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HAL Id: hal-00586470
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Submitted on 16 Apr 2011

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A composite biochemical system for bacterial nitrate and nitrite assimilation as exemplified by Paracoccus denitrificans

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Running title: Nitrate and nitrite assimilation in Paracoccus denitrificans.

Keywords: nitrate reductase, nitrite reductase, nitrate transport, Paracoccus denitrificans.

Abbreviations used: Nas, assimilatory nitrate reductase; Nar, membrane-bound nitrate reductase; Nap, periplasmic nitrate reductase; FAD, flavin-adenine dinucleotide; NAD(P)+ and NAD(P)H, oxidized and reduced nicotinamide-adenine dinucleotide (phosphate); MV, Methyl Viologen; KM, Michaelis constant; O.D., optical density; \( \mu_{\text{max(app)}} \), apparent maximum growth rate.

The denitrifying bacterium Paracoccus denitrificans can grow aerobically or anaerobically using nitrate or nitrite as the sole N-sources. The biochemical pathway responsible is expressed from a gene cluster comprising a: nitrate/nitrite transporter (NasA), nitrite transporter (NasH), nitrite reductase (NasB), ferredoxin (NasG) and nitrate reductase (NasC). NasB and NasG are essential for growth with nitrate or nitrite as N-source. NADH serves as electron-donor for nitrate and nitrite reduction, but only NasB has a NADH-oxidising domain. Nitrate and nitrite reductase activities show the same \( KM \) for NADH and can be separated by anion-exchange chromatography, but only fractions containing NasB retain the ability to oxidise NADH. This implies that NasG mediates electron-flux from the NADH-oxidising site in NasB to the sites of nitrate and nitrite reduction in NasC and NasB, respectively. Delivery of extracellular nitrate to NasBGC is mediated by NasA, but both NasA and NasH contribute to nitrite uptake. The roles of NasA and NasC can be substituted during anaerobic growth by the biochemically-distinct membrane-bound respiratory nitrate reductase (Nar), demonstrating functional overlap. nasG is highly conserved in nitrate/nitrite assimilation gene clusters, consistent with a key role for the NasG ferredoxin, as part of a phylogenetically widespread composite nitrate and nitrite reductase system.

INTRODUCTION

The importance of inorganic nitrate as a key nutritional component of the global nitrogen cycle, particularly for marine and freshwater autotrophic phytoplankton is long recognised. This highly soluble anion can make a significant environmental impact, supporting accelerated biomass formation or ‘blooms’ in nitrate and phosphate polluted water courses that may have an important role as CO\(_2\) sinks. Accordingly, the biochemistry of nitrate assimilation has been well studied in cyanobacteria where assimilatory nitrate reduction is functionally linked to photosynthetic processes, and both nitrate and nitrite reductases use photosynthetically reduced ferredoxin as
electron donor. By contrast, the utilisation of nitrate by heterotrophic bacteria has received less attention. The ability of heterotrophic bacteria and archaea to metabolise nitrate or nitrite as the sole nitrogen source (N-source) for growth is phylogenetically widespread. However, only a few physiological, genetic and biochemical studies have been performed, most notably early studies on Enterobacter aerogenes [1] and more recent studies on the γ-proteobacterium Klebsiella oxytoca [2], the photoheterotroph Rhodobacter capsulatus [3], the Gram positive bacterium Bacillus subtilis [4] and the diazotroph Azotobacter vinelandii [5]. In contrast to cyanobacteria the reductases from most heterotrophic bacteria are thought to be dependent on the cytoplasmic reduced pyridine nucleotide pool, which enables them to be coupled to organic carbon catabolism [6]. In fact, recent data suggest heterotrophic bacterial species that can utilise nitrate for the biosynthesis of essential cellular components during growth may also be significant consumers of inorganic nitrogen globally, particularly in environments where there are high concentrations of dissolved organic carbon relative to dissolved organic nitrogen [7-9]. This is due to the high bioenergetic demand for reducing equivalents required for the assimilatory reduction of nitrate to ammonia, which requires eight electrons:

\[
\text{NO}_3^- + 2H^+ + 2e^- \rightarrow \text{NO}_2^- + H_2O \quad \text{Equation 1}
\]

\[
\text{NO}_2^- + 8H^+ + 6e^- \rightarrow \text{NH}_4^+ + 2H_2O \quad \text{Equation 2}
\]

Consequently assimilatory nitrate reduction is a good route for disposal of the excess reductant present in a reduced organic carbon pool [10]. However, the biochemical mechanism by which bacterial assimilatory nitrate reductases access this pool of cellular reductant is not well understood, particularly because analysis of the primary structure of heterotrophic bacterial assimilatory nitrate reductases suggests that they do not have a NAD(P)H binding domain [2, 11].

In addition to being a substrate for nitrogen assimilation in heterotrophs, nitrate can also be a substrate for anaerobic respiration, for example in denitrifying bacteria that can reduce nitrate, via nitrite, nitric oxide and nitrous oxide, to dinitrogen gas and enterobacteria that can reduce nitrate to ammonium [1, 12]. One of the paradigm heterotrophic denitrifiers, Paracoccus denitrificans, synthesises two heterotrimeric respiratory ubiquinol/nitrate oxidoreductases, Nar and Nap (Fig. 1). The membrane-bound enzyme (NarGHI) reduces nitrate as the first step of growth-linked anaerobic denitrification while the other, a periplasmic system (NapABC), serves to dissipate excess reducing equivalents formed during aerobic growth [12, 13]. These enzymes have been studied at the biochemical level and derive electrons from the membrane-confined ubiquinol pool [14, 15], which can be coupled to NADH generated from oxidative metabolism via the NADH-ubiquinone oxidoreductase. In P. denitrificans NarGHI, the active site for nitrate reduction is exposed to the cytoplasm and therefore it is dependent on a nitrate transport protein NarK, a fusion protein of two transmembrane domains NarK1 and NarK2, to deliver nitrate into the cell (Fig. 1). These two functional components have putative roles in nitrogen oxyanion trafficking: NarK1 is a proposed proton-linked nitrate importer, and NarK2 is a putative nitrate/nitrite antiporter [16, 17].

Paracoccus species can also assimilate nitrate via a third cytoplasmic reductase that has not yet been characterised, but is known to be distinct from the two respiratory systems [18]. In general, a bacterial nitrate assimilation system (Nas) involves a cytoplasmic molybdenum-dependent nitrate reductase that reduces nitrate to nitrite (Equation 1), which is further reduced to ammonium by a sirohaem-dependent nitrite reductase (Equation 2) [2]. Like the respiratory Nar system, the cytoplasmic assimilatory system is also dependent on nitrate transport into the cell. However, a major biochemical conundrum is that it is not clear how the assimilatory nitrate reductase is coupled to NADH oxidation. This is because primary sequence analysis of bacterial assimilatory nitrate reductases suggests that, in contrast to the nitrite reductases, they do not possess an NADH binding
domain [2, 11]. The absence of such a site is unimportant for photoautotrophic metabolism in cyanobacteria, where the electron donor is ferredoxin that is photoreduced by photosystem I [19], but it is an important issue in organoheterotrophic metabolism where the nitrate reductase needs to be coupled to NADH released from oxidative metabolism of organic substrates. In this study we identify a key role for a putative Rieske-type [2Fe-2S] ferredoxin in \textit{P. denitrificans} that is widely conserved in other bacterial Nas systems and show that this protein is essential for coupling of NADH oxidation to both nitrate and nitrite reduction. A three-component ferredoxin-nitrate-nitrite reductase system is proposed, where the ferredoxin mediates electron transfer from a single NADH-oxidising site within the nitrite reductase to the sites of nitrate and nitrite reduction present in the nitrite reductase and nitrate reductase components, respectively. Bioinformatic analysis of \textit{nas} gene clusters suggests that this is a widespread mechanism amongst heterotrophic bacterial species and so provides the biochemical link between the nitrate reductase and the cytoplasmic NADH pool. In addition we demonstrate a degree of biochemical overlap between the assimilatory Nas system and the respiratory Nar system at the level of nitrate transport and reduction.

**EXPERIMENTAL**

**Bacterial strains, media and growth conditions**

All bacterial strains and plasmids used in this study are listed in Table 1. \textit{P. denitrificans} was routinely cultured under aerobic conditions at 30 °C in either Luria-Bertani (LB) medium or a defined mineral salts medium with 50 mM succinate as the carbon source [20, 21]. Ammonium chloride (10 mM), potassium nitrate (20 mM), potassium nitrite (10 mM) or sodium L-glutamate (5 mM) were used as nitrogen sources. For aerobic batch culture, 50 ml volumes were rotated at 250 rpm in 250 ml flasks. During anaerobic growth, nitrate (30 mM) or nitrite also acted as the respective terminal electron acceptors for cellular respiration. The \textit{Escherichia coli} strains were cultured aerobically on LB medium at 37 °C. Cell growth was followed by measuring the optical density (O.D.) of cultures at 600 nm. Antibiotics were used at the following final concentrations (μg∙ml⁻¹): ampicillin (Ap), 100; kanamycin (Km), 25; rifampicin (Rif), 100; spectinomycin (Spec), 25; streptomycin (Sm), 60; tetracycline (Tc), 10; gentamycin (Gm), 20; chloramphenicol (Cm), 50. Where shown in the manuscript Figs bacterial growth curves are presented as arithmetic plots to minimise distortion of small changes in biomass during the early stages of the growth curve. For determination of growth rates, curves were analysed as semi-log plots from which the apparent maximum growth rate, $\mu_{\text{max(app)}}$ was determined from the gradient of the exponential growth phase.

**Analytical methods**

For preparation of subcellular fractions, \textit{P. denitrificans} strains were cultured in mineral salts medium with nitrate and glutamate in a BioFlo IV fermenter (New Brunswick Scientific, USA) that was maintained at 30 °C, pH 7.2 with dissolved O₂ > 95%. Upon reaching an O.D.₆₀₀ value of approx. 0.6, a 10 litre culture volume was harvested and cells and fractionated to prepare cytoplasmic fractions (supplementary information). Assimilatory nitrate or nitrite reductase activity was assayed spectrophotometrically at pH 7.5 in the presence of the following electron donors: NADH (100 μM), NAD(P)H (100 μM) or dithionite-reduced Methyl Viologen (MV) at 1 mM. Activity assays were performed in quartz cuvettes of 1 cm path length. The reactions were followed by measuring the decrease in absorbance observed over time at 340 nm for NADH (or NADPH) dependent oxidation rates, or at 600 nm when monitoring re-oxidation of the reduced viologen cation radical [22]. Experiments were initiated by addition of NaNO₃ and NaNO₂, as required. NADH dependent assays performed on cytoplasmic cell fractions showed a constant background oxidation that was proportional to the amount of extract used. This rate was unaffected when experiments were performed under strict anaerobic conditions and addition of NAD⁺ up to approx. 1 mM did not affect the rate of NADH-dependent nitrate or nitrite reduction. MV dependent rates were obtained under strict anaerobic conditions, using stock solutions of sodium nitrite and dithionite prepared and
stored anaerobically at 4 °C prior to use [15]. The following molar extinction coefficients, $\varepsilon_{340 \text{ nm}} = 6.22 \times 10^3 \text{ M}^{-1} \cdot \text{cm}^{-1}$ (NADH) and $\varepsilon_{600 \text{ nm}} = 13.7 \times 10^3 \text{ M}^{-1} \cdot \text{cm}^{-1}$ (MV) were used to calculate specific activities. Extracellular nitrate concentration was determined using a Dionex ICS-900 HPLC system fitted with a DSS conductivity detector and AS40 automated sampler. Samples were diluted into analytical reagent grade water (Fisher Scientific, total N <0.1 ppm) and passed through a 0.2 μm syringe filter prior to injection onto a 2 x 250 mm IonPac® AS22 analytical carbonate eluent anion-exchange column. Nitrite concentration present in the extracellular medium was determined colourmetrically as described by Nicholas and Nason [23]. For separation of nitrate and nitrite reductase activities by anion-exchange chromatography a DEAE-Sepharose™ (GE Healthcare) column matrix was equilibrated in 5 mM L-ascorbate, 5mM EDTA, 50 mM Tris-HCl, pH 7.5. The column was loaded with cytoplasmic extract (obtained from P. denitrificans WT cells grown with nitrate as sole N-source), washed with 2 column volumes and then developed with a linear gradient of 0-0.5 M NaCl, over 1 column volume, at 1.5 ml-min$^{-1}$ flow rate.

Samples for two-dimensional polyacrylamide gel electrophoresis (2D-PAGE) were prepared from P. denitrificans WT cells that were washed twice with 50 mM Tris-HCl (pH 8.0) and re-suspended in 10 mM Tris-HCl (pH 9.0) buffer solution containing DNaseI, RNaseA and protease inhibitors prior to lysis by sonication. Unbroken cells and cellular debris were removed by centrifugation (14000 x g) for 20 minutes at 4 °C. Supernatants were then subject to ultracentrifugation (40000 x g) for 1 hour at 4 °C to obtain soluble protein extracts. Protein was quantified using a 2-D Quant kit (GE Healthcare) according to the manufacturer’s instructions and precipitated in 10% (w/v) trichloroacetic acid solution by incubation on ice for 2 hours, followed by centrifugation (14000 x g) for 20 minutes. Protein pellets were washed twice in the following solutions: 50 mM Tris-HCl (pH 8.0), 50 mM Tris (pH unadjusted) and 80% (v/v) ice-cold acetone. Final re-suspension was in 800 μl of solubilisation buffer that contained 7 M urea, 2 M thiourea, 4% (w/v) 3-[3-cholamidopropyl]dimethylammonio]propane-1-sulphonic acid (CHAPS), 1% (w/v) Dithiothreitol (DTT), 1.5% (v/v) IPG buffer (pH range 4-7, GE Healthcare) and a trace of bromophenol blue. This mixture was vortexed for 2 hours and centrifuged (14000 x g) for 30 minutes after which the supernatant was recovered for use. Immobiline DryStrips (11 cm in length, pH range 4-7 from GE Healthcare) were rehydrated with 350 μg of protein for 12 hours into IPTG strip holders (GE Healthcare). Isoelectric focusing (IEF) of samples was then performed in an IPGphor ceramic manifold, covered with Plusone DryStrip cover fluid. Sample strips were focused for 20000 Volt hours in an IPGphor isoelectric focusing system (GE Healthcare). Following IEF, strips were equilibrated as previously described [24] and applied to 12.5% polyacrylamide gels performed with 30% acrylamide/bis solution, 37.5:1 or 29:1 ratio (Bio-Rad). Second dimension separation was performed by using the system Hoefer SE600 (GE Healthcare) and protein spots were visualised using Coomassie staining (2 g/l² Coomassie Brilliant Blue G250 and 0.5 g/l² R250 in 5% methanol, 42.5% ethanol and 10% glacial acetic acid). Triplicate 2D-PAGE separations were generated for each sample condition and gels were imaged using the GS-800 calibrated densitometer (Bio-Rad).

Protein identification was performed in the UCO-SCAI proteomics facility (University of Córdoba, Córdoba, Spain), a member of ProteoRed network. Protein spots of interest were excised automatically in a ProPic station (Genomic Solutions) and subjected to automated digestion with trypsin according to standard protocols in a ProGest station (Genomic Solutions). Peptide fragments were analyzed in a 4700 Proteomics Analyzer MALDI-TOF/TOF mass spectrometer (Applied Biosystems) with an accelerating voltage of 20 kV, in the m/z range 800 to 4000 (reflectron mode). Proteins were identified by peptide mass fingerprinting and confirmed by MS/MS analysis of the 3 most abundant peptide ions. The MASCOT search engine (Matrixscience) was used for protein identification over the non-redundant National Center for Biotechnology Information (NCBI) database of proteins. The confidence in the peptide mass fingerprinting matches ($p < 0.05$) was based on the Molecular weight.
search method (MOWSE) score (higher than 65) and C.I. > 99.8%, and confirmed by the accurate overlapping of the matched peptides with major peaks present in the mass spectrum. The detailed methodologies for cell fractionation and the construction and complementation of the nas mutants is described in the Supplementary Material.

RESULTS

Nitrate and nitrite as nitrogen sources for assimilation by P. denitrificans

In the absence of ammonium, P. denitrificans 1222 was able to grow aerobically using nitrate (Fig. 2A) or nitrite (Fig. 3A) as the sole N-source with values for $\mu_{\text{max(app)}}$ of 0.27 and 0.23 (± 0.01) $h^{-1}$ respectively at pH 7.2 (Table S2). Approximately 10 mM of nitrate or nitrite was consumed during batch culture with 50 mM succinate present as carbon substrate (Figs. 2B and 3B). A maximum O.D. value of 2.15 (± 0.05) was reached after approx. 16 h, corresponding to a growth yield of ~100 mg dry wt cells·mM N$^{-1}$ which were comparable to those obtained from cultures assimilating nitrogen from ammonium under carbon-sufficient growth conditions. With nitrate as sole N-source, a transient accumulation of ~1 mM nitrite in the extracellular medium was observed during growth (Fig. 2C). To probe the biochemical basis of this growth physiology, spectrophotometric solution assays were performed on subcellular fractions from P. denitrificans using reduced pyridine nucleotides as electron donor and either nitrate or nitrite as electron acceptor. Cytoplasmic fractions prepared from cells cultured with nitrate present as the sole N-source showed clear nitrate and nitrite dependent NADH-oxidation rates (Fig. 4). These activities were not detected in either periplasmic or membrane fractions prepared from the same cell cultures, or in any cell fraction when NADPH was used in place of NADH as electron donor. In addition, no activity above a stable background non-specific oxidation rate, which was proportional to the amount of cell extract used, was detected in cytoplasmic fractions from P. denitrificans cells when ammonium was the sole N-source (Fig. 4). This pattern of activity is consistent with the regulation of other bacterial nas systems that are subject to ammonium repression and nitrate induction [2, 5, 19, 31].

Analysis of the P. denitrificans genome (http://genome.jgi-psf.org/parde/parde.home.html) reveals the presence of three gene clusters that likely code for different nitrate reductase systems. The genes for the respiratory systems Nar and Nap are located on chromosome 2 (NC_008687) and plasmid 1 (NC_008688), respectively. These clusters have been characterised previously in the closely related organism Paracoccus pantotrophus [12, 16, 32, 33]. In P. denitrificans, a third putative nitrate reductase gene is present within a cluster on chromosome 2 that is predicted to encode both the regulatory and structural elements for a cytoplasmic nitrate and nitrite reductase system (Pden_4455-4449). This gene cluster comprises seven open reading frames, nasTSABGHC (from 5' to 3') and spans some 10 kilobases from base pairs 1,657,840 to 1,667,370. A non-coding region of approx. 200 bases divides this cluster into two distinct functional units (Fig. 1A). The larger coding region, i.e., nasABGHC, which is the focus of this study, codes for putative redox proteins and substrate transport proteins and lies downstream of two genes encoding a putative nitrate and nitrite responsive two-component regulatory system, nasT and nasS [5]. The role nasABGHC in the assimilation of nitrogen from nitrate was confirmed by insertion of a kanamycin resistance marker into the nasA gene (nasAΔ::Km*). Here, the configuration of the resistance cassette was selected such that transcriptional terminators were present to cause polar effect and prevent expression of all genes collectively transcribed downstream of nasA. Significantly, the nasAΔ::Km* mutant lost the capacity of the wild-type (WT) organism for aerobic growth with both nitrate and nitrite and thus established the importance of the nasABGHC region in the assimilation of both N-sources.
Biochemical properties of cytoplasmic NADH-dependent assimilatory nitrate and nitrite reduction

Spectrophotometric assays were performed to define the kinetic properties of the NADH-dependent nitrate reductase and nitrite reductase activities present in cytoplasmic fractions of *P. denitrificans*. Activity was measured as the concentration of NADH was varied at fixed saturating concentrations of nitrate or nitrite (Fig. 5A, outlined symbols), and conversely as the concentration of nitrate or nitrite was varied at fixed saturating NADH (Fig. 5A, solid symbols). In all cases, enzyme activity varied in accordance with the Michaelis-Menten description and Hanes analysis was performed to define kinetic constants for nitrate (Fig. 5B) and nitrite (Fig. 5C) reduction. Values for \( V_{\text{max}} \) of 111 and 302 (± 12) nmol-min\(^{-1}\)-mg protein\(^{-1}\) were determined for NADH oxidation with nitrate and nitrite present as electron acceptor, respectively. The \( V_{\text{max}} \) expressed as a function of NADH consumed for the nitrite reductase reaction was ~3-fold higher than that for the nitrate reductase reaction. However, when the electron stoichiometries of each reaction are taken into account, i.e., 2e/\( \text{NO}_3^- \) and 6e/\( \text{NO}_2^- \), the rates of nitrate and nitrite reduction are evenly matched, which would minimise the accumulation of toxic nitrite in the cytoplasm. The values of the Michaelis constant (K\( _M \)) for the reduction of nitrate and nitrite were 17 (± 4) and 5 (± 2) μM, respectively. By contrast K\( _M \) values determined for NADH-oxidation during the nitrate reductase or nitrite reductase reactions were in good agreement, at 51 (± 6) and 58 (± 8) μM, respectively.

The elution of nitrate and nitrite reductase activities was monitored when a cytoplasmic fraction was subject to anion-exchange chromatography. Column fractions were assayed for nitrate and nitrite reductase activity using the non-physiological electron donor reduced Methyl Viologen (MV), which has been shown to donate electrons to both nitrate and nitrite reductases (either directly to the active sites or via electron transferring iron sulphur centres [14, 15, 34]). The two activities did not co-elute, with a large peak of MV-dependent nitrate reductase activity eluting at approx. 0.2 M NaCl, and the major peak of MV-dependent nitrite reductase activity eluting at higher approx. 0.3 M NaCl (Fig. 6A). Significantly, the nitrite reductase peak retained NADH-dependent nitrite reductase activity, but the nitrate reductase peak did not (Fig. 6B). A small protein population, eluting at approx. 0.28 M salt, retained both NADH-dependent and MV-dependent nitrate and nitrite reductase activities.

Genetic basis for a composite NADH-linked NasBGC nitrate and nitrite reductase system

Analysis of the *P. denitrificans* NasC primary amino acid sequence suggests that it binds an N-terminal [4Fe-4S] cluster and a molybdenum containing cofactor and so shares a similar general organisation to the assimilatory nitrate reductase of cyanobacteria (NarB) and the catalytic unit of the structurally-defined respiratory periplasmic nitrate reductases (NapA) [35-37]. It is also predicted to contain an additional C-terminal region of ~200 residues that may bind a [2Fe-2S] cluster, as also proposed for the nitrate reductase from *K. oxytoca* (NasA) [2, 31, 38, 39] (Fig. S1). Significantly, none of these nitrate reductases has a canonical NADH binding domain. A *P. denitrificans* strain mutated in nasC lost the capacity for aerobic growth with nitrate as N-source (\( \mu_{\text{max(app)}} < 0.01 \text{ h}^{-1} \)), maximum O.D. < 0.05), but retained the ability to grow using nitrite and displayed similar growth kinetics to WT (\( \mu_{\text{max(app)}} = 0.23 \pm 0.02 \text{ h}^{-1} \), maximum O.D. of 1.21 ± 0.05 was reached after approx. 16 h) (Fig. 7A and Table S2). This finding is consistent with NasC being the sole assimilatory nitrate reductase present during aerobic growth, reducing nitrate to nitrite, but playing no further role in the subsequent reduction of nitrite to ammonium. The nasC mutant could be grown in the presence of glutamate and nitrate (\( \mu_{\text{max(app)}} = 0.25 \pm 0.02 \), O.D.\(_{\text{max}} = 1.3 \pm 0.1 \)). Under these conditions, cytoplasmic fractions from WT cells display both MV- and NADH-dependent nitrate reductase activities, but both activities were absent in the nasC mutant (Table 2).

In order for the assimilation of nitrogen from nitrate to proceed, the cytoplasmic nitrite generated by NasC must be further reduced to ammonium. NasB shares significant sequence homology to flavin, Fe-S, sirohaem-containing nitrite reductases [2, 11, 40] (Fig. S2). The *P. denitrificans* NasB polypeptide is predicted to contain N-terminal FAD and NADH binding domains, while highly conserved central and C-terminal sequence regions contain the cysteine residues.
required for iron-sulphur cluster coordination and the nitrate/sulphite reductase ferredoxin half-domain associated with sirohaem binding (Fig. S2). A P. denitrificans nasB mutant was unable to grow aerobically with either nitrate or nitrite as sole N-source. To confirm that these growth defects were not caused by a downstream effect of the gene disruption process, the nasB strain was complemented with a pEG276-nasB expression construct. The presence of this plasmid allowed the nasB mutant to grow to near WT levels with either nitrate or nitrite as sole N-source, see Table S2 ($\mu_{\text{max(app)}} = 0.20 \pm 0.02 \, \text{h}^{-1}$, maximum O.D. = 1.23 ± 0.05). However, in the absence of the pEG276-nasB expression construct, no growth of the nasB mutant was observed, despite prolonged incubation for several days. This observation excludes the possibility of growth recovery through spontaneous mutation that may up-regulate a cryptic nitrite reductase. Cytoplasmic fractions obtained from the nasB mutant, grown in the presence of glutamate and nitrate, were assayed for NADH-dependent nitrate reductase and nitrite reductase activity. By contrast to that observed for WT cytoplasmic fractions, nitrite reductase activity was not detected in this mutant, consistent with the loss of the assimilatory nitrate reductase, NasB (Table 2). Significantly, nitrate reductase activity was also absent with NADH present as electron donor. Analysis of the NasC primary structure suggests that it lacks the NADH and FAD binding domains present in NasB that would be required for self-contained coupling of NADH oxidation to nitrate reduction (Figs S1 and S2). Therefore the absence of NADH-dependent nitrate reduction in the nasB mutant suggests a model in which the NAD-dehydrogenase domain of NasB provides electrons for both nitrite reduction by the sirohaem domain of NasB and nitrate reduction by NasC (Fig. 1B). Such a model is consistent with the similar $K_m$ values for NADH observed with nitrate or nitrite in cytoplasmic extracts, and also the loss of NADH-nitrate reductase activity when nitrate reductase is separated from nitrite reductase by anion-exchange chromatography. Further evidence in support of this model was forthcoming from measuring nitrate reductase activity in the NasB mutant using the artificial electron donor MV, which can donate electrons directly to the nitrate reductase. Significantly, MV-dependent nitrate reductase activity was detected in the nasB mutant, which confirmed the presence of functional NasC that is unable to couple to NADH oxidation in the absence of NasB.

If the NADH-binding domain of NasB also serves NasC, then this raises the question of how electron transfer between NasB and NasC might occur. NasG is a strong candidate for mediating such electron transfer since it is predicted to be a Rieske-type iron-sulphur protein in which all residues (2 cysteine and 2 histidine) essential for coordination of a [2Fe-2S] redox site are conserved (Fig. S3). A nasG mutant was unable to grow with either nitrate or nitrite as sole N-source, under aerobic conditions. Expression of nasG in trans from a pEG276-nasG expression construct complemented the growth deficiencies of the nasG strain observed with nitrate and nitrite ($\mu_{\text{max(app)}} = 0.22 \pm 0.07 \, \text{h}^{-1}$, maximum O.D. = 1.31 ± 0.05), confirming specific disruption of nasG with no downstream effects, see Table S2. Unlike NasC and NasB there is no direct enzymatic assay with which to establish the synthesis of NasG. However, two-dimensional polyacrylamide gel electrophoresis (2D-PAGE) of soluble extracts from P. denitrificans WT, grown aerobically in the presence of glutamate and nitrate, revealed a protein with the mass and charge characteristics (12.1 kDa and pI of 5.6) of NasG that was absent in the nasG mutant (Fig. 8). Analysis by mass spectrometry confirmed that this spot was the NasG polypeptide (MASCOT Protein Score = 314; Table S3). Cytoplasmic fractions prepared from cells of the nasG mutant grown with glutamate and nitrate were devoid of NADH-dependent nitrate reductase or nitrite reductase activities, but MV-dependent activities were detected (Table 2). These findings confirm that NasG is essential for both NADH-dependent nitrate and nitrite reduction, consistent with the protein mediating electron transfer from NADH to the active sites of both NasB and NasC (Fig. 1B). It was also notable that the MV-dependent nitrite reductase activity was unstable with a half-life of approx. 50 minutes following preparation of the cytoplasmic extract. This instability was reflected in 2D-PAGE analysis of the WT and nasG strains. In WT extract a triad of protein spots of ~88 kDa and pI of ~5.6 were each established by mass spectrometry to be NasB (MASCOT Protein Score = 622; Table S3) (Fig. 8A). As
expected this triad was absent in the nasB mutant. However, they could also not be identified in
extracts from the NasG mutant despite analysis of a number of samples at different protein loadings.
By contrast the NasG spot could be detected at ~WT levels in 2D-PAGE analysis of the nasB strain
(Fig. 8). Thus NasG is stable in the absence of NasB, but may be required for NasB stability. It was
notable that in the nasB strain a new protein spot was very prominent in cells grown with nitrate
and glutamate. This spot was identified by mass spectrometry to be a member of the Hsp20 family
of chaperones that protect unfolded proteins from aggregation (MASCOT Protein Score = 632; Table
S3) [41]. This response may reflect the need to protect NasG whilst it is being assembled in the
absence of its NasB partner or a response to protein damage by nitrosative stress arising from a
lesion in cytoplasmic nitrite reduction.

The contribution of NasA and NasH to nitrate and nitrite transport
Delivery of nitrate and nitrite from the external environment to the cytoplasmic NasBGC system
requires that the two N-oxyanions are transported across the cytoplasmic membrane against a
membrane potential that is negative on the inside of the membrane. NasA and NasH are good
candidate transporters for facilitating assimilatory N-oxyanion import. NasA is predicted to be a 12
trans-membrane helix transporter of the major facilitator super-family (MFS), see Fig.s 1B and S4. P.
denitrificans synthesizes another well characterised MFS family member in the presence of nitrate
under anoxic conditions, NarK that serves to transport nitrate for the respiratory nitrate reductase
system, NarGHI [16, 17, 33] (Fig. 1B). A non-polar nasA strain was constructed and was found to be
strongly attenuated for aerobic growth with nitrate as sole N-source (μ_max(app) = 0.28 ± 0.01 h^{-1},
maximum O.D. = 1.79 ± 0.09) to that observed for WT, when cultured aerobically with either nitrate
or nitrite as sole N-source at pH 7.2 (Fig.s 2 and 3). The pattern of nitrite consumption from the extracellular medium during growth with
nitrate as sole N-source was also similar in the WT and nasH strains (Fig. 3B), as was the transient
accumulation of approx. 1 mM nitrite observed during the mid to late exponential growth phase
when nitrate was present as sole N-source (Fig. 2C). A double nasA nasH mutant also retained the
ability to grow with nitrite as sole N-source, at pH 7.2 (μ_max(app) = 0.20 ± 0.01 h^{-1}, maximum O.D. =
1.72 ± 0.05), displaying similar growth kinetics to the nasA strain (Fig. 3A and Table S2). Nitrite is a
protonatable anion that exists in equilibrium with nitrous acid (NO_2^- + H^+ ⇌ HNO_2), with a pK_a value
of 3.3 [17]. Thus, at pH 7 with an external nitrite concentration of 10 mM, the concentration of HNO_2
is present in the low micromolar range. This acid could freely diffuse across the phospholipid bilayer,
dissociate in the cytoplasm, and so deliver nitrite to the NasBGC complex without recourse to a

NasH is a putative member of the formate-nitrite transporter super-family that includes NirC
from E. coli (Fig. S5) [42-44]. Recent evidence suggests that NirC can move nitrite bi-directionally
across the cytoplasmic membrane during anaerobic growth of E. coli (29). NasH is thus a prime
candidate for mediating nitrite uptake or export and so may be important for nitrite homeostasis
during nitrate assimilation. Perhaps surprisingly though, the P. denitrificans nasH mutant displayed
similar growth kinetics and yields (μ_max(app) = 0.28 ± 0.01 h^{-1}, maximum O.D. = 1.79 ± 0.09) to that
observed for WT, when cultured aerobically with either nitrate or nitrite as sole N-source at pH 7.2
(Fig.s 2 and 3). The pattern of nitrite consumption from the extracellular medium during growth with
nitrate as sole N-source was also similar in the WT and nasH strains (Fig. 3B), as was the transient
accumulation of approx. 1 mM nitrite observed during the mid to late exponential growth phase
when nitrate was present as sole N-source (Fig. 2C). A double nasA nasH mutant also retained the
ability to grow with nitrite as sole N-source, at pH 7.2 (μ_max(app) = 0.20 ± 0.01 h^{-1}, maximum O.D. =
1.72 ± 0.05), displaying similar growth kinetics to the nasA strain (Fig. 3A and Table S2). Nitrite is a
protonatable anion that exists in equilibrium with nitrous acid (NO_2^- + H^+ ⇌ HNO_2), with a pK_a value
of 3.3 [17]. Thus, at pH 7 with an external nitrite concentration of 10 mM, the concentration of HNO_2
is present in the low micromolar range. This acid could freely diffuse across the phospholipid bilayer,
dissociate in the cytoplasm, and so deliver nitrite to the NasBGC complex without recourse to a

8
specific nitrite uptake system. The extent to which this could occur will be decreased at higher pH. It was therefore notable that when the nasH and nasA nasH mutants were grown at pH 9.2 with nitrite as the sole N-source, significant attenuation in growth and nitrite consumption was observed in both cases, thus demonstrating a role for NasH in nitrite import (Figs 3C, 3D and Table S2).

Functional substitution of Nar components for Nas components in anaerobic nitrate assimilation

P. denitrificans could grow anaerobically, as well as aerobically, with nitrate or nitrite as the sole N-source (Fig. 7 and Table S2). Under these growth conditions energy conservation is via nitrate and nitrite respiration through the anaerobically synthesised Nar and Nir systems, respectively [12]. The Nar system includes the respiratory ubiquinol/nitrate oxidoreductase, NarGHI of which the NarG nitrate-reductase subunit is located at the cytoplasmic face of the cytoplasmic membrane and a fusion protein of two NarK-type modules facilitates nitrate and nitrite movement across the membrane (Fig. 1B). To investigate whether the NarG and NarK proteins could functionally substitute for NasC and NasA, the nas mutants were cultured under anaerobic conditions with nitrate present as sole N-source and electron acceptor anoxic, conditions that result in nar gene expression. Both the nasA and nasC mutants showed significant growth under these conditions (Fig. 7B), despite being unable to grow aerobically with nitrate as sole N-source (compare Figs 2A and 7B). The nasC mutant was also able to grow anaerobically with nitrite present as both sole N-source and respiratory electron acceptor (Fig. 7C). Unlike the nasC strain, however, neither the nasB or nasG mutants retained the ability to grow anaerobically with nitrate or nitrite, demonstrating that the NADH-dependent NasBG nitrite reductase was indispensible to both oxic and anoxic assimilation of nitrate and nitrite.

DISCUSSION

This work has established that P. denitrificans NasC and NasB are both part of a cytoplasmic NADH-dependent assimilatory nitrate and nitrite reduction system. However, analysis of the primary structures of both proteins revealed that only NasB has a canonical FAD-dependent NADH binding domain. A bioinformatic analysis of predicted gene products for nasC and nasB homologues from the diverse bacterial phyla suggests that this is a common feature (Fig. S6). There is no bacterial assimilatory nitrate reductase that we can identify that has an NAD(P)H binding site. As such, this makes them quite distinct from plant and fungal assimilatory nitrate reductases in which NAD(P)H binding domains are ubiquitous [45]. In the present study we have reported genetic and biochemical data that suggests that the Nitrooxidising FAD domain of NasB provides electrons for both nitrite reduction by the NasB ferredoxin:sirohaem active site and nitrate reduction by the NasC molybdenum cofactor active site: (i) NADH-dependent nitrate reductase activity is lost when the nitrate reductase is separated from the NADH-dependent nitrite reductase; (ii) the K_m value for NADH determined with either nitrate or nitrite is the same in cytoplasmatic fractions from WT cells; (iii) non-polar deletion of nasB results in loss of aerobic growth with nitrate as sole N-source; (iv) non-polar deletion of nasB results in loss of NADH-dependent nitrate reductase activity, but not MV-dependent nitrate reductase activity. We also show that the putative Rieske [2Fe-2S] ferredoxin, NasG is required for these NADH-dependent electron transfer processes because in a nasG strain: (i) no growth is observed with either nitrate or nitrite as sole N-source and (ii) NADH-dependent nitrate and nitrite reductase activities are absent in cytoplasmatic extracts, but MV-dependent activities are detected. These findings imply that NasG can interact in the cytoplasm with both NasB and NasC, and lead us to propose a model in which it serves at the interface of a composite NADH-dependent nitrate and nitrite reductase system, NasBGC (Fig. 1B).

It is notable that many bacterial nas clusters that we have examined encode a NasG-like protein, in addition to an NADH-oxidising sirohaem-dependent nitrite reductase, suggesting an important conserved function (Fig. S6). It is absent in the Synechococcus elongatus cluster (Fig. 9),
but in this case the photoautotroph uses reduced ferredoxin generated from photosystem I to drive
nitrate and nitrite reduction [19]. A nosG homologue is also absent from the nas cluster of *Klebsiella*
species (Fig. S6) [39]. However, these novel larger NasB proteins show an extended C-terminal
region of approx. 100 residues that shares homology with NasG. In addition, in *Klebsiella oxytoca*
there is a gene in the nas operon that codes for a flavoprotein which may substitute for NasG or
support it in enabling electron transfer from NADH to the nitrate reductase subunit. A homologue of
this gene may also be playing such a role in *Bacillus subtilis* [4], whilst in *Klebsiella pneumoniae* this
gene appears to be fused to the gene for the nitrite reductase (Fig. S6). Nevertheless, even taking
these exceptions into account, the widespread distribution of NasG-type modules leads us to
propose that the composite NasBGC system exemplified here by *P. denitrificans* is a very common
feature of Nas systems in phylogenetically diverse bacteria. Though the interaction between NasC
and NasBG does not resist anion-exchange chromatography, there is precedent for a stable
interaction between a molybdenum cofactor dependent enzyme and Rieske-type ferredoxin.

Intriguingly, the catalytic subunit of the arsenite oxidase from *Alcaligenes faecalis* forms a stable
heterodimeric complex and co-crystallises with its redox partner, a Rieske-type [2Fe-2S] protein that
shares sequence similarity with NasG (~40 %) [46, 47]. Structural studies also revealed that the iron-
sulphur centres present in each subunit are ideally situated, at <14 Å (edge-to-edge) from one
another across the heterodimeric interface, to facilitate rapid electron transfer that does not limit
catalysis [47]. Thus, the NasC-NasG interaction may be a weaker manifestation of the protein-
protein interaction observed in the arsenite oxidase complex. The genetic evidence that NasG is a
dedicated ferredoxin for the NasBC system and that the NasB protein is possibly unstable is perhaps
surprising given that *P. denitrificans* genome predicted to encode a number of small cytoplasmic
ferredoxins. However, precedent for this may be found in the *E. coli* cytoplasmic nitrite reductase
system. *E. coli* is unable to grow aerobically with nitrite as sole N-source, but when grown under
nitrate-rich anoxic conditions a respiratory nitrate reductase NarG and a sirohaem:ferredoxin-type
nitrite reductase, NirB operate in the cytoplasm to respire nitrate and detoxify the nitrite product
(Fig. S6) [50]. *E. coli* can also grow anaerobically with nitrite as sole N-source under conditions
where the nirB gene encoding this anaerobically-inducible nitrite reductase is expressed [50, 51]. *E.
coli* nirB is a homologue of *P. denitrificans* nasB (65% similarity) and both genes are found upstream
of their ferredoxin partners, *E. coli* nirD and *P. denitrificans* nasG, respectively, which share 59%
similarity (Fig. S6). Significantly, like the *P. denitrificans* nasG mutant, NADH-dependent nitrite
reductase activity is also lost in an *E. coli* nirD mutant [52]. In both *E. coli* and *P. denitrificans* the
nirB/nasB and nirD/nasG loci lie immediately upstream of a gene encoding a transporter nirC/nasH
(55% similarity) in their respective genomes (Fig. S6). Here, by growing *P. denitrificans* at high pH to
minimise HNO₂ formation, we have shown that nasH contributes to nitrate uptake. These
observations show a clear genetic and biochemical link between two nitrite reductase systems with
distinct primary functions in nitrite assimilation and detoxification.

Turning finally to the rescue of nasA and nasC mutants under anaerobic growth conditions
by the respiratory Nar system. This is consistent with functional overlap between two physiologically
distinct systems whose cellular function commonly requires the import and cytoplasmic based
reduction of nitrate. In this respect, it is notable that an assimilatory nitrate reductase gene is absent
from some assimilatory gene clusters in nitrate-assimilating bacteria where the respiratory nitrate
reductase *nas* gene is present at a different genetic locus in the bacterium. A noteworthy example
is *Mycobacterium* (Fig. S6), in which narG mutants cannot grow with nitrate as sole N-source [48,
49]. The interchangeability between NasC and NarGHI in anaerobic assimilatory nitrate reduction is
also consistent with the dissociation of NasC from NasBG observed during anion-exchange
chromatography, suggesting a modular arrangement in which NasBG can exist as a stable functional
entity in the absence of NasC.
ACKNOWLEDGEMENTS

This work was supported by the Biotechnology and Biological Sciences Research Council [grant numbers BBE0219991 and BBD5230191]. DJR is a Royal Society and Wolfson Foundation for Merit Award Fellow. MDR thanks the Ministerio de Ciencia y Tecnología for supporting the work through Grants BIO2005-07741-C02-01 and BIO2008-04542-C02-01 and the Junta de Andalucía for Grant CVI1728. VML-A was recipient of a postdoctoral fellowship from the Ministerio de Ciencia y Tecnología, Spain. We thank Dr Niels-Ulrik Frigaard (University of Copenhagen, Denmark) for providing the pSRA2 plasmid containing the streptomycin and spectinomycin resistance cassette and Dr Eva Pérez Reinado (University of Cordoba, Spain) for the mobilizable vector pSUP202*. We are also grateful to the U.S. Department of Energy for providing the funds to sequence the genome of Paracoccus denitrificans PD1222.

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47 Ellis, P. J., Conrads, T., Hille, R. and Kuhn, P. (2001) Crystal structure of the 100 kDa arsenite oxidase from *Alcaligenes faecalis* in two crystal forms at 1.64 Å and 2.03 Å. Structure 9, 125-132
FIGURE LEGENDS

Fig. 1. Genetic and proposed functional organisation of the assimilatory nitrate reductase system from *P. denitrificans* PD1222. The *nas* gene cluster includes seven open reading frames, *nasTSABGHC* (A). The gene products have the following putative roles, two regulatory components (*nasS* and *nasT*), two nitrogen oxyanion transporters (*nasA* and *nasH*), nitrate and nitrite reductases (*nasC* and *nasB*, respectively) and a ferredoxin (*nasG*). Three distinct nitrate reductase systems are present in *P. denitrificans* (B). The periplasmic (NapABC) and membrane-bound (NarGHI) enzymes are ubiquinol-dependent respiratory nitrate reductases. NarK, a nitrate importer, moves nitrate into the cytoplasm and also exports nitrite, the product of nitrate reduction, to the periplasm to support respiratory denitrification. For assimilatory nitrate reduction, electrons likely derived from NADH within the FAD-containing nitrite reductase (NasB) flow to the nitrate reductase (NasC), possibly via the small ferredoxin (NasG). In the Nas system there are two transporters, NasA and NasH, which are predicted to be involved in nitrate and nitrite transport, respectively. Note that there is no common nomenclature for assimilatory nitrate and nitrite reductase genes in prokaryotes. In the case of nitrite reductase genes the ‘*nir*’ prefix is quite widely used, but since *P. denitrificans* has a separate respiratory nitrite reductase ‘*nir*’ gene cluster, this term would be inappropriate. Likewise the ‘*nar*’ prefix is sometimes used for the assimilatory nitrate reductase genes, but this would also be inappropriate for *P. denitrificans* which also has a *nar* gene cluster encoding the respiratory nitrate reductase system. Hence we have adopted the *nas* prefix for the genes encoding the assimilatory nitrate and nitrite reductase system of *P. denitrificans*. The term ‘nH+’ indicates that the number of protons (n) moved across the membrane is not known.

Fig. 2. Aerobic growth of *P. denitrificans* WT (squares), *nasA* (circles), *nasH* (triangles) and *nasA nasH* (inverted triangles) strains with nitrate present as the sole nitrogen source (A). Extracellular nitrate (B) and nitrite (C) concentrations are shown for growth of strains described in (A). Data shown are the average of triplicate determinations.

Fig. 3. Aerobic growth of *P. denitrificans* WT (squares), *nasA* (circles), *nasH* (triangles) and *nasA nasH* (inverted triangles) strains with nitrite present as the sole nitrogen source. Cells were cultured at pH 7.2 (A) and pH 9.2 (C), during which extracellular nitrite concentration was determined (shown in B and C, respectively). Data shown are the average of triplicate determinations.

Fig. 4. The nitrate and nitrite reductase activity of cytoplasmic fractions of *P. denitrificans*. Fractions prepared from cells grown with either nitrate (solid lines) or ammonium (dashed lines) as sole nitrogen source were assayed for nitrate (A) and nitrite (B) reductase activity. Spectrophotometric assays were performed at pH 7.5 in the presence of NADH (100 µM). The reaction was initiated by addition of either nitrate or nitrite and followed by measuring the decrease in absorbance observed over time at 340 nm.

Fig. 5. Kinetic properties of NADH-dependent assimilatory nitrate and nitrite reduction. NADH-dependent nitrate (squares) and nitrite (circles) reductase activities present in cytoplasmic fractions from *P. denitrificans* grown with nitrate as sole nitrogen source (A). Solid and outlined symbols show (i) NADH oxidation rates observed with substrate concentration varied against fixed NADH (200 µM), and (ii) NADH varied against fixed substrate concentration (200 µM), respectively. Hanes analysis of nitrate reductase (B) and nitrite reductase activities (C) presented in A. Values for $K_M$ of 17 and 5 (± 2) µM were derived for nitrate and nitrite reduction, respectively. Similar $K_M$ values for NADH of 58 and 51 (± 8) µM were determined with nitrate or nitrite as electron acceptor, respectively. From (i) $V_{max}$ values for nitrate and nitrite reduction were 95 and 86 (± 10) units...
respectively, and (ii) $V_{\text{max}}$ values of 111 and 302 (±12) units were determined for NADH oxidation with nitrite and nitrite, respectively (1 unit ≡ 1 nmol·min$^{-1}$·mg protein$^{-1}$).

**Fig. 6.** A representative activity-elution profile observed during anion exchange chromatography. Panels A and B show MV- and NADH-dependent nitrate (solid symbols) or nitrite (outlined symbols) reductase activities present in column fractions, respectively. DEAE-Sepharose™ column matrix was equilibrated in 5 mM L-ascorbate, 5mM EDTA, 50 mM Tris-HCl, pH 7.5. The column was loaded with a cytoplasmic extract from *P. denitrificans* grown with nitrate as sole nitrogen source, washed with 2 column volumes and then developed with a linear gradient of 0-0.5 M NaCl, over 1 column volume at 1.5 ml·min$^{-1}$ flow rate.

**Fig. 7.** Growth curves for the *nasC* and *nasA* strains under aerobic and anaerobic conditions. Aerobic growth of the *nasC* strain with either nitrate (squares) or nitrite (circles) present as the sole nitrogen source (A). Anaerobic growth of WT (squares), *nasA* (circles) and *nasC* (triangles) strains with either nitrate (B) or nitrite (C) present as the sole nitrogen source. Data shown are the average of triplicate determinations.

**Fig. 8.** 2D-PAGE analysis of soluble extracts from *P. denitrificans*. 350 µg of protein was applied to 11 cm strips. Isoelectric focusing was performed in the range 4-7. The 12.5% polyacrylamide gels formed with either with 30% acrylamide/bis solution, 37.5:1 (A) or 29:1 ratio (B).
Table 1. Bacterial strains and plasmids used in this work.

<table>
<thead>
<tr>
<th>Strain or plasmid</th>
<th>Relevant characteristics</th>
<th>Source or reference</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Bacteria</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Paracoccus denitrificans</td>
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<td>wild-type, PD1222</td>
<td>Rif(^r), Spec(^r), enhanced conjugation frequencies</td>
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<td>nasA(_\Delta::\text{Km})(^*)</td>
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<tr>
<td>nasB(_\Delta::\text{Sm})</td>
<td>Sm(^r)</td>
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<td>nasG(_\Delta::\text{Sm})</td>
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<tr>
<td>nasH(_\Delta::\text{Sm})</td>
<td>Sm(^r)</td>
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<td>nasC(_\Delta::\text{Tc})</td>
<td>Tc(^r)</td>
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<td>nasA(<em>\Delta::\text{Km}/\text{nasH}(</em>\Delta::\text{Sm})</td>
<td>Km(^r), Sm(^r)</td>
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<td><strong>Escherichia coli</strong></td>
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<td>pEG276-nasG</td>
<td>Gm(^r), <em>P. denitrificans nasG</em> expression construct</td>
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Table 2. NADH- and reduced MV-dependent nitrate and nitrite reductase activity of cytoplasmic fractions prepared from *P. denitrificans* strains affected in *nasB*, *nasG* and *nasC* grown in the presence of nitrate plus glutamate.

<table>
<thead>
<tr>
<th>Strain</th>
<th>Electron acceptor</th>
<th>Electron donor</th>
<th>Electron donor NADH</th>
<th>Electron donor MV</th>
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<tr>
<td>WT</td>
<td>NO$_3^-$</td>
<td>13 ± 4</td>
<td>20 ± 1</td>
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<tr>
<td></td>
<td>NO$_2^-$</td>
<td>35 ± 2</td>
<td>203 ± 22</td>
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<td><em>nasC</em></td>
<td>NO$_3^-$</td>
<td>n.d.</td>
<td>n.d.</td>
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<tr>
<td></td>
<td>NO$_2^-$</td>
<td>39 ± 4</td>
<td>205 ± 20</td>
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<tr>
<td><em>nasB</em></td>
<td>NO$_3^-$</td>
<td>n.d.</td>
<td>13 ± 2</td>
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<td>NO$_2^-$</td>
<td>n.d.</td>
<td>n.d.</td>
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<td><em>nasG</em></td>
<td>NO$_3^-$</td>
<td>n.d.</td>
<td>142 ± 4</td>
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<td></td>
<td>NO$_2^-$</td>
<td>n.d.</td>
<td>103 ± 7*</td>
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</table>

Activity units = nmoles·min$^{-1}$·mg protein$^{-1}$

n.d. = not detectable

* Activity decayed with t$_{1/2}$ of approx. 50 minutes
Fig. 1.
Fig. 2.
Fig. 3.

A

B

C

D

Extracellular [nitrite] (mM)

Time (h)

OD$_{600nm}$
Fig. 4.

A

Cytoplasmic fraction

NaNO$_3$ (1mM)

NH$_4^+$ grown control

NO$_3^-$ grown cells

B

Cytoplasmic fraction

NaNO$_2$ (1mM)

NH$_4^+$ grown control

NO$_3^-$ grown cells
Fig. 5.

**A**

NADH oxidation (nmol min\(^{-1}\) mg protein\(^{-1}\))

[S] (\(\mu\)M)

**B**

[S]/\(V_{\text{max}}\) (\(\mu\)M nmol min\(^{-1}\) mg protein\(^{-1}\))

[S] (\(\mu\)M)

**C**

\[V_{\text{max}}(\text{NO}_3^-) = 96 \pm 8 \text{ units}\]

\[V_{\text{max}}(\text{NADH}) = 111 \pm 10 \text{ units}\]

\[V_{\text{max}}(\text{NO}_2^-) = 85 \pm 6 \text{ units}\]

\[V_{\text{max}}(\text{NADH}) = 302 \pm 8 \text{ units}\]
Fig. 6.
Fig. 7.
Fig. 8.