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Crystal Structure of the Redox-Active Cofactor Dibromothymoquinone Bound to Circadian Clock Protein KaiA and Structural Basis for Dibromothymoquinone's Ability to Prevent Stimulation of KaiC Phosphorylation by KaiA

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Supporting Information

ABSTRACT: KaiA protein that stimulates KaiC phosphorylation in the cyanobacterial circadian clock was recently shown to be destabilized by dibromothymoquinone (DBMIB), thus revealing KaiA as a sensor of the plastoquinone (PQ) redox state and suggesting an indirect control of the clock by light through PQ redox changes. Here we show using X-ray crystallography that several DBMIBs are bound to KaiA dimer. Some binding modes are consistent with oligomerization of N-terminal KaiA pseudoreceiver domains and/or reduced interdomain flexibility. DBMIB bound to the C-terminal KaiA (C-KaiA) domain and limited stimulation of KaiC kinase activity by C-KaiA in the presence of DBMIB demonstrate that the cofactor may weakly inhibit KaiA-KaiC binding.

In the photosynthetic cyanobacterium *Synechococcus elongatus* (*S. elongatus*) the KaiA, KaiB, and KaiC proteins constitute a post-translational circadian oscillator (PTO).[1−4] The discovery that regular patterns of KaiC phosphorylation and dephosphorylation with a period of 24 h are generated when the three proteins are incubated in a test tube in the presence of ATP,[5] rendered this system an attractive target for biochemical and biophysical investigations of the inner workings of a molecular clock. The central cog, KaiC, exhibits autophosphorylation and -dephosphorylation[6,7] as well as ATPase activities.[8] Dephosphorylation proceeds via a phosphotransferase mechanism that returns phosphates from Ser and Thr back to ADP, thus endowing KaiC with an ATP synthase activity.[9] KaiA enhances KaiC phosphorylation,[10,11] and KaiB antagonizes KaiA action.[11,12]

The input and output pathways of the clock comprise a variety of factors that transmit environmental cues to the inner timer and deliver temporal information based on the phosphorylation loop to downstream cellular processes that include clock-controlled gene expression, respectively (reviewed in refs 3 and 4). Proteins participating in the input pathway that have been characterized to date include LdpA[13,14] and CikA.[15,16] Both are redox-active factors; CikA is a histidine kinase and LdpA is an iron sulfur protein. CikA was shown to be required for resetting of the phase after a dark pulse,[15] and mutations in the protein resulted in shortened periods of the oscillator and altered patterns of KaiC phosphorylation.

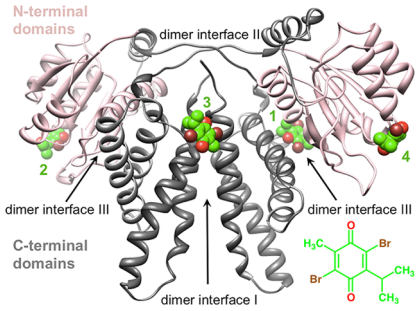

Figure 1. Overall view of the crystal structure of the *S. elongatus* KaiA:DBMIB complex. The KaiA dimer is depicted in a secondary structure cartoon mode, and the oxidized form of DBMIB is shown at the bottom right, with carbon, oxygen, and bromine atoms colored in light green, red, and brown, respectively. N- (residues 1−139) and C-terminal (residues 140−282) domains of KaiA are colored in pink and gray, respectively, and are labeled along with dimer interfaces. Bound DBMIBs are shown in space filling mode and are numbered 1−4.

The brominated and water-soluble plastoquinone (PQ) analogue 2,5-dibromo-3-methyl-6-isopropyl-*p*-benzoquinone (DBMIB; Figure 1)[17] was found to destabilize both LdpA and CikA.[14] The so-called pseudoreceiver (PsR) domain of CikA is able to bind DBMIB and a series of additional quinone analogues,[18,19] thus implicating this His kinase in indirect information transfer on the light environment to the central cyanobacterial timer via redox changes in bound quinone.[18]

A more recent study also established binding between the PsR domain of KaiA and DBMIB and therefore provided evidence for KaiA acting as a sensor of environmental signals and modulating the circadian clock as a result of changes in the redox state.[20] Accordingly, the oxidized but not the reduced form of DBMIB binds to KaiA and induces protein oligomerization, ultimately preventing KaiA from binding to KaiC and stimulating phosphorylation of the latter.[20] KaiA forms a domain-swapped dimer[21] (Figure 1), whereby the N-terminal domains (N-KaiA) adopt a PsR-like fold[11,21] and the C-terminal α-helical bundle domains (C-KaiA)[22,23] are responsible for dimerization and KaiC binding.[24] Native polyacrylamide gel electrophoresis (PAGE) in conjunction

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with NMR solution experiments supported binding of DBMIB to the N-KaiA PsR domain as the underlying cause of protein aggregation.[20] Conversely, lack of mobility changes in native PAGE assays of mixtures of C-KaiA and DBMIB appeared to argue against an involvement of this domain in light-induced control of the clock mediated by KaiA. However, this study did not characterize the binding modes of DBMIB in detail.

To establish the precise KaiA binding sites and coordination modes of DBMIB, we determined the crystal structure of full-length *S. elongatus* KaiA soaked in a solution of the oxidized form of DBMIB at a resolution of 2.38 Å (see the Supporting Information for experimental details, Table S1 for refinement parameters, Figures S1 and S2 for the quality of the final electron density, Figure S3 for KaiA loop conformations, and Figure S4 for a temperature factor analysis). We established four unique binding sites for DBMIB (DBMIBs 1−4; Figure 1), such that each KaiA dimer in the crystal is surrounded by eight DBMIB molecules (Figure S5 in the Supporting Information; the KaiA dimer does not adopt crystallographic 2-fold symmetry). DBMIB 1 is located between the N- and C-KaiA domains from different subunits at dimer interface III. DBMIBs 2 and 4 are interacting mainly with N-KaiA, but like molecule 1, they establish contacts to domains from symmetry-related KaiAs. By contrast, DBMIB 3 is bound at dimer interface I of C-KaiA domains and is exclusively associated with one KaiA dimer (Figure 1), thus revealing an unexpected binding mode.

Closer examination of the binding modes of DBMIB molecules reveals common features and a preference for a particular folding topology (Figure S6 in the Supporting Information). In all four cases, the quinone analogue sits adjacent to the N-terminus of an α-helix that is preceded by a turn involving proline (Figures 1 and 2). For DBMIBs 1, 2, and 4, the turn is between a β-strand and the α-helix and DBMIB 3 sits close to a turn between α-helices. Whereas P115a is located at some distance from DBMIB 1 (Figure 2A), DBMIB 3 actually stacks onto P229a (Figure 2C) and DBMIBs 2 and 4 are associated with P61b and P61a, respectively (Figure 2B,D). With DBMIB 1 and DMBIB 4, a lysine and an arginine, respectively, snake along the aromatic moiety of the binder, thus providing a hydrophobic platform. In two cases there is potential for formation of a halogen bond involving close vicinity (<3.3 Å) between an electronegative moiety (keto or caboxylate oxygen) and bromine (asterisk in Figure 2 A,B). Further, DBMIBs 2 and 4 are adjacent to newly built loops in the complex structure [missing in the native KaiA structure[21] (Figure S3 in the Supporting Information)] and establish

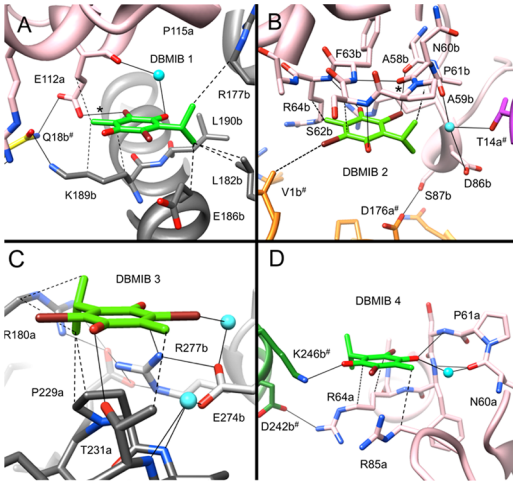

Figure 2. Coordination modes of DBMIB molecules (A) 1, (B) 2, (C) 3, and (D) 4 to KaiA. The coloring of N-KaiA and C-KaiA domains in the original dimer matches that in Figure 1. Residues belonging to four different symmetry-related KaiA dimers are highlighted in yellow (A), orange and magenta (B), and green (D). Selected side chains are depicted with oxygen in red and nitrogen in blue and are labeled (a and b indicate subunits and # indicates a symmetry mate). Hydrogen bonds are indicated by thin solid lines, putative halogen bonds are marked with an asterisk, and hydrophobic contacts as well as a van der Waals contact by bromine (panel B) are indicated by dashed lines.

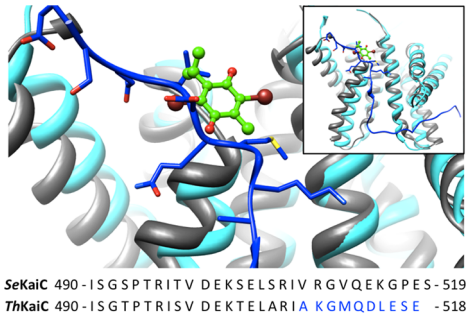

Figure 3. Putative clash between DBMIB 3 coordinated between C-terminal domains of the KaiA dimer (see panel C of Figure 2 for a close-up) and a portion of a KaiC C-terminal peptide bound to KaiA dimer (see inset for an overall view). The NMR structure of the *Thermosynechococcus elongatus* (*T. elongatus*) C-KaiA dimer (cyan) bound to the last 30 residues of KaiC (blue)[24] was superimposed onto the C-KaiA portion with DBMIB 3 bound as observed in our crystal structure (gray). Sequences of the C-terminal stretches of KaiCs from *S. elongatus* and *T. elongatus* are shown at the bottom. In the crystal structure of *S. elongatus* KaiC hexamer,[25] one of the C-terminal tails exhibits a conformation very similar to that seen for the peptide in the solution structure of the *T. elongatus* KaiA:KaiC peptide complex. DBMIB coordinated at that site would interfere with binding of the last 10 residues of KaiC (highlighted in blue in the sequence) and result in overlaps with the backbone and side chains from at least five amino acids. As in the case of *S. elongatus* KaiA, DBMIB causes aggregation of *T. elongatus* KaiA. However, addition of DBMIB to the KaiB protein from either organism has no effect at all (Figures S7 and S8 in the Supporting Information).

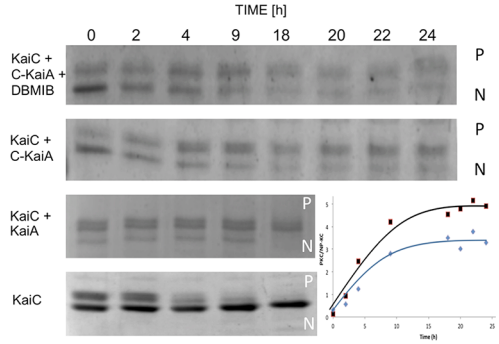

Figure 4. SDS-PAGE assay of *S. elongatus* KaiC phosphorylation, separating the more slowly migrating phosphorylated form (P) from the nonphosphorylated form (N). From top to bottom: KaiC, C-KaiA and oxidized form of DBMIB; KaiC and C-KaiA; KaiC and full-length KaiA (KaiA stimulates KaiC phosphorylation more strongly than C-KaiA); and KaiC alone (KaiC autodephosphorylates without KaiA). DBMIB affects C-KaiA action as indicated by the lower P-KaiC/KaiC ratio (blue) compared to that ratio in the absence of DBMIB (black; graph at bottom right).

