HupW Protease Specifically Required for Processing of the Catalytic Subunit of the Uptake Hydrogenase in the Cyanobacterium *Nostoc* sp. Strain PCC 7120

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The maturation process of [NiFe] hydrogenases includes a proteolytic cleavage of the large subunit. We constructed a mutant of *Nostoc* strain PCC 7120 in which hupW, encoding a putative hydrogenase-specific protease, is inactivated. Our results indicate that the protein product of hupW selectively cleaves the uptake hydrogenase in this cyanobacterium.

The [NiFe] hydrogenases are multisubunit enzymes that undergo an extensive maturation process carried out by an array of accessory proteins. Independent of the number of subunits, the core of the hydrogenases is always made up of a small subunit, containing FeS clusters for electron transport, and a large subunit, which contains the [NiFe] active site. The maturation process for the large subunit has been elucidated most extensively in *Escherichia coli* (1, 6), where a group of enzymes called the Hyp proteins are responsible for assembly of the active site of the hydrogenase, which includes the incorporation of the iron and nickel metals as well as CN and CO ligands. This assembly is followed by proteolytic cleavage of the C-terminal end of the large subunit, performed by a hydrogenase-specific protease. The protease binds to the hydrogenase after insertion of nickel into the active site and cleaves off around 20 amino acids, depending on the type of hydrogenase and strain (12, 21). The cleavage takes place after the conserved amino acid sequence PCXXCXXXR, making the histidine or arginine residue the new C terminus (7, 12, 15, 18). For bacterial strains that possess more than one [NiFe] hydrogenase, one set of Hyp proteins may be responsible for maturation of the active site of the different hydrogenases in the cell. For the proteolytic cleavage, however, different proteases that will specifically cleave only one type of hydrogenase are generally present (1).

In cyanobacteria, three key enzymes may be involved in the hydrogen metabolism: nitrogenase, which produces hydrogen as a by-product of nitrogen fixation; a heterodimeric uptake hydrogenase (HupSL), the role of which is to reoxidize hydrogen gas released by the nitrogenase; and a pentameric bidirectional hydrogenase (HoxYHEFU), which can take up or produce hydrogen evolution from nitrogen-fixing cultures, grown in BG11o medium (17) under continuous illumination (40 \(\mu\)mol photons s\(^{-1}\) m\(^{-2}\)) at 25°C, of *Nostoc* PCC 7120 wild type and a *hupW* mutant strain, as previously described (16). Figure 2 shows the signal from the hydrogen electrode in one representative experiment for each strain. It was found that the *hupW* mutant strain released hydrogen gas at an average rate of 3.3 \(\mu\)mol H\(_2\) mg chlorophyll \(a\) (Chl \(a\))\(^{-1}\) h\(^{-1}\) (Table 1), while the wild-type strain released only small amounts of hydrogen (Fig. 2; Table 1). From these results, it is clear that disrupting the *hupW* gene in *Nostoc* PCC 7120, two genes that may encode hydrogenase-specific proteases, hoxW and *hupW*, have been identified (23). In order to examine the function of these genes and the respective encoded proteins further, with a focus on the putative specificity of cyanobacterial hydrogenase-specific proteases, we constructed a *hupW* mutant knockout strain of *Nostoc* PCC 7120. This is the first study where the function and specificity of putative hydrogenase-specific proteases are investigated in cyanobacteria.

In *Nostoc* PCC 7120, two genes that may encode hydrogenase-specific proteases, hoxW and *hupW*, have been identified (23). In order to examine the function of these genes and the respective encoded proteins further, with a focus on the putative specificity of cyanobacterial hydrogenase-specific proteases, we constructed a *hupW* mutant knockout strain of *Nostoc* PCC 7120. This is the first study where the function and specificity of putative hydrogenase-specific proteases are investigated in cyanobacteria.

