9} M (Fig. 6H and supplemental Fig. S10). Thus, CoaR, in common with the two zinc sensors, binds Ni(II) more weakly than InrS (Fig. 6I).

Ni(II) Partitions to InrS from Zur, ZiaR, and CoaR—To confirm that InrS outcompetes each of the other sensors for Ni(II), apo-InrS was added to Ni(II)-bound forms of Zur, ZiaR, and CoaR, and reactions were analyzed for metal exchange. Unlike InrS, Zur has fluorescent residues (five Tyr) allowing the proteins to be distinguished by fluorescence. Addition of Ni(II) to Zur quenches intrinsic InrS fluorescence, and this is reversed upon addition of apo-InrS (Fig. 7A). ZiaR also contains fluorescent residues (four Tyr); however, there is no change in fluorescence upon addition of Ni(II) (supplemental Fig. S11). Metal transfer was thus monitored by ICP-MS after separation by heparin affinity chromatography after addition of apo-InrS to Ni(II)-ZiaR. Ni(II) becomes associated with InrS with negligible amounts retained on ZiaR (Fig. 7B). Addition of apo-InrS to Ni(II)-CoaR, which exhibits negligible absorbance between 300–400 nm), generates a spectral feature at 333 nm of equivalent intensity to that obtained with identical concentrations of Ni(II)-InrS alone (Fig. 7C). Thus, apo-InrS avidly removes Ni(II) from Ni(II) species of the other three sensors.

DISCUSSION

In this research we discover cryptic transcription start sites within the nrs operon which enable independent (of other nrs genes) transcription of nrsD in response to cytosolic Ni(II) (Figs. 2 and 3 and supplemental Figs. S5 and S6). When surplus Ni(II) accumulates in the periplasm the nrs operon is expressed under the control of NrsS/NrsR, allowing efflux across the outer membrane (25, 26), but it is now evident that surplus Ni(II) in the cytosol is also sensed by a DNA-binding protein of the CsoR/RcnR family which represses nrsD. Ni(II)-dependent derepression of nrsD alone will allow export from the cytosol to the periplasm consistent with enhanced nickel resistance and reduced nickel accumulation of ΔinrS (Fig. 4 and supplemental Fig. S12). That Ni(II) is the metal effector of this new family member implies analogy to RcnR, yet its metal-dependent spectral properties are more akin to those of Cu(I)-sensing CsoR (Fig. 1), and hence the protein is independently named InrS (for internal nickel-responsive sensor); however, these observations question why InrS responds to Ni(II) rather than Cu(I).

CsoR binds Cu(I) in a trigonal coordination site which includes imidazole N1 of His-61; Cu(I) binding repositions the CsoR/RcnR family which represses nrsD. Ni(II)-dependent derepression of nrsD alone will allow export from the cytosol to the periplasm consistent with enhanced nickel resistance and reduced nickel accumulation of ΔinrS (Fig. 4 and supplemental Fig. S12). That Ni(II) is the metal effector of this new family member implies analogy to RcnR, yet its metal-dependent spectral properties are more akin to those of Cu(I)-sensing CsoR (Fig. 1), and hence the protein is independently named InrS (for internal nickel-responsive sensor); however, these observations question why InrS responds to Ni(II) rather than Cu(I).
InrS and Ni(II) Specificity

FIGURE 7. Ni(II) partitions from Zur, ZiaR, and CoaR to InrS. A, fluorescence emission spectrum of apo-Zur (10 μM) (black line) and following quenching with Ni(II) (10 μM) (blue line). Addition of apo-InrS (10 μM) to Ni(II)-Zur fully alleviates quenching (red line). B, ZiaR (20 μM) equilibrated with Ni(II) (9.5 μM) before addition of apo-InrS (20 μM). Proteins were separated by heparin affinity chromatography and fractions assayed for nickel by ICP-MS and protein by SDS-PAGE. C, absorption spectrum of Ni(II)-InrS (2.4 μM Ni(II), 5 μM InrS) (black line). Addition of apo-InrS (5 μM) to Ni(II)-CoaR (2.4 μM Ni(II), 5 μM CoaR, which shows negligible absorbance in this region and is used as base line) generates a spectrum (red line) which overlays that for 2.4 μM Ni(II)-InrS.

ducing this signal due to the absence of a vital secondary shell residue.

