Functional roles of CymA and NapC in reduction of nitrate and nitrite by *Shewanella putrefaciens* W3-18-1

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*Shewanella putrefaciens* W3-18-1 harbours two periplasmic nitrate reductase (Nap) gene clusters, NapC-associated *nap-alpha* (*napEDABC*) and CymA-dependent *nap-beta* (*napDAGHB*), for dissimilatory nitrate respiration. CymA is a member of the NapC/NirT quinol dehydrogenase family and acts as a hub to support different respiratory pathways, including those on iron [Fe(III)] and manganese [Mn(III, IV)] (hydr)oxide, nitrate, nitrite, fumarate and arsenate in *Shewanella* strains. However, in our analysis it was shown that another NapC/NirT family protein, NapC, was only involved in nitrate reduction, although both CymA and NapC can transfer quinol-derived electrons to a periplasmic terminal reductase or an electron acceptor. Furthermore, our results showed that NapC could only interact specifically with the Nap-alpha nitrate reductase while CymA could interact promiscuously with Nap-alpha, Nap-beta and the NrfA nitrite reductase for nitrate and nitrite reduction. To further explore the difference in specificity, site-directed mutagenesis on both CymA and NapC was conducted and the phenotypic changes in nitrate and nitrite reduction were tested. Our analyses demonstrated that the Lys-91 residue played a key role in nitrate reduction for quinol oxidation and the Asp-166 residue might influence the maturation of CymA. The Asp-97 residue might be one of the key factors that influence the interaction of CymA with the cytochromes NapB and NrfA.

**INTRODUCTION**

Most of the *Shewanella* strains display psychrophily or psychrotolerance as well as respiration flexibility and can utilize a series of substances including nitrate, nitrite, [Fe(III)] and manganese [Mn(III, IV)] (hydr)oxide sulphur compounds, heavy metals and metalloids, DMSO, and trimetlyamine oxide (TMAO) for respiration (Fredrickson et al., 2008; Hau & Gralnick, 2007). Comparative genomic analysis reveals that most *Shewanella* strains contain two types of periplasmic nitrate reductases (Nap), NapC-associated *nap-alpha* (*napEDABC*) and CymA-dependent *nap-beta* (*napDAGBH*). The well-characterized *Shewanella oneidensis* MR-1 strain contains only *nap-beta* (*napDAGBH*) for nitrate ammonification (Chen et al., 2011; Dong et al., 2012; Simpson et al., 2010) while the *Shewanella putrefaciens* W3-18-1 strain harbours both CymA- and NapC-dependent nitrate reductases, as well as the NapGH ubiquinol oxidase. These seemingly redundant respiratory chain components may be differentially expressed and functioning under environmental condition gradients such as different oxygen tensions and availability of electron acceptors (Qiu et al., 2013).

NapC and CymA are both membrane-associated tetraheme cytochromes, and are similar in protein size and amino acid

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**Abbreviations:** NAP, periplasmic nitrate reductase; RT, reverse transcription.

Seven supplementary figures and three supplementary tables are available with the online Supplementary Material.
sequence (Gescher et al., 2008; Marritt et al., 2012a). NapC and its homologues oxidize quinol in the cytoplasmic membrane and transfer the electrons released to their redox partners, such as nitrate reductase complex NapAB in the periplasm (Berks et al., 1995; Potter et al., 2001; Roldan et al., 1998). However, NapC is absent in S. oneidensis MR-1, and a possible less-specific homologous protein, CymA, is encoded. Moreover, it had been demonstrated previously that NapC is involved in reduction of iron(III), fumarate and nitrate (Dong et al., 2012; Fu et al., 2014; Meyer et al., 2004; Myers & Myers, 1997, 2000). More interestingly, NapC of Escherichia coli and CymA of S. oneidensis MR-1 had the same function under conditions of dissimilatory nitrate reduction (Cruz-Garcia et al., 2007). It was also shown that expression of cymA and napC, respectively, in conjunction with fecA, encoding the soluble fumarate reductase of S. oneidensis MR-1, could complement an frdABCD mutation in E. coli. Additionally and surprisingly, it was indicated that NapC, despite its "specialized" function in the nitrate respiratory pathway, was functionally equivalent to CymA in its role in vivo as a soluble iron reductase, although at a lower rate (Gescher et al., 2008).

Thus, we proposed whether NapC and CymA in the S. putrefaciens W3-18-1 strain can function equivalently in nitrate reduction. As shown previously, CymA, a central part of electron transfer pathways that support respiratory flexibility of Shewanella, functions as an electron-transfer hub in anaerobic respiration (Cordova et al., 2011; Marritt et al., 2012a, b). CymA can support the reduction of many electron acceptors, such as nitrate, nitrite, fumarate, DMSO, Fe$^{3+}$, Mn$^{4+}$, Cr$^{4+}$ and arsenate (Fonseca et al., 2013; McMillan et al., 2012; Murphy & Saltikov, 2007; Szeinbaum et al., 2014). Also, it has recently been shown that CymA is essential for selenite reduction by S. oneidensis MR-1 (Li et al., 2014). Our results indicated that NapC and CymA had no equivalent function in nitrate reduction, although both CymA and NapC can catalyse the same reaction transferring quinol-derived electrons to a periplasmic terminal reductase or an electron acceptor. NapC is only involved in nitrate reduction and can only interact specifically with Nap-alpha nitrite reductase, while CymA can interact promiscuously with Nap-alpha, Nap-beta and the NrfA nitrite reductase for nitrate and nitrite reduction. Moreover, site-directed mutagenesis was conducted to construct a series of NapC and CymA mutants for genetic complementation to probe their difference in specificity based on sequence alignment and a previous study (Zargar & Saltikov, 2009). It was found that the Lys-91, Asp-97 and Asp-166 residues of CymA play a key role in nitrate and nitrite reduction. Our results could provide insights into the molecular evolution of bacterial respiration in Shewanella and other bacteria.

METHODS

**Bacterial strains and culture conditions.** S. putrefaciens W3-18-1 was usually cultured in Luria–Bertani (LB) broth or on LB plates at 28°C (supplemented with 15 µg ml$^{-1}$ gentamycin and 50 µg ml$^{-1}$ kanamycin when necessary) (Murray et al., 2001). The microaerobic culture (without shaking) was conducted in modified M1 minimal medium (Beliaev et al., 2005; Myers & Nealson, 1988) supplemented with 50 mM sodium lactate as carbon source and electron donor and 2 mM sodium nitrate or sodium nitrite as electron acceptor (supplemented with 50 µg ml$^{-1}$ kanamycin when necessary).

**In-frame deletion.** By taking advantage of the easy genetic manipulation in the S. putrefaciens W3-18-1 strain (Table S1, available in the online Supplementary Material) (Qui et al., 2013), we generated a series of in-frame deletion mutants in this strain and tested their nitrate and nitrite reduction. The two-step protocol of selection (single crossover, antibiotic resistance) and counter-selection (double crossover, sucrose sensitivity) was applied for in-frame deletion of specific genes by using suicide vector pDS3.0 (R6K replicon, sacB, Gm$^R$, Table S1)-based constructs carrying a fusion of upstream and downstream sequences of target genes as described previously (Wan et al., 2004). The suicide vector was introduced into S. putrefaciens W3-18-1 by mating with E. coli WM3064 (Table S1) as the donor strain. Primers used are listed in Table S2.

**Genetic complementation.** The plasmids pBBR1MCS-2-cymA and pBBR1MCS-2-napC were constructed for complementation analyses in the S. putrefaciens W3-18-1napC/cymA double mutant (Table S1). PCR was used to amplify the cymA and napC genes from chromosomal DNA, and the PCR products were digested by using endonucleases EcoRI and XbaI and ligated into the digested broad-host-range plasmid pBBR1MCS-2 (Table S1, abbreviated as pBBR-2 in the figures) (Kovach et al., 1994; Kovach & Peterson, 1995; Pinchuk et al., 2009; Wu et al., 2011) to generate the constructs for genetic complementation. All the constructs were verified by PCR amplification, restriction mapping and sequencing. The resultant constructs were transferred into the S. putrefaciens W3-18-1napC/cymA double mutant, respectively, via conjugation by using E. coli WM3064 as the donor. The transconjugants were selected by plating on LB agar supplemented with kanamycin and without dia-minopimelic acids. Kanamycin-resistant colonies were streak-purified several times on LB agar plates containing kanamycin.

All mutated genes were cloned by using crossover PCR with appropriate primers. To clone those mutated genes, the ligation, verification, conjugation and selection were conducted as described above. To detect the expression of recombinant proteins, a His-tag was added to the C-terminal end of all genes. Primers used are listed in Table S2.

**Western blot analysis.** Subcultures were grown in LB with 50 µg kanamycin ml$^{-1}$ at 28°C and 220 r.p.m. for 8 h. The protein samples were then prepared by the standard procedures of the KeyGEN Biotech kit (KGP450, keyGEN). Proteins were analysed by 12% SDS-PAGE and electro-transferred onto the 0.45 µm PVDF membrane in transfer buffer (47.8 mM Tris, 36.7 mM glycine, 1.3 mM SDS, 20% (v/v) methanol). His-tagged proteins were probed with His monoclonal primary antibodies (Beyotime) at 1:100 dilution and immuno-coupled with anti-Mouse IgG (H+L)-HRP (Beyotime) according to the manufacturer’s instructions. ECL Plus (Biosharp) was used for detection, and film images were digitized using ImageQuant LAS4000 mini. The PVDF membrane stained with Coomassie brilliant blue after imaging was used as a loading control in the Western blot analysis (Gilda & Gomes, 2013; Welinder & Ekblad, 2011).

**Heme staining.** Subcultures were grown in LB with 50 µg kanamycin ml$^{-1}$ at 28°C and 220 r.p.m. for 12 h. To detect CymA and NapC proteins, cells were centrifuged and resuspended in SDS loading buffer. The samples were separated by 18% SDS-PAGE after being boiled and centrifuged. Heme stains were performed using 3,3′,5,5′-tetrachloromethylbenzidine (TMBZ) as previously described by Francis & Becker, (1984) and Thomas et al. (1976).
Reduction of nitrate and nitrite. In *S. putrefaciens* W3-18-1, nitrite can only be produced from nitrate by NAP nitrate reductases or from nitroalkane by 2-nitropropane dioxygenase (*Sputw3181_0570*). Thus, the changes of the nitrate and nitrite in the medium can be an indication of dissimilatory nitrate and nitrite reduction in modified M1 minimal medium without nitroalkane. The concentration of nitrate and nitrite in the medium was measured simultaneously by using a standard colorimetric method (China EPA, 2002; Nicholas & Nason, 1957).

RNA extraction, reverse-transcription (RT)-PCR and real-time PCR analysis of gene transcription. Total RNA was extracted by using the standard procedures of RNAiso Plus (Takara). The integrity of RNA was evaluated by agarose (1 %) gel electrophoresis. To prepare cDNA, 2 μg total RNA was reversely transcribed using a PrimeScript RT reagent Kit with gDNA Eraser (Takara) according to the manufacturer’s protocol. Real-time PCR was then carried out with SYBR Premix Ex TaqII (Tli RNaseH Plus, Takara) on a Real-Time PCR System Light Cycler 480II (Roche). The relative mRNA levels were determined by normalization to the expression of 16S rRNA transcript (Livak & Schmittgen, 2001; Schmittgen & Livak, 2008).

Meanwhile, RT-PCR was conducted with the same cDNA. The PCR thermal cycles were: 5 min at 95 °C for cDNA denaturation, followed by 27–30 cycles of 30 s at 95 °C, 30 s at 55 °C and 30 s at 72 °C. A final elongation step was performed for 10 min at 72 °C. RT-PCR products were separated on a 1 % agarose gel containing ethidium bromide and visualized by ultraviolet light and BioRad Image software. The data presented were relative mRNA levels normalized against 16S rRNA transcript levels, and the value of the control was set to 1.

All the experiments described were performed in triplicate to obtain means and SD. The PCR products were also sequenced to confirm amplification of target genes. Primers used are listed in Table S2.

RESULTS

Sequential reduction of nitrate and nitrite and diauxic growth

The well-studied *S. oneidensis* MR-1 strain conducts dissimilatory respiratory nitrate ammonification and exhibits sequential reduction of nitrate to nitrite and then to ammonium under anaerobic nitrate reduction conditions (Cruz-Garcia et al., 2007; Gao et al., 2009). We also monitored the temporal changes of nitrate, nitrite and ammonium levels over the course of nitrate ammonification by both *S. putrefaciens* W3-18-1 and *S. putrefaciens* CN-32 strains. It was shown that nitrate was rapidly reduced into nitrite, which accumulated in the culture medium first before being further reduced into ammonium. The significant increase in ammonium levels coincided with the decrease in nitrite levels (Fig. S1, available in the online Supplementary Material). This two-step manner of nitrate ammonification is consistent with previous findings in *S. oneidensis* MR-1 (Cruz-Garcia et al., 2007). In agreement with these measurements, bacterial growth of the *S. putrefaciens* W3-18-1 strain exhibited a diauxic pattern, which was more notable in the modified M1 minimal medium (Fig. 1). An obvious lag phase appeared during diauxic shift from utilization of nitrate to nitrite as the electron acceptor in the *S. putrefaciens* W3-18-1 culture grown in the minimal medium (Fig. 1).

NapC- and CymA-dependent nitrate reduction

The in-frame cymA (locus *Sputw3181_3916*) deletion mutant (Table S1) was generated in *S. putrefaciens* W3-18-1. It was shown that deletion of *cymA* led to significant decreases in reduction of ferric citrate (data not shown), suggesting that CymA plays a similar role in *S. putrefaciens* W3-18-1 as its ortholog in both *S. oneidensis* MR-1 and *Shewanella* sp. ANA-3 strains.

The in-frame napC deletion single mutant (Table S1) and the ∆napCΔcymA double mutant were also generated for exploring the functions of each gene. Deletion of *napC*, encoded within the *nap-alpha* operon, had no apparent effects on the bacterial growth on nitrate and the population growth also exhibited a diauxic pattern. On the other hand, the population

![Fig. 1. Bacterial growth (OD₆₀₀) of wild-type *Shewanella putrefaciens* W3-18-1, in-frame deletion mutants ∆cymA, ∆napC and ∆napCΔcymA double mutant on nitrate (2 mM) in the rich (1 % tryptone and 0.5 % yeast extract, w/v) and modified M1 minimal medium supplemented with 50 mM sodium lactate as electron donor and carbon source. The wild-type strain grown in culture medium without nitrate added was used as control.](image-url)
growth and cell density of the cymA deletion mutant were significantly lower than those of the wild-type and napC mutant. The bacterial growth of the cymA mutant was still comparable with those of the wild-type and napC mutant in the initial stage (up to the sixth hour) corresponding to the stage of nitrate reduction, indicating that the nitrate reduction had not been severely affected by deletion of cymA, and bacteria could no longer grow on nitrite in the absence of CymA. The deletion of both napC and cymA severely affected the bacterial growth on nitrate (Fig. 1), indicating that both of them were involved in nitrate reduction of S. putrefaciens W3-18-1. Time-course measurements of the nitrate and nitrite concentration in the culture broths also confirmed that nitrite was not further reduced to ammonium when cymA was deleted.

CymA and NapC do not function equivalently in nitrate reduction

A series of in-frame deletion mutants in S. putrefaciens W3-18-1 were generated and a series of constructs were constructed for genetic complementation analyses. By means of monitoring their nitrate and nitrite reduction in different test groups, it was demonstrated that CymA and NapC had no equivalent function in nitrate reduction. The results that the NapC with NapC in the ΔcymAΔnapB (Table S1) mutant could still reduce nitrate to nitrite and loss of CymA resulted in deficiency of nitrite reduction, and the ΔnapBΔnapC (Table S1) mutant could still reduce nitrate and nitrite indicated that NapC could interact with NapB and CymA could interact with NapB and NrfA nitrite reductase (Fig. 2a). Moreover, NapC was unable to complement the nitrate reduction of the ΔcymAΔnapB (Table S1) mutant and CymA could complement the nitrate and nitrite reduction of the ΔcymAΔnapB mutant, which indicated that NapC was unable to interact with NapB and NrfA nitrite reductase while CymA could interact with NapB (Fig. 2b).

Western blot and heme staining analyses on CymA recombinant proteins

We hypothesized that the specificity of NapC and the promiscuity of CymA in the nitrate and nitrite reduction may
depend on differences in both polypeptide sequence and structure. Sequence alignment between NapC and CymA revealed the CymA-specific motif DPE (166–168) (Fig. 3); therefore, a series of site-directed mutants of the cymA gene were generated for genetic complementation analyses (Table S3). Moreover, the pBBR1MCS-2-cymA<sup>K91Q</sup> and pBBR1MCS-2-cymA<sup>D97A</sup> constructs (Table S3) were constructed based on previous experimental and bioinformatics analyses (Zargar & Saltikov, 2009). To monitor whether the recombinant proteins were expressed in the <i>S. putrefaciens</i> W3-18-1<sup>ΔnapCΔcymA</sup> host strain, the C-terminus of each mutant was modified with a His-tag by recombinant technology. His-tagged CymA and NapC, expressed off the pBBR1MCS-2-napC-His and pBBR1MCS-2-cymA-His plasmids, functioned equivalently with the untagged wild-type cytochromes in the <i>ΔnapCΔcymA</i> double mutant, suggesting that His-tags had no effects on the cellular functions (Fig. S2). All the His-tagged recombinant proteins were detected by Western blot analyses using anti-His-tag antibodies. Significant bands were detected in the <i>ΔnapCΔcymA</i> strains carrying cymA or its mutants, but not in the control strain carrying the empty pBBR1MCS-2 vector (Fig. 4a).

As NapC and CymA are both tetraheme <i>c</i>-cytochromes, heme staining was used to detect the expression and maturation of various recombinant proteins. It was demonstrated that CymA recombinant proteins were readily detectable by heme staining (Fig. 4b), suggesting that the Asp-166 residue of CymA may be crucial for the maturation of this tetraheme cytochrome.

**Lys-91 and Asp-97 of CymA play a key role in nitrate reduction**

All the CymA recombinant proteins were detected by Western blot, but CymA<sup>ΔPE</sup>, CymA<sup>Δ166</sup> and CymA<sup>Δ166A</sup> cytochromes were not detected by heme staining. Thus, it was concluded that the Asp-166 was a key site for maturation of CymA, which was consistent with the phenotypic observations that CymA<sup>ΔPE</sup>, CymA<sup>Δ166</sup> and CymA<sup>Δ166A</sup> were unable to restore nitrate or nitrite reduction to the <i>ΔnapCΔcymA</i> double mutant (Fig. S3). To verify the function of other sites, we tested whether the relevant mutants could restore nitrate or nitrite reduction to the <i>ΔnapCΔcymA</i> double mutant. It was demonstrated that deletion of Pro-167 and Glu-168 had no effects on the function of CymA (Table 1). It was previously suggested that Lys-91 might be involved in the interaction of CymA with the quinol pool (Zargar & Saltikov, 2009) and substitution of Lys-91 with glutamine (Gln or Q) (designated CymA<sup>K91Q</sup>) also resulted in the deficiency in both nitrate and nitrite reduction (Fig. 5). Furthermore, our finding that CymA<sup>D97A</sup> recombinant protein was deficient in nitrite reduction indicated that Asp-97 (corresponding to Glu-104 of NapC) might be the key factor determining electron transfer from CymA to NrfA and NapAB (Fig. 6). However, substitution of Lys-96 with Gln (Q) had no effects on the function of CymA<sup>K90Q</sup> in nitrate reduction (Table 1).

**Western blot and heme staining analyses on NapC recombinant proteins**

Site-directed mutagenesis was conducted on the NapC of high specificity in interacting only with Nap-alpha.

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**Fig. 3.** Multiple sequence alignment of NapC and CymA revealed their specific amino acid residues (boxed). The D-166, P-167 and E-168 (boxed) of CymA, absent in NapC, may play a key role in the nitrate/nitrite reduction. K-91, K-96 and D-97 of CymA (arrow pointed) have been previously predicted to be the three sites involved in electron transfer. The heme-bound CXXCH motifs are highlighted in shadow. An * (asterisk) indicates positions which have a single, fully conserved residue. A : (colon) indicates conservation between groups of strongly similar properties. A . (full point) indicates conservation between groups of weakly similar properties.
Sequence alignment between NapC and CymA revealed multiple NapC-specific amino acid residues and sequence motifs, including LDKLKK (residues 2–7), N61, DM (188–189) and the C-terminal VEGF (192–195) (Fig. 3). Therefore, a series of NapC mutants with deletion of those residues and motifs were generated (Table S3). Moreover, Glu-104(E) of NapC corresponded to the crucial residue Asp-97(D) of CymA as described above. We proposed that Glu-104(E) of NapC corresponded to the crucial residue and motifs were generated (Table S3). Moreover, a series of NapC mutants with deletion of those residues and motifs were generated (Table S3). Therefore, a series of NapC mutants with deletion of those residues and motifs were generated (Table S3). Moreover, Glu-104(E) of NapC corresponded to the crucial residue Asp-97(D) of CymA as described above. We proposed that Glu-104(E) of NapC corresponded to the crucial residue Asp-97(D) of CymA as described above. We proposed that Glu-104(E) of NapC corresponded to the crucial residue Asp-97(D) of CymA as described above. We proposed that Glu-104(E) of NapC corresponded to the crucial residue Asp-97(D) of CymA as described above. We proposed that

As described above, Western blot and heme staining analyses were conducted to detect these recombinant NapC proteins. Our results indicated that CymA might be more stable than NapC because CymA was more readily detected (Fig. S4). Furthermore, it was more difficult to detect the NapCALDKLKKANADMAVEGF polypeptide than the other NapC recombinant proteins (Fig. 4c). It is suggested that simultaneous deletion of the four NapC-specific motifs might have made the NapC mutant more unstable.

Site-directed mutagenesis on NapC

A series of mutants of napC was generated to test the functions of some NapC- and CymA-specific residues and motifs (Fig. 3). While the NapC mutants with deletion of the N61 residue, LDKLKK or VEGF motif could restore nitrate reduction to the ΔnapCΔcymA double mutant in a similar way to that of the wild-type, the mutant without the DM motif exhibited significantly reduced nitrate reduction (Fig. S5). Similarly, the substitution and addition of a CymA-specific residue and motifs to NapC, including NapC(+E104Q), NapC+D and NapC+DPE, still resulted in the same phenotype as NapC. In a word, those plasmid-borne napC mutants could still mediate nitrate reduction but conferred no nitrate reduction to the double mutant strain (Table 1).

However, the resultant napC mutant with simultaneous deletion of all four NapC-specific motifs (NapCALDKLKKANADMAVEGF) could complement neither nitrate reduction nor nitrite reduction in the ΔnapCΔcymA double mutant strain. Furthermore, the simultaneous deletion of

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<th>Constructs used in this study</th>
<th>Phenotype</th>
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<th>Nitrite reduction</th>
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+++ Nitrate and nitration reduction rate comparable to that of the wild-type.
++ Nitrate reduction rate between the wild-type and the double mutant ΔnapCΔcymA.
+ Nitrate reduction rate of the double mutant ΔnapCΔcymA.
− Indicates no nitrate reduction.