The *hupW* mutant strain of *Nostoc* PCC 7120 was constructed by the introduction of a neomycin (Nm) resistance cassette (from the pUCK4 vector, GenBank accession no. X06404) into *hupW* using standard cloning procedures and transfer of the interrupted gene into *Nostoc* PCC 7120 by triparental conjugation and homologous recombination according to established procedures (2, 5, 9) (Fig. 1A). The cargo vector used was pRL271 (GenBank accession no. L05081). The isolation of a fully segregated *hupW* mutant strain was confirmed by PCR (Fig. 1B) using primers alr1423-F and -R (5'-TGCTGTAGGGTAGTATCACTCG-3' and 5'-TTTATTTAATTGAGGGCGGG-3', respectively), resulting in a 1,629-bp product corresponding to the insertion of the Nm cassette into the gene *hupW*, while no shorter products were observed. A second primer pair, 2-alr1423-F and -R (5'-CTCAGCATCAGATCACCCGAAAAGCA-3' and 5'-GAGCTCTTAAAAAGG-3', respectively), gave similar results.

A hydrogen electrode was used to measure *in vivo* aerobic hydrogen evolution from nitrogen-fixing cultures, grown in BG11, medium (17) under continuous illumination (40 \(\mu\)mol photons s\(^{-1}\) m\(^{-2}\)) at 25°C, of *Nostoc* PCC 7120 wild type and a *hupW* mutant strain, as previously described (16). Figure 2 shows the signal from the hydrogen electrode in one representative experiment for each strain. It was found that the *hupW* mutant strain released hydrogen gas at an average rate of 3.3 \(\mu\)mol H\(_2\) mg chlorophyll \(a\) (Chl \(a\))\(^{-1}\) h\(^{-1}\) (Table 1), while the wild-type strain released only small amounts of hydrogen (Fig. 2; Table 1). From these results, it is clear that disrupting the *hupW* gene in *Nostoc* PCC 7120 results in a significant reduction in hydrogen evolution.
PCC 7120 had a direct effect on the function of the heterodimeric uptake hydrogenase (HupSL). The function of the uptake hydrogenase is to reoxidize hydrogen produced as a by-product during nitrogen fixation by the nitrogenase (19). When the uptake hydrogenase is inactivated, by interruption of the structural genes as well as the accessory genes, hydrogen will be released into the atmosphere and can easily be detected, as has previously been shown in several species and strains, such as Anabaena variabilis, Nostoc punctiforme ATCC 29133, Nostoc PCC 7120, and Nostoc PCC 7422 (8, 11, 13, 24). The rate at which hydrogen is produced in our hupW mutant strain is in the same range as the rate measured for a hupL mutant strain of Nostoc punctiforme, 7 to 14 μmol H₂/(mg Chl a/ h) (11). Comparisons with the other hupL mutant strains mentioned above cannot easily be made, since in those studies, hydrogen produced by the cultures was measured under an argon atmosphere, which will cause much higher hydrogen evolution from the nitrogenase.

In Nostoc PCC 7120, it has previously been shown that the bidirectional Hox hydrogenase cannot replace the function of the uptake hydrogenase (13). Instead, it was shown that a hoxH mutant in Nostoc PCC 7120 will actually produce less hydrogen than the wild type during nitrogen fixation and that the nitrogenase activity, as measured by acetylene reduction activity, will be slightly lower (13). Thus, our results showing enhanced hydrogen evolution from nitrogen-fixing cells of the hupW mutant strain, together with previous studies, suggest that this release of molecular hydrogen in the hupW mutant strain cannot be coupled to inactivation of the large subunit of the bidirectional hydrogenase but is the result of inactivation of the uptake hydrogenase.

A potential cleavage site for proteolytic processing analogous to the corresponding sites in other organisms has been identified at a position 16 amino acids (aa) from the C-terminal end of the protein in the sequence of Nostoc PCC 7120 HupL, immediately after the sequence DSCCLVCTVH (23). A cleavage at that position will result in a processed protein with a molecular mass of 58.4 kDa, compared to the full-length, unprocessed HupL, which has a calculated molecular mass of 60.2 kDa. SDS-PAGE follow by Western immunoblotting using standard procedures was used to detect the HupL protein in cell extracts of nitrogen-fixing cultures of both wild-type Nostoc PCC 7120 and the hupW mutant strain (Fig. 3). Anti-HupL antibodies were produced using a synthetic peptide with the amino acid sequence LAHEDKYQKPTIEGR, corresponding to a part of HupL from Nostoc punctiforme ATCC 29133, as antigen for the generation of specific polyclonal antibodies (Agrisera, Sweden).