Clearly, Ni(II) does drive the allosteric mechanism of InrS (Figs. 2 and 3). The spectral feature of Ni(II)-InrS at 333 nm has similarity to Ni(II)-substituted CsoR and to Ni(II)-NikR (12, 45). The d-d transition and LMCT features of Ni(II)-InrS are within the range of wavelengths and intensities for model complexes containing at least one sulfur ligand and square planar (but not octahedral) geometry (52); the spectra are also dissimilar to Ni(II)-substituted proteins with tetrahedral geometry (53, 54). Additionally, in contrast to Co(II)-RcnR the extinction coefficient for d-d transitions observed in Co(II)-InrS suggests the presence of a tetrahedral coordination environment at saturating levels of Co(II) (44, 45). These data indicate that InrS possesses a Ni(II) sensing site with analogy to NikR rather than RcnR, implying independent evolution of similar sensory motifs within distinct protein scaffolds suggestive of a limited, but relatively facile to evolve, repertoire of biorganic solutions that favor Ni(II). In turn, the metal site of the ArsR/SmtB family Ni(II) sensor NmtR has commonality with RcnR (55).

InrS possesses an N-terminal extension (relative to CsoR and RcnR) rich in His residues (supplemental Fig. S1). Similar extensions occur in several proteins of Ni(II) homeostasis and may aid Ni(II) acquisition from exchangeable cytosolic Ni(II) pools, a notable example being the hydrogenase assembly metallochaperone HypB from Bradyrhizobium japonicum (56). A mobile C-terminal metal binding region of NmtR may also act in this manner (55). Proteins related to InrS, with a similar ligand motif and/or deduced to regulate nrsD-like genes, form two clades (supplemental Fig. S13). Moreover, both clades are distinct from RcnR.

Each bacterium contains some complement of metal sensors from multiple families. Regardless of the molecular mechanism or family, the correct sensor in the set must respond to the correct metal. There are often inconsistencies in protein metal affinities measured in different studies (6, 57, 58), but here affinities of the tightest exchangeable site of Synechocystis sensors (InrS, ZiaR, CoaR, and Zur), representing four distinct sensor families, have been determined concurrently by common methods to discover that the bona fide Ni(II) sensor InrS does indeed have the tightest $K_D$ (Ni(II)) of this set (Figs. 5 and 6 and supplemental Figs. S8 and S9). By controlling the buffered concentration of a metal in the cytosol each sensor has the capacity to influence the metals detected by other sensors in the same cell by maintaining a metal concentration below their binding constants. Thus, CoaR, Zur, and ZiaR may never bind Ni(II) in vivo and so fail to respond even if Ni(II) could otherwise trigger their allosteric mechanisms (supplemental Fig. S14). The metal sensors in each organism may thus have evolved as a set based, in part, upon their relative metal affinities (6). Inability of mycobacterial NmtR to detect Ni(II) in a cyanobacterial cytosol (27), and gain of Mn(II) detection by Fe(II)-sensing DtxR when transferred from Corynebacterium diphtheria to B. subtilis (59), are explained by such a model.

Metal affinities are a function of metal exchange via free solution, yet it is anticipated that the cytosol contains negligible hexa-aqua Ni(II). For example, if Ni(II) were buffered to $2 \times 10^{-14}$ M (noting that the cell is expected to depart from thermodynamic equilibrium) a free Ni(II) atom would only occur in one cell in 100,000, or in each cell for a 1/100,000 of the time (assuming that one atom/cell volume approximates nanomolar) (60). Associative metal exchange is expected to occur in vivo via the polydisperse buffer of the cytosol. The $K_D$ values (Fig. 6f) will correctly rank the sensors’ preferences for Ni(II) in vivo if (as an initial approximation) their rates of exchange with cytosolic ligands retain the same rank order, but crucially the reported $K_D$ values will not be indicative of in vivo kinetics.

Hydrogenase is Ni(II)-limited in many cyanobacteria (28–32), and in Synechocystis this enzyme dissipates surplus products of photosynthesis. Mutants without InrS have depleted Ni(II) content (Fig. 4A), and so hydrogenase is speculated to be even less active. An increase in protective pigments is predicted to dampen the light reactions of photosynthesis and hence to lessen demand for hydrogenase activity, which is consistent with the observed decline in chlorophyll $a$ fluorescence in ΔinrS (Fig. 4, B–D). Conversely, and tantalizingly, allosterically competent InrS variants with weaker $K_D$ Ni(II) should maintain an elevated cytosolic [Ni(II)] and sus-
tain greater rates of hydrogen evolution. In this way, metal sensors may be exploited to engineer metal supply for useful chemical transformations.

REFERENCES