http://mic.microbiologyresearch.org 935
Fig. 4. (a) Western blot analyses on the expression of a series of plasmid-borne cymA and mutated cymA genes with the His-tag. Lane 1 is the size marker and lane 2 is the empty-vector-carrying ΔnapCΔcymA double mutant used as negative control. Other lanes include His-tagged CymA (lane 3), CymA\textsuperscript{K91Q} (lane 4), CymA\textsuperscript{D97A} (lane 5), CymA\textsuperscript{D166A} (lane 6), CymA\textsuperscript{D166} (lane 7), CymA\textsuperscript{DPE} (lane 8), CymA\textsuperscript{D166} (lane 9), CymA\textsuperscript{D168} (lane 10) and CymA\textsuperscript{D168} (lane 11) recombinant proteins detected by anti-His-tag antibody, respectively. (b) Heme staining analyses on the expression of a series of plasmid-borne cymA and mutated cymA genes. Lane 1 is the size marker, lane 2 is the empty-vector-carrying \\textit{S. putrefaciens} W3-18-1 wild-type strain as the positive control (untagged wild-type CymA) and lane 3 is the empty-vector-carrying ΔnapCΔcymA double mutant used as the negative control. Other lanes include the His-tagged CymA (lane 4), His-tagged CymA\textsuperscript{K91Q} (lane 5), His-tagged CymA\textsuperscript{D97A} (lane 6), His-tagged CymA\textsuperscript{DPE} (lane 7), His-tagged CymA\textsuperscript{D166} (lane 8), His-tagged CymA\textsuperscript{D166A} (lane 9), His-tagged CymA\textsuperscript{D168} (lane 10), His-tagged CymA\textsuperscript{D168} (lane 11) and His-tagged CymA\textsuperscript{D168} (lane 12) recombinant proteins expressed off plasmids in the double mutant and detected by TMBZ, respectively. (c) Western blot analyses on the expression of a series of plasmid-borne napC and mutated napC genes with the His-tag. Lane 1 is the size marker and lane 2...
NapC-specific motifs and addition of CymA-specific motifs (NapCΔLDKLKKANADMVEGF+DPEΔE104D) conferred no nitrite reduction capacity to the NapC mutant (Fig. S6). These results were consistent with the Western blot results suggesting that these NapC-specific residues and motifs might play a key role in either electron transfer or protein stability but might not be related to the specificity of NapC. More efforts are needed in this gain-of-function approach to determine crucial amino acid residues and motifs for the specificity of NapC.

**Crp regulates transcription of cymA**

It is well established that Crp plays a crucial role in the regulation of anaerobic respiration in *S. oneidensis* MR-1, while this small regulatory protein regulates different cellular processes in closely related bacteria such as *E. coli* (Saffarini et al., 2003). The putative Crp binding site has been identified in the upstream of *napB, nrfA* and *narQP* operons in *Shewanella loihica* PV-4, *S. oneidensis* MR-1 and *S. putrefaciens* W3-18-1 strains (Dong et al., 2012; Gao et al., 2010; Qiu et al., 2013; Stewart et al., 2009). It has been previously confirmed that *napB* is independent of Crp-regulation (Qiu et al., 2013), and a putative Crp binding site was present upstream of *cymA* in *S. oneidensis* MR-1 and *S. putrefaciens* W3-18-1 strains (Fig. S7). The transcription levels of *napC* and *cymA* in the wild-type strain and the Δcrp mutant (Table S1) were analysed by using RT-PCR and real-time PCR. The expression of *cymA* decreased significantly in the Δcrp mutant while napC transcription remained largely unchanged (Fig. 7a, b). These results are consistent with our previous finding that napB was independent of Crp regulation (Qiu et al., 2013). The expression of *cymA* is regulated by Crp in both *S. oneidensis* MR-1 and *S. putrefaciens* W3-18-1 strains.

**DISCUSSION**

**Sequential reduction of nitrate and nitrite**

The two-step manner of nitrate ammonification may be common among the *Shewanella* strains. Previously it was proposed that the sequential reduction of nitrate and nitrite may be due to the oxygen sensitivity of nitrite reductase, which is normally expressed after the expression of nitrate reductase. However, the sole nitrate and nitrite reductases, NapA and NrfA, were simultaneously expressed in *S. oneidensis* MR-1 and it was argued that NapB helped to channel the CymA-mediated electron transport into NapA for nitrate reduction first because deletion of napB resulted in a coupled nitrate and nitrite reduction (Gao et al., 2009). On the other hand, it was elucidated that STC and FccA are necessary to bridge the periplasmic gap between the inner membrane-associated CymA and the outer membrane cytochromes in *S. oneidensis* MR-1 (Schuetz et al., 2009; Sturm et al., 2015); the electron transfer direction may be regulated by these two electron-transfer hubs. Moreover, NMR analysis provides the opportunity to explore the dynamics of multidomain cytochromes and heme enzymes (Neto et al., 2014); the mechanism of the two-step reduction of nitrate and the difference of NapC and CymA in the interactions with NapAs and NrfA may be further explored this way.

**The ΔnapCΔcymA double mutant can still reduce nitrate to nitrite**

A much slower nitrate reduction was observed in the ΔnapCΔcymA double mutant because the concentration of nitrite in the medium slowly increased (Fig. 4). This suggests the existence of additional enzymes responsible for nitrate reduction in *S. putrefaciens* W3-18-1. *Shewanella* strains are well known for their respiration flexibility, owing largely to their numerous c-type cytochromes, many of which are uncharacterized functionally. Recently, it was reported that cytochrome bct and CymA are functionally overlapping in nitrate/nitrite reduction in the *S. oneidensis* MR-1 strain (Fu et al., 2013, 2014). Moreover, SirCD can replace CymA for respiration of fumarate, ferric citrate and DMSO in *S. oneidensis* MR-1 (Cordova et al., 2011). Therefore, other redox proteins may have functional similarity to that of CymA and NapC in terms of nitrate reduction in the *S. putrefaciens* W3-18-1 envelope.

**Exploration of the functional sites in CymA and NapC**

The napC gene is part of the napEDABC gene cluster, whereas cymA is a monocistronic gene in *Shewanella*. The NapC/NrfH family tetraheme cytochrome NrfH mediates the electron transfer from menaquinol to the nitrite reductase catalytic subunit (NrfA) of *Wolinella succinogenes* (Simon et al., 2000). Therefore, it was previously predicted that CymA might have derived from NrfH because CymA was required for nitrate reduction in *S. oneidensis* MR-1 (Gao et al., 2009). It had also been proposed that NapC might only participate in nitrate reduction, while CymA could play multiple roles in different electron transfer pathways (Meyer et al., 2004). Our analyses confirm that NapC is specific for nitrate reduction, while CymA is involved in...
reductions of nitrate as well as nitrite in *S. putrefaciens* W3-18-1.

Potential key amino acid residues of NapC and CymA were investigated, which may be attributed to the functional difference of these two members of the same protein family. Based on the alignment of their amino acid sequences and previous research, a series of mutants of NapC and CymA were generated to identify the loss-of-function mutations in *cymA* and gain-of-function mutations in *napC*. The Lys-91 residue was required for both nitrate and nitrite reduction, which is consistent with the previous finding that this residue is required for arsenate reduction and is probably crucial for quinol oxidation (Zargar & Saltikov, 2009). In addition, it was found that the Asp-166 residue of CymA may play an important role in maturation of the cytochrome but is not involved in the specificity of CymA. However, it was found that the amino acid residue Asp-97 may be crucial for the functional diversity of CymA since the mutant CymA<sup>D97A</sup> could still confer a nitrate reduction phenotype but not nitrite reduction. The nitrate reduction rate catalysed by this CymA mutant was slower than that of NapC, and the nitrite reduction was abolished. It is suggested that Asp-97 may facilitate the interaction of CymA with the cytochromes NapB and NrfA but not the NapA nitrate reductase.

**Regulation and evolution of the Nap operons**

It is usually considered that Napα may be involved in denitrification or redox balancing and Napβ may serve in ammonification (Simpson *et al.*, 2010). Moreover, previously, there was an evolutionary scenario of NAPs in *Shewanella*: Napβ as the prototype at the beginning, Napα was subsequently obtained to form the dual NAP systems containing both Napα and Napβ, which would finally evolve to a single Napα (Chen *et al.*, 2011). It seems that the data presented in this paper and our previous analysis (Qiu *et al.*, 2013) are consistent with this evolutionary scenario of the Naps. Napα is independent of Crp regulation, and CymA, which is involved in the nitrate/nitrite reduction of Napβ, is Crp-regulated (Figs 7 and S6) (Qiu *et al.*, 2013). Crp is a
major regulator that plays an important role in cell division, starvation functions, motility and anaerobiosis (Botsford & Harman, 1992; Gao et al., 2010; Saffarini et al., 2003). Probably, the initial Crp-regulated NapB can meet the needs for survival, and the concurrent Crp-independent NapA may enhance the flexibility of Shewanella to diverse habitats. Nitrogen pollution has become increasingly severe, and therefore the Crp-independent NapA required for denitrification may become the predominant functional cluster, whose expression is earlier than that of NapB in S. putrefaciens W3-18-1 (Qiu et al., 2013).

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