The immunoblot results show a band in protein extracts from the hupW mutant strain that is larger than that in the wild type. The size difference is in agreement with cleavage of an 1.8-kDa
portion of HupL, corresponding to cleavage at the predicted site. This result clearly points to HupW being the protease responsible for cleavage of HupL in Nostoc PCC 7120. Furthermore, as seen in Fig. 3 (upper panel), the amount of HupL protein is substantially smaller in the hupW mutant strain than in the wild type. This effect could be explained by a lower stability of the unprocessed form of HupL. When the protein is not properly processed, it may be prevented from forming a stable complex with the small subunit HupS and thus may be targeted for degradation to a larger extent than the properly matured HupL in the wild type. In a proteomics study on the previously mentioned HupL− strain of Nostoc punctiforme, it was observed that when HupL is missing from the cells, the small subunit of the uptake hydrogenase, HupS, is greatly reduced in abundance as well (4). This may be due to a similar degradation on the small subunit in the absence of a complete and stable hydrogenase.

In order to investigate whether inactivation of HupW affects the bidirectional hydrogenase in Nostoc PCC 7120, measurements of bidirectional hydrogenase activity were carried out. Methyl viologen was used as an artificial electron donor to the hydrogenase. The assays were performed as previously described (20), with the following modifications: Cells were sparged with pure argon gas for 3 h in the dark before addition of 10 mM methyl viologen and 30 mM sodium dithionite. The amount of evolved hydrogen was determined by gas chromatography using a Perkin-Elmer Clarus 500 gas chromatograph (GC) equipped with a thermal conductivity detector (TCD). In assays using cells harvested from non-nitrogen-fixing cultures, grown in BG11 medium (17), it was found that the hupW mutant strain produced amounts of H2 similar to, or even slightly larger than, those produced by the wild-type Nostoc PCC 7120 (Table 1). Experiments were also performed using cultures grown under nitrogen-fixing conditions, resulting in observed activities that were higher than those for non-nitrogen-fixing cultures but still similar between wild type and the hupW mutant strain (Table 1). It is known that the assay used is specific for the bidirectional hydrogenase (10), and thus, the observed activities under nitrogen-fixing conditions cannot stem from the uptake hydrogenase. These results indicate that inactivating HupW has no effect on the bidirectional hydrogenase, and therefore, the HupW activity is specific for the uptake hydrogenase.

By producing a hupW mutant in Nostoc PCC 7120, we can now examine the function and specificity of hydrogenase-specific proteases in detail in cyanobacteria. It is known from studies in other organisms that a protease performs a proteolytic cleavage on the large subunit of [NiFe] hydrogenases (1, 12, 21). A phylogenetic study has shown that the proteases can be divided into groups comparable to the phylogenetic groups identified for the hydrogenases (3), and that HupW and HoxW, like the uptake and the bidirectional hydrogenase, belong to two different clades within the tree (3, 22). The same study also revealed, by in silico studies, a HoxW-specific sequence, the HOXBOX, which may be part of the mechanism(s) behind the observed specificity. The HOXBOX is situated in a part of the protease which is conserved within all hydrogenase-specific proteases. While this conserved part in other groups of hydrogenase-specific proteases consists of the sequence D(G/C)GT, in members of the HoxW group it is replaced by an HQL sequence (aa 42 to 44 in HoxW of Nostoc PCC 7120) (3). This is the only reported difference in amino acid levels between groups of hydrogenase-specific proteases. Since the hydrogenase-specific proteases in Nostoc PCC 7120 belong to two different groups, with and without this HOXBOX, this strain will be ideal for further studies on the importance of this amino acid sequence for protease function and/or substrate recognition.

This is the first time that the function of a cyanobacterial hydrogenase-specific protease has been demonstrated experimentally. By inactivation of the hupW gene, we were able to show that the protein product of hupW is specific for the uptake hydrogenase in Nostoc PCC 7120. In the hupW mutant strain, the uptake hydrogenase is dysfunctional due to an incomplete maturation process, while the bidirectional hydrogenase retains full activity. This study may form the basis for further studies of the substrate recognition (possibly by the HOXBOX) and function of hydrogenase-specific proteases in cyanobacteria.

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REFERENCES