Formation of cristae and crista junctions in mitochondria depends on antagonism between Fcj1 and Su e/g


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Introduction

Mitochondria are ubiquitous organelles and fulfill a multitude of crucial functions in eukaryotic organisms. Mitochondria are made up by two membranes: the outer membrane (OM) and the inner membrane (IM). The IM is composed of two subdomains: the inner boundary membrane (IBM) and the crista membrane (CM). The IBM is closely apposed to the OM, both forming a double-layered envelope of the organelle. CMs are invaginations of the IBM that protrude into the matrix space. Large variations exist in the morphology of CMs (Munn, 1974; Fawcett, 1981; for review see Zick et al., 2009), and aberrant mitochondrial structures have been described for numerous pathological situations in humans (DiMauro et al., 1985; Wallace, 2005). Tubular-, lamellar-, and even triangle-shaped structures of the CM have been observed (Fawcett, 1981). Cristae are connected to the IBM by narrow tubular- or slotlike structures of varying length, so-called crista junctions (CJs), as revealed by EM of serial sections of mitochondria (Daems and Wisse, 1966) and by electron tomography (Mannella et al., 1994; Perkins et al., 1997, 1998; Nicastro et al., 2000; Frey et al., 2002; for reviews see Frey and Mannella, 2000; Mannella et al., 2001). The diameter of CJs was found to be rather small, ranging from 12 to 40 nm (Nicastro et al., 2000; Perkins et al., 2003; for review see Frey and Mannella, 2000). This led to the suggestion of CJs forming barriers for the movement of proteins and metabolites between the intracristal and the intermembrane space as well as

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Abbreviations used in this paper: BN-PAGE, blue native PAGE; CJ, crista junction; CM, crista membrane; DIC, differential interference contrast; IBM, inner boundary membrane; IM, inner membrane; mtDNA, mitochondrial DNA; OM, outer membrane; PK, proteinase K; SEC, size exclusion chromatography; TAP, tandem affinity purification.

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between the CM and the IBM (Mannella et al., 1994). Such a role of CJs has been proposed to have important consequences for the regulation of oxidative phosphorylation, as a barrier of this kind might limit the diffusion of metabolites like ADP into the intracristal space and modulate the pH gradient across the IM (Perkins et al., 1997; Renken et al., 2002; for reviews see Mannella et al., 2001; Mannella, 2006a). Also, subcompartmentalization of the IM was suggested based on biochemical subfractionation of mitochondria (Werner and Neupert, 1972; Pon et al., 1989), localization of individual mitochondrial proteins by immuno-EM (Gilkerson et al., 2003), or fluorescence microscopy (Wurm and Jakobs, 2006). Recently, this subcompartmentalization was addressed by determining the distribution of 20 mitochondrial proteins using quantitative immuno-EM (Vogel et al., 2006). The IBM appears to be segregated from the CM by the CJ, yet proteins are able to dynamically redistribute between the two subcompartments of the IM depending on the physiological state of the cell (Vogel et al., 2006). Furthermore, CJs undergo remodeling during apoptosis; this was suggested to allow release of the intracristal pool of cytochrome c to the cytoplasm, thereby triggering programmed cell death (Scorrano et al., 2002; Cipolat et al., 2006; Frezza et al., 2006).

Despite the apparent importance of the structural organization of mitochondria, the components responsible for the morphology and biogenesis of cristae, and in particular of CJs, are largely unknown. Deletion of the dimer-specific subunit e (Su e) or Su g of the F1F0-ATP synthase (F1F0) leads to defective oligomerization of this complex (Arnold et al., 1998) and to altered cristae morphology with extended onion-like structures in yeast (Paumard et al., 2002). Furthermore, remodeling of CJs during apoptosis was reported to depend on the mitochondrial dynamin-like protein OPA1 (Frezza et al., 2006). Prohibitins were recently suggested to play a role in cristae morphogenesis by controlling OPA1 processing (Merkwirth et al., 2008). The yeast orthologue of OPA1, Mgm1, was proposed to be required for cristae maintenance in addition to its role in IM fusion (Wong et al., 2003; Meueen et al., 2006). Another protein reported to determine cristae morphology in human cells is mitofilin. Down-regulation of this protein led to massive proliferation of the IM, resulting in multiple layers that appear to be interconnected accompanied by a disappearance of CJs (John et al., 2005). Mitofilin was initially named heart muscle protein, as it is highly expressed in rat heart tissue (Ichino et al., 1994). Proteomic analysis of human heart mitochondria further indicated high abundance of this protein in mitochondria (Taylor et al., 2003). The name mitofilin was coined because of its colocalization with filament-like mitochondria in fibroblasts (Odgren et al., 1996).

In summary, a few proteins are known to influence cristae morphology, but, so far, no protein has been shown to be specifically localized to CJs or to be part of a CJ protein complex. In this study, we investigated the molecular basis governing the architecture of cristae and CJs in mitochondria of the yeast Saccharomyces cerevisiae. We describe ultrastructural alterations of the IM of yeast mitochondria lacking the open reading frame AIM28 (YKR016w/FMP13) with hitherto unknown function. This gene was recently listed as a putative orthologue of mammalian mitofilin (Olichon et al., 2006). We provide both morphological and biochemical evidence that this protein is directly involved in the formation and molecular structure of CJs and is specifically enriched at CJs. We propose to name it Fcj1 (formation of CJ protein 1). Fcj1 regulates the oligomeric state of the F1F0 supercomplex in an adverse manner, and, moreover, CJ formation and structure turn out to be dependent on F1F0 supercomplex formation itself. Furthermore, Su e and Su g of F1F0, which promote oligomerization of F1F0, are essential for the formation of endings of cristae, the tips, or rims. The F1F0 complex has been proposed to represent a key element in the determination of cristae structure (Paumard et al., 2002), a proposal which rests on its very high abundance in the mitochondrial IM. In this study, we present a working model that explains the control of cristae architecture by the antagonistic effects of Fcj1 and F1F0 Su e and Su g on the oligomeric state of F1F0.

Results
Deletion of Fcj1 leads to altered mitochondrial morphology and partial loss of mitochondrial DNA (mtