Routes of iron entry into, and exit from, the catalytic ferroxidase sites of the prokaryotic ferritin SynFtn†

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Ferritins are multimers comprised of 4 α-helical bundle monomers that co-assemble to form protein shells surrounding an approximately spherical internal cavity. The assembled multimers acquire Fe\(^{3+}\) from their surroundings by utilising channels that penetrate the protein for the transportation of iron to diiron catalytic centres buried within the monomeric units. Here oxidation of the substrate to Fe\(^{3+}\) is coupled to the reduction of O\(_2\) and/or peroxide to yield the precursor to a ferric oxy hydroxide mineral that is stored within the internal cavity. The rhombic dodecahedral quaternary structure results in channels of 4-fold and 3-fold symmetry, located at the vertices, which are common to all 24mer-ferritins. Ferritins isolated from higher eukaryotes have been demonstrated to take up Fe\(^{2+}\) via the 3-fold channels. One of the defining features of ferritins isolated from prokaryotes is the presence of a further 24 channels, the B-channels, and these are thought to play an important role in Fe\(^{2+}\) uptake in this sub-family. SynFtn is an unusual ferritin isolated from the marine cyanobacterium Synechococcus CC9311. The reported structure of SynFtn derived from Fe\(^{2+}\) soaked crystals revealed the presence of a fully hydrated Fe\(^{2+}\) associated with three aspartate residues (Asp137 from each of the three symmetry related subunits) within each three-fold channel, suggesting that it might be the route for Fe\(^{2+}\) entry. Here, we present structural and spectrokinetic data on two variants of SynFtn, D137A and E62A, designed to assess this possibility. Glu62 is equivalent to residues demonstrated to be important in the transfer of iron from the inner exit of the 3-fold channel to the catalytic centre in animal ferritins. As expected replacing Asp137 with a non-coordinating residue eliminated rapid iron oxidation by SynFtn. In contrast the rate of mineral core formation was severely impaired whilst the rate of iron transit into the catalytic centre was largely unaffected upon introducing a non-coordinating residue in place of Glu62 suggesting a role for this residue in release of the oxidised product. The identification of these two residues in SynFtn maps out major routes for Fe\(^{2+}\) entry to, and exit from, the catalytic ferroxidase centres.

Introduction

Iron is an essential micronutrient required for the correct functioning of proteins involved in such processes as electron transfer, catalysis and signalling. In many cases the biological function of iron is underpinned by the facile inter-conversion of the Fe\(^{2+}\) and Fe\(^{3+}\) oxidation states. However, in the presence of peroxide and superoxide, formed as by-products of aerobic respiration, iron redox chemistry can be detrimental as it catalyses the production of damaging hydroxyl radicals. Furthermore, Fe\(^{3+}\), the most stable oxidation state of iron at ambient dissolved oxygen concentrations, is poorly soluble at pH ≥ 3.1 Thus, living systems must sequester sufficient iron to meet requirements, and tightly regulate intracellular concentrations of the free metal ion. Members of the ferritin superfamily of proteins are critical to achieving this in many organisms ranging from prokaryotes to higher mammals.2−4

Ferritins are typically composed of 24 four α-helical bundle subunits approximately 45 Å along their longest axis, which are of two types: H-chain and L-chain. Buried within H-chain type subunits is a catalytic diiron centre, called the ferroxidase centre, which is responsible for driving Fe\(^{2+}\) oxidation/mineralization. While animal ferritins are almost always heteropolymers of H- and L-chain subunits, plant and prokaryotic ferri-
tins are composed of only H-chain type subunits. The 24 sub-units co-assemble into hollow rhombic dodecahedra with external and internal diameters of 120 Å and 80 Å respectively. The protein cages are penetrated by channels 12–15 Å in length located at the 3-fold and 4-fold vertices of these dodecahedra (Fig. 1A and B). Following Fe$^{3+}$ oxidation, up to several thousand equivalents of Fe$^{3+}$ can be stored as a hydrated ferric-oxo mineral within the ferritin molecule’s internal cavity.\textsuperscript{2-4} The diiron ferroxidase centres are located at the centre of H-chain type α-helical bundles. They are not accessible to Fe$^{2+}$ directly through the subunit, and they are at least 20 Å away from any of the protein channels. Therefore, ferritin activity requires a route of Fe$^{2+}$ transit from the exterior of the protein to the site of its oxidation.

The route of iron transit has been elucidated for recombinantly expressed homopolymers of human H and frog M ferritin, largely due to the work of the groups of Theil, Turano and Mangani.\textsuperscript{5-10} The peptide sequences of the ferritins of higher eukaryotes are highly conserved with respect to residues located close to the 3-fold channel (Fig. S1†), and both crystallographic data and disruption of this channel by site directed mutagenesis demonstrate that this is the route of iron entry into these proteins.\textsuperscript{5,10,11} Specifically, two conserved carboxylate residues (Asp127 and Glu130, Frog M numbering) generate two symmetry-related binding sites for hexaquo-Fe$^{2+}$ within each channel.

A further two conserved Glu residues (Glu57 and Glu136, Frog M numbering) were identified as important for Fe$^{2+}$ uptake in animal ferritins and are conserved in their counterparts isolated from plants (Fig. S1†), suggesting a similar route for substrate transport, but this is not the case for the prokaryotic ferritins (Ftns). Whilst there is a great deal of similarity in the peptide sequences at the 3-fold axes within the Ftns, these are distinct from those of the animal- and phyto-ferritins (Fig. S1†), such that the 3-fold channels would be expected to transport Fe$^{3+}$ or other ionic species. Intriguingly however the ‘transfer carboxylates’ Glu57 and Glu136 of Frog M ferritin are conserved in the Ftn proteins suggesting that they may undertake varying or multiple roles.

Residues lining the 4-fold channels of ferritins are, in general, less well conserved than those at the 3-fold channels, and this remains the case within the Ftn subfamily. However, despite the variability in peptide sequence, the 4-fold channels of Ftns are again mostly comprised of residues with hydrophobic sidechains (Fig. S1†), and, as such, are unlikely to transport Fe$^{2+}$ from bulk solution to the interior of the protein.

A third ferritin channel, named the B-channel, is found almost exclusively in proteins from prokaryotes.\textsuperscript{14-16} The B-channels are located at the intersection of three monomeric units (Fig. 1C) and are lined with two carboxylate side chains providing a favourable electrostatic environment for Fe$^{2+}$ transport (Fig. S1†). Metal ions have been observed bound to these B-channels\textsuperscript{37} and their disruption by mutagenesis has been shown to impair Fe$^{2+}$ oxidation and mineralisation\textsuperscript{16} suggesting that in at least a subset of prokaryotic ferritins these B-channels constitute the major route of iron uptake. However it is by no means clear that this is the case for the entire subfamily of Ftns.

A bacterial ferritin, called SynFtn, isolated from the coastal marine cyanobacterium Synechococcus strain CC9311 was recently shown to be unusual in that it more closely resembles eukaryotic H-chain ferritins than previously studied Ftn proteins.\textsuperscript{18} This study demonstrated that SynFtn oxidises iron via a mechanism that is unique among diiron proteins characterised to date. The protein as isolated was free from metal ions. Addition of Fe$^{2+}$ led to rapid binding at the ferroxidase centre and, in the presence of O$_2$, oxidation to Fe$^{3+}$ in a multiphasic reaction. Quantification of the absorbance change associated with the most rapid of these phases revealed that this corresponded to the oxidation of only one equivalent of Fe$^{2+}$ per
protein monomer despite the product of O₂ reduction being peroxide (a 2 electron reduction). Time resolved EPR showed this rapid burst of iron oxidation to be due to formation of a Fe²⁺/Fe³⁺ mixed valent ferroxidase centre (MVFC) from the di-Fe³⁺ site. A transient radical signal from a conserved tyrosine residue (Y40) also formed during the initial rapid iron oxidation event, but not in sufficient yield to provide the second reducing equivalent to oxygen. Rather, this residue served to initiate an electron transport chain enabling each of two di-Fe³⁺ sites to deliver a single electron to O₂ bound at only one, generating two MVFC per O₂ reduced. The MVFC was metastable in the presence of O₂, decaying to an EPR silent species with a half-life of approximately 10 s. Quantification of the total absorbance change demonstrated that this was due to further oxidation of the MVFC to a di-Fe⁴⁺ state, akin to that reported for other ferritins, which is unstable leading to release of iron from the di-Fe³⁺ centres into the internal cavity, regenerating apo sites capable of reacting again with Fe²⁺ and O₂ to support mineralisation of up to 2000 Fe per Ftn within the core of SynFtn. Thus in the overall reaction, 4 Fe²⁺ ions bind at 2 ferroxidase centres and react sequentially with 2 equivalents of O₂ generating initially 2 MVFCs and one equivalent of H₂O₂, then 2 di-Fe³⁺ centres and a further equivalent of H₂O₂. Regeneration of the rapid activity associated with apo centres suggested that, in the absence of further incoming Fe²⁺, release of the mineral precursors into the interior cavity begins almost immediately but requires 60 min to reach completion.

The high resolution structure of SynFtn derived from crystals soaked in a Fe²⁺ containing solution for 20 min (PDB entry 6GKA) revealed a Fe²⁺ ion within the 3-fold channel.¹⁸ The original report focussed on the mechanism of iron oxidation and therefore the significance of this observation was not discussed. However, the presence of iron in the 3-fold channel of this prokaryotic ferritin provided our motivation to probe the route of Fe²⁺ entry into SynFtn.

The relative disposition of the interior exits of the 3-fold channels of ferritins and their ferroxidase centres (Fig. 1D) means that rapid, direct transfer of metal ions between the two is highly unlikely. In animal ferritins two transient iron binding sites on the inner surface of the protein, termed Fe₃ and Fe₄, are thought to rapidly guide incoming Fe²⁺ from the 3-fold channel to the site of its oxidation.⁸,⁹ SynFtn lacks coordinating residues at the equivalent position to site Fe₄. However a glutamic acid residue (E62) is structurally equivalent to the Fe₃ ligands H54 (Frog M) and Q58 (human H).

Here, we report structural and spectro-kinetic data acquired for two SynFtn variants and compare these to data previously reported for the wild type protein. SynFtn D137A was designed to investigate whether the 3-fold channel constitutes the major route of Fe²⁺ entry. SynFtn E62A was designed to investigate whether a common pathway linking the 3-fold channel to the ferroxidase centres via the inner surface of the protein is shared by SynFtn and the animal ferritins. The data, which only partially support a common transit route, reveal fundamental aspects of Fe²⁺ entry and Fe³⁺ exit routes to and from the ferroxidase centre of this prokaryotic ferritin.

Results and discussion

The protein coat channels of SynFtn

Comparison of the sequence of SynFtn to other selected Ftns revealed that the B channel contains an aliphatic residue in place of one of the carboxylate residues conserved amongst the other proteins (Fig. S1†) meaning the environment in the SynFtn B channel is more hydrophobic than that of other Ftns. Furthermore, the peptide sequence of SynFtn contains an N-terminal extension relative to other prokaryotic ferritins and inspection of the previously reported structure of the wild type protein¹⁸ revealed that this forms a cap over the exterior entrance to the B channel (Fig. S2†) meaning this is unlikely to be the route of Fe²⁺ entry to SynFtn.

The 3-fold channel of SynFtn has little sequence similarity to those of the animal proteins for which Fe²⁺ entry via this route has been demonstrated (Fig. S1†), and the peptide sequence also lacks the conserved carboxylates that transfer the Fe²⁺ from the internal channel exits to the site of its oxidation. Nonetheless, the 3-fold channel of SynFtn is lined by carboxylates from three symmetry equivalent Asp137 residues, and the crystallographically observed Fe²⁺, present as [Fe(H₂O)₆]²⁺, was located only 4.0 Å away from oxygen atoms of these side chains (Fig. 2A). This suggests that the 3-fold channel may constitute the major route of Fe²⁺ uptake.

Crystal structures of D137A SynFtn reveal iron at the ferroxidase sites but not in the three-fold channels

The 2.13 Å crystal structure of the D137A variant of SynFtn (PDB entry 6SOM) revealed no significant structural perturbation other than the sidechain of the substituted residue (Fig. S3, Tables S1 and S3†). However, structures obtained from crystals aerobically soaked in a 5 mM Fe²⁺ ion solution
for 20 min (PDB entry 6SOO) contained no electron density associated with iron within the 3-fold channel (Fig. 2B). The iron-soaked structures did contain additional areas of electron density at the ferroxidase centre sites and data sets collected at the iron absorption edge were consistent with these arising from the binding of iron (Fig. S4†). However, significant differences in metal binding were apparent between the iron-soaked structures of D137A SynFtn and those reported for the wild type protein.18 Crystals soaked in Fe²⁺ for 2 min (PDB entry 6SON) contained iron bound at both the Fe₆ and Fe₇ sites of the ferroxidase centre (Fig. 3), but with low occupancy (Table S3†). The distance between the two metals was 3.54 Å, shorter than the 3.90 Å observed for the equivalent 2 min soak of wild type protein crystals. The ferroxidase centre reaction requires the simultaneous occupancy of both iron binding sites together with the availability of O₂. Hydrolysis of the resulting oxidised ferroxidase centre species leads to incorporation of a bridging (hydr)oxo ion between the metal centres.18 Therefore the lack of any bridging density between the metals, together with the low occupancy indicates that this structure represents a superposition of unreacted Fe²⁺ ions in singly occupied catalytic centres.

Increasing the soaking time to 20 min led to an increase in the occupancy of both the Fe₆ and Fe₇ sites (Table S3†), and the appearance of bridging density between the metals that was modelled as water/(hydr)oxo. These observations, together with an inter-metal distance of 3.62 Å indicates that this structure represents the di-ferric form of the active site.12 This interpretation of the structural data was supported by the solution phase kinetics of iron oxidation observed for D137A.

**Rapid Fe²⁺ oxidation, but not mineralization, is abolished in D137A SynFtn**

In common with most ferritins, SynFtn exhibits kinetically distinct phases of iron oxidation following addition of Fe²⁺ to the metal free protein. The apo protein contains 48 vacant metal binding sites, two at each of 24 ferroxidase centres. For catalytically active proteins, aerobic addition of up to 48 equivalents of Fe²⁺ results in rapid transport of the metal to the ferroxidase centre where it binds and is oxidised to the Fe³⁺ state in 10–20 s. The mineralisation activity of ferritins is only observed spectroscopically when Fe³⁺ is added in excess of 48 equivalents. Here 48 equivalents are again rapidly oxidised at the ferroxidase sites but further reaction requires that the Fe³⁺ product be cleared from the catalytic centres, forming the mineral core, to allow further Fe³⁺ binding. This process typically occurs on the timescale of minutes. Thus, whilst Fe³⁺ contained within ferritins absorbs light at 340 nm regardless of whether it is bound at ferroxidase centres or located in the core, the process monitored by spectrophotometric assays is readily interpreted by considering the rate of oxidation in conjunction with the excess of Fe²⁺ over protein added.

Stopped flow absorbance measurements conducted under identical conditions to those reported for wild type SynFtn revealed that the rapid phase of iron oxidation was abolished by the D137A substitution (Fig. 4A and B). In contrast, assays of iron mineralisation activity (conducted with 400 Fe²⁺ per Ftn) showed that the variant protein was capable of laying down a mineral core at 75% of the initial rate reported for the wild type protein. Pre-treatment of the protein with Zn³⁺, a potent inhibitor of ferroxidase centres, resulted in a reduction in the rate of mineral formation (Fig. S5†) demonstrating that the catalytic centre is required for the activity observed for D137A. Thus, the data indicate that the ferroxidase centre remains competent in variant D137A and that the loss of rapid iron oxidation, for which Fe²⁺-binding is rate limiting even in wild type protein, is the result of disruption of the route of iron transit.

**MVFC and Tyr radical formation are observed in D137A SynFtn**

As a consequence of the reduced rate of iron flux through variant D137A SynFtn, occupancy of the Fe₆ and Fe₇ sites in D137A crystals was lower than that observed for the wild type protein crystals treated equivalently, and so the structure of the MVFC form of the catalytic centre was not observed. Mechanistically unperturbed functioning of the ferroxidase centre in this variant, with a reaction cycle that proceeds through formation of a MVFC, was, however, confirmed using the time dependence of the EPR spectrum (Fig. 5). Apo SynFtn is essentially EPR silent whilst samples frozen at varying time points after the aerobic mixing of D137A apo protein with 72 equivalents of Fe²⁺ contained the same three paramagnetic species identified in the wild type protein: mono-nuclear high spin Fe⁴⁺, a tyrosyl radical and the MVFC (Fig. S6†). Importantly, though, the concentration of these species reached maximum intensity approximately 20 s after mixing at ambient temperature (Fig. 5 and Fig. S6†), compared to 1 s at 4 °C for the wild type protein.18 The MVFC signal then decayed over the following 40 s, the concomitant increase in 340 nm absorbance in equivalent samples showing this to be due to formation of the EPR silent di-Fe³⁺ state. Variant D137A forms...
exactly the same paramagnetic species as wild type SynFtn suggesting the same unusual mechanism of iron oxidation is utilised by this protein. However the kinetics of the ferroxidase reaction are reduced by at least an order of magnitude. The data are, therefore, fully consistent with variant D137A containing a competent catalytic centre within a protein cage that has an impaired ability to acquire Fe$^{2+}$ from solution.

Residue Glu62 does not form part of a transit site for Fe$^{3+}$ entry

A transient site (referred to as Fe3 by Pozzi et al.$^{8,9}$) close to the ferroxidase centre is thought to form part of a conserved route of Fe$^{2+}$ transport from three-fold channels to ferroxidase centres in ferritins of the higher eukaryotes. Fe3 is ligated by four residues in frog M ferritin but only three in human H-chain ferritin.$^{8,9}$ SynFtn contains potential Fe$^{2+}$ ligands at equivalent positions to the three residues that form part of the Fe3 site in both of the eukaryotic proteins. Of these, Glu110 acts as a ferroxidase centre ligand whilst Asp65 of SynFtn is structurally equivalent to glutamic acid residues that act as a ligand to both sites Fe3 and Fe4 in the animal ferritins. Therefore, the remaining residue, Glu62, was selected for substitution in an attempt to disrupt any potential site in SynFtn analogous to Fe3.

The 1.93 Å structure of E62A SynFtn (PDB entry 6SOP) revealed no significant changes beyond the substituted sidechain [Fig. S7 and Tables S2 and S3†]; in particular, the disposition of the amino acid sidechains making up the ferroxidase centre were unaffected (Fig. 3D and Fig. S7†). Crystals soaked for 2 min in an aerobic Fe$^{2+}$ solution (PDB entry 6SOQ) revealed two areas of electron density at the ferroxidase centre. Datasets collected at the iron K absorption edge (1.7389 Å) showed strong anomalous scattering associated with these two areas of electron density, which were modelled as iron accordingly (Table S3†). However, in contrast to variant D137A, the metal ions were at a separation of 3.34 Å, the shortest Fe–Fe distance observed in crystals of SynFtn to date, with a clear
area of bridging electron density between them (Fig. 3E). Therefore, the structural data suggest that following a 2 min Fe\textsuperscript{2+} soak the majority of iron containing ferroxidase centres in crystals of E62A SynFtn have bound and reacted with O\textsubscript{2}. However these centres are not in the MVFC state. Increasing the soaking time to 20 min (PDB entry 6SOR) resulted in no change to the metal–metal distance (3.34 Å) suggesting that in both metal soaked structures the form of the ferroxidase centre is most likely oxo-bridged di-Fe\textsuperscript{3+} that is only observed in 20 min Fe\textsuperscript{2+} soaks for wild type and D137A SynFtn.

As with variant D137A, formation of a MVFC was confirmed using EPR spectroscopy (Fig. 5B and Fig. S6), suggesting that the failure to observe this state in crystal soaking experiments was the result of altered iron transport and oxidation kinetics. The expected consequence of disruption of an Fe3-like site by the E62A substitution was impaired transit of Fe\textsuperscript{2+} to the catalytic centre, similar to that observed in variant D137A. However, the observation at both long and short soaking times of oxo-bridged iron clusters at the ferroxidase centre with structure very similar to that of the 20 min Fe\textsuperscript{2+} soak of wild type and D137A SynFtn.

Residue Glu62 facilitates transfer of Fe\textsuperscript{3+} from the ferroxidase centre to the cavity

Glu62 could play an important role after the initial oxidation of Fe\textsuperscript{2+} at the ferroxidase centre by affecting the oxidation of the MVFC, such that the E62A mutation leads to an increase in the activation energy for oxidation of the MVFC and a consequent reduction of the rate of formation of di-Fe\textsuperscript{3+} centres. Alternatively, Glu62 might be important for the transport of Fe\textsuperscript{3+} to the internal cavity, such that its substitution prolongs the lifetime of the di-Fe\textsuperscript{3+} form. A combination of timeresolved EPR and stopped-flow absorbance measurements was employed in order to distinguish these possibilities.

As with the wild type protein,\textsuperscript{18} the observed increase in absorbance at 340 nm in the first several seconds following the aerobic mixing of apo protein and Fe\textsuperscript{2+} could not be fitted to a single phase when the iron loading was ≥18 Fe\textsuperscript{2+} per Ftn, but was well described by a bi-exponential function (Fig. 4). This biphasic response is due to formation of the MVFC in the first several hundred milliseconds followed by further oxidation to the di-Fe\textsuperscript{3+} state at a much lower rate over the following several seconds.\textsuperscript{18} The rate of the slower of these two processes, \(k_a\), is almost invariant with Fe\textsuperscript{2+} concentration proceeding with an apparent rate constant of approximately 0.1 s\textsuperscript{-1} in all cases, as observed for the wild type protein. This phase is due to the reaction between MVFCs and a second equivalent of O\textsubscript{2} that generates the di-Fe\textsuperscript{3+} centre. Furthermore decay of the MVFC EPR signal intensity, caused by its oxidation to a diamagnetic di-Fe\textsuperscript{3+} cluster, also occurs at a similar rate in both proteins (Fig. 5). The data therefore suggest that the rate of the second oxidative step, that of conversion of the MVFC to a di-Fe\textsuperscript{3+} centre, is unaffected by mutation of Glu62 consistent with the failure to identify this form of the catalytic centre crystallographically. However, we note that the amplitude of the slower phase following addition of 96 Fe\textsuperscript{2+} per protein is significantly lower in E62A SynFtn compared to the wild type protein. In fact, the amplitude observed here corresponds to that expected for the oxidation of 48 Fe\textsuperscript{2+} ions per protein for wild type SynFtn, suggesting that Fe\textsuperscript{2+} oxidation subsequent to the oxidation of the initial 48 Fe\textsuperscript{2+} at ferroxidase centres, i.e. the mineralisation process, is severely affected.

To explore this possibility further, the rate at which iron was released from fully oxidised centres was assessed using stopped-flow absorbance. Protein was incubated with 400 Fe\textsuperscript{2+} per Ftn and the mineralization reaction allowed to proceed to completion. The rate of iron oxidation was then monitored following mixing with a further 72 Fe\textsuperscript{3+} per Ftn. In the case of the wild type protein, the maximum recovery of the amplitude of the rapid phase of oxidation associated with vacant ferroxidase centres (corresponding to 80% of the value observed for apo protein) was observed at 60 min after the addition of 400 equivalents of Fe\textsuperscript{2+}.\textsuperscript{18} The rate of recovery of rapid oxidation was much slower for variant E62A (Fig. 6) with only 60% of the amplitude observed for apo protein recovered following incubation with 400 Fe per Ftn for 16 h. Therefore, the lower rate of mineralization in this protein is most likely due to impaired release of the oxidized ferric-oxo product to regenerate empty catalytic centres capable of binding further equivalents of Fe\textsuperscript{2+}.

Experimental

Protein overexpression and purification

Plasmids for the expression of SynFtn variants E62A and D137A based on pET21a (Novagen) were purchased from
β-Protein was precipitated from the supernatant via a further round of centrifugation (40 000 g for 45 min). Thermally unstable proteins were precipitated from the supernatant by heating to 65 °C for 15 min and removed by centrifugation at 40 000 g for 45 min. Protein was exchanged into 100 mM MES pH 6.5 containing Fe2+ ions at 5 mM concentration and pH adjusted to 6.5. Crystals were then cryo-protected and frozen as above but using a solution containing 5 mM Fe2+ in addition to 30% (v/v) glycerol. Diffraction data was collected at the Diamond Light Source using beamline i03 (variant E62A) and i04 (variant D137A). The wavelength used was 0.9795 Å in all cases. Additional, highly redundant anomalous scattering data were collected either from the same or identically treated iron-containing crystals of E62A and D137A SymFtn at wavelengths corresponding to the peak of the iron K-edge (around 1.7389 Å). All data was indexed and processed using XDS and Aimless as part of the automatic xia2 pipeline. Reprocessing was carried out as necessary using Aimless as part of the CCP4 programme suite.

Statistics for X-ray data collection, structure solution and refinement are summarized in Table S1 and S2.

Structure solution was performed by molecular replacement using phenix.phaser MR with the 2.0 Å resolution structure of E. coli FtnA, PDB entry 1EUM, as the search model. In all cases the asymmetric unit contained a single copy of the monomer subunit. Placement of metal ions was confirmed by reference to Bijvoet-difference Fourier maps calculated from anomalous scattering data. Model refinement employed iterative cycles using phenix.refine and manual correction using COOT.

No metal coordination restraints were applied to metal sites during refinement of iron-containing structures. Anisotropic temperature factor refinement was employed for all metal ions and their occupancies were manually adjusted to ensure that the average B factor of the metal fell within ±14% of the B factors of atoms of their environment. The coordination geometry of metal binding sites was analysed after refinement using the CheckMyMetal web server.

Statistics relating to the metal binding sites in the refined structures can be found in Table S3.

Kinetic analysis of iron oxidation and mineralization by SymFtn

Rates of Fe2+ oxidation were deduced from the rate of increase in absorbance at 340 nm due to the resulting ferric-oxo species, be they iron bound at the ferroxidase centre or in the mineral core. Assays employed 0.5 µM SymFtn in 100 mM MES pH 6.5 at 25 °C. Aerobic oxidation of ferroxidase centre bound Fe5+ followed addition to apo wild type SymFtn was complete in ~20 s. Accordingly the ability of variants E62A and D137A to support similar chemistry was monitored using stopped-flow
absorbance spectroscopy. 1.0 µM protein in 100 mM MES pH 6.5 was mixed with an equal volume of Fe^{2+} of the appropriate concentration in 1 mM HCl using an Applied Photophysics Bio-Sequential DX.17MV spectrophotometer with a 1 cm path length observation cell. In the case of variant E62A the time dependences of absorbance increase at 340 nm were fitted to the sum of two exponential processes, encompassing rapid (r) and slow (s) components, using OriginPro 8 (OriginLab):\[\Delta A_{340}(t) = \Delta A_{340}^{(\text{tot})} - \Delta A_{340}^{e-r} \delta - \Delta A_{340}^{s-e-k_s t}. \quad (1)\]

The extent to which oxidized Fe^{3+} vacates the ferric oxide centres of E62A SynFtn was investigated by monitoring the regeneration of the rapid phase of Fe^{3+} oxidation associated with the apo protein. 1 µM protein was incubated with 400 µM Fe^{2+} at 25 °C until the absorbance at 340 nm became invariant with time. Equivalent samples were then mixed with an equal volume of 72 µM Fe^{2+} in 1 mM HCl either immediately or following a further period of incubation of 2, 5, 15 or 60 min. An additional sample incubated at 25 °C for 60 min was subsequently incubated for further 15 h at 4 °C. After re-equilibration at 25 °C the protein was mixed with an equal volume of 72 µM Fe^{2+} in 1 mM HCl as above.

Assays to assess the rate at which the proteins were able to mineralize iron within the internal cavity employed a higher iron to protein stoichiometry of 400 Fe^{2+} per SynFtn. Dependences of absorbance on time were recorded on a Hitachi U-2900 spectrometer following manual mixing of 6.4 µL of a 50 mM Fe^{2+} solution in 50 mM HCl to a 1.6 mL sample of 0.5 µM protein in 100 mM MES pH 6.5. The increased ratio of Fe^{2+}:protein resulted in dependences that were approximately linear for the initial 180 s of the reaction. Initial rates of iron mineralization were deduced from the gradient of this linear region and an extinction coefficient for the mineral core calculated from the net absorbance change upon complete oxidation of the 200 µM Fe^{2+} added.

Electron paramagnetic resonance (EPR) spectroscopy

EPR spectra were recorded at 10 K on a Bruker EMX (X-band) EPR spectrometer equipped with an Oxford Instruments liquid helium system and a spherical high-quality ER 4122 SP 9703 Bruker resonator. Protein samples in EPR tubes were mixed with the appropriate volume of a 25 mM stock Fe^{2+} solution and frozen at least 10 s thereafter by plunging the tubes into methanol cooled with solid CO_{2}. Final protein concentration was 4.17 µM (100 µM in monomer) in all cases. Proteins were in 100 mM MES pH 6.5 and Fe^{2+} solutions in 50 mM HCl. Instrument parameters for EPR measurements were as follows: microwave frequency \( \nu_{\text{mw}} = 9.4657 \text{ GHz} \), modulation frequency \( \nu_{\text{m}} = 100 \text{ kHz} \), time constant \( \tau = 82 \text{ ms} \), microwave power = 3.19 mw, modulation amplitude \( A_{\text{m}} = 5 \text{ G} \), scan rate = 22.6 G s^{-1}.

Conclusions

The channels that penetrate ferritin protein cages have attracted considerable study, not only with the aim of understanding how Fe^{2+} substrate and Fe^{3+} product are transported to and from an active site buried within an α-helical bundle, but also due to their potential as mimics for membrane ion channels that are embedded within a water soluble matrix.\(^5,6,10,16,25\) As such, it is desirable to determine which of the channels and residues lining the interior of the channels are required for efficient transport of the substrate. The 3-fold channel of animal ferritins has been identified as the route of iron entry in Frog M and Human H chain ferritin, and the peptide sequences of other animal ferritins are strictly conserved in the vicinity of this channel. Together with the identification of conserved glutamate residues at positions intermediate between the channel exits and the ferroxidase centre (Glu57 and Glu136 in Frog M numbering) this is suggestive of a common route of iron entry across all animal (and possibly plant) ferritins. In contrast, the B-channel of prokaryotic ferritins have been proposed to be a major route of Fe^{3+} entry and this has been demonstrated for \textit{E. coli} bacterioferritin.\(^{16}\)

The data presented here identifies the 3-fold channel of the prokaryotic ferritin SynFtn as the major route of iron entry into this protein, despite significant variation in its composition compared to those in animal ferritins. Three-fold channels of the animal proteins contain three symmetry related copies of each of two carboxylates, an Asp and a Glu (Asp127 and Glu130, Frog M numbering). Disruption of either by site directed mutagenesis significantly affected the rate of Fe^{3+} oxidation supported by the ferroxidase centre, even in the case of conservative substitutions such as E130D. Replacement of either carboxylate by Ala resulted in almost undetectable rapid oxidation of Fe^{2+} by the catalytic centres at Fe^{2+} loadings ≥96 Fe per cage.\(^{25}\) However, the three-fold channel of SynFtn contains only one symmetry-related carboxylate, Asp137, which is at a position equivalent to Glu130, and is shown here to be essential for rapid oxidation of Fe^{2+} at the ferroxidase centre. At the equivalent position to Asp127 of animal ferritins, it contains a Val (V134). Thus, the SynFtn three-fold channel has a significantly lower concentration of negatively charged carboxylates. Despite this, it is capable of supporting Fe^{3+} transport at a rate comparable to those of the animal ferritins.

In further contrast to animal ferritins, disruption of a potential Fe3 transient binding site in SynFtn through substitution of Glu62 impaired the rate of release of the oxidised ferric-oxo product from catalytic centres, rather than the uptake of Fe^{2+} substrate. Therefore, it seems likely that the only requirement for rapid transport of Fe^{2+} through the 3-fold channels of ferritins is a carboxylate residue with a sidechain directed toward the mid-channel position (D137 in SynFtn, E130 in Frog M ferritin). The stringent requirements on animal ferritins for a Glu at the mid-channel position and an Asp at the interior channel exit most likely arise from the need to efficiently deliver the substrate into the Fe4 transit site rather than for rapid transport through the channel itself.

The route utilised to transfer Fe^{2+} from the interior exit of the 3-fold channel of SynFtn to the ferroxidase centre is as yet undefined, but must either require a different trajectory of incoming substrate, or be more tolerant of variation in it,
allowing the channel to function efficiently with only the mid-channel carboxylate.

Although the D137A substitution abolished rapid Fe^{2+} oxidation at the ferroxidase centres of SynFtn, it is noteworthy that overall mineralization activity was ~75% that of the wild type protein. In the E62A variant, initial oxidation was rapid, but mineralization was only ~38% of wild type SynFtn. These data indicate that, for SynFtn, while the rate-limiting step of the initial ferroxidase centre Fe^{2+} oxidation reaction is the binding of Fe^{3+}, this is not the case for the overall mineralization process. Instead, the rate-limiting step of mineralization is associated with Fe^{3+} egress from the ferroxidase centre.

Finally, whilst iron uptake has now been demonstrated to occur through both the 3-fold and B-channels in different prokaryotic ferritins, and Fe^{2+} binding in a B-channel has been observed in another Ftn-like example,^{16,17} data on iron transit in the Ftn proteins remains, on the whole, scarce. Whilst the prokaryotic ferritins appear to exhibit greater variability in their mechanism of iron uptake than their animal counterparts, the examples characterized to date are drawn from distinct subfamilies. E. coli bacterioferritin, in which the B-channel is the major route in for Fe^{2+}, is a heme-containing ferritin with a distinct ferroxidase centre architecture and mechanism of Fe^{3+} oxidation,^{20,27} whilst SynFtn represents the first characterized example of a subset of ferritins, found almost exclusively within marine picocyanobacteria, which combine structural features previously considered to define ferritins as either eukaryotic or prokaryotic.^{18} Therefore, the field would benefit from further work towards elucidating the route for Fe^{2+} entry into the most widely distributed class of prokaryotic Ftns, of which EcFtnA remains the best characterized example.

Conflicts of interest

There are no conflicts to declare.

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