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indirect or direct contacts with a residue from the loop (i.e., S87b, DBMIB 2, and R85a, DMBIB 4, respectively).

In addition to the above similarities, there are a number of differences between the binding modes of individual DBMIB molecules. For example, DBMIB 1 is wedged between two antiparallel amide moieties, the top one contributed by E112a and the bottom one by K189b, such that the keto oxygen of E112a establishes a water-mediated contact to a DBMIB keto oxygen (Figure 2A). In the case of DBMIB 2, a tight turn in the N-KaiA backbone sits atop the aromatic moiety and amide N−H groups from S62b and R64b (Figure 2B) are directed toward DBMIB keto oxygens. An N−H from a third residue (F63b) forms a hydrogen bond to the keto oxygen from N60b three residues away, thus tying together the turn, with the hydrogen bond positioned more or less parallel to the DBMIB ring.

The locations of DBMIB binding sites allow a more detailed understanding of the cofactor's mode of action in terms of transmitting environmental cues, i.e., light conditions, to the KaiABC timer. Residues from the N-KaiA PsR-like domain are responsible for the majority of interactions seen for DBMIBs 1, 2, and 4 (Figure 2; N-KaiA domains of the original dimer in the crystal are colored in pink). Residues interacting with DBMIB (i.e., E112a and K189b; DBMIB 1), closely associated with DBMIB (i.e., A59b, water-mediated; DBMIB 2) or DBMIB atoms themselves (i.e., Br2, DBMIB 2) then establish contacts to N-KaiA domains from symmetry mates, consistent with the aggregation model.[20] The coordination site observed for DBMIB 1, stitching together PsR N-KaiA and C-KaiA domains (Figure 2A), and the improved ordering of loops directly associated with cofactor binding (DBMIB 2, 4; Figure 2B,D) are also consistent with reduced flexibility and aggregation.

The association of DBMIB 3 exclusively with C-KaiA domains prompted us to examine an additional mode of interference of DBMIB with KaiA-stimulated phosphorylation of KaiC. The binding site of DBMIB 3 overlaps with a portion of the binding interface between KaiC C-terminal peptide and KaiA dimer[24] (Figure 3) but cannot be expected to result in a bandshift in native PAGE.[20] Whereas the structure of the C-KaiA:KaiC peptide complex in solution discloses binding of two peptides per KaiA dimer,[24] in the crystal the site equivalent to the one occupied by DBMIB 3 on the opposite side of the dimer is sealed off by a lattice contact between KaiA symmetry mates. SDS-PAGE assays of C-KaiA-stimulated KaiC phosphorylation in the presence and absence of the oxidized form of DBMIB reveal a slightly impaired activity of KaiA in the former case (Figure 4, top two panels), providing support for DBMIB affecting KaiC-peptide binding.

In summary, the binding modes of three of the DBMIBs visualized in the structure of the KaiA:DBMIB complex are consistent with N-KaiA PsR-domain aggregation[20] and reduced KaiA interdomain flexibility. The newly discovered DBMIB associated with C-KaiA alone together with the reduced ability of this domain to enhance KaiC phosphorylation in the presence of DBMIB suggest a more complex involvement of the cofactor in the mediation of the clock's light input pathway.

■ ASSOCIATED CONTENT

Supporting Information

Methods and materials, Table S1, and Figures S1−S8. This material is available free of charge via the Internet at http://pubs.acs.org.

Accession Codes

The PDB code (http://www.rcsb.org) for the complex is 4G86.

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Notes

The authors declare no competing financial interest.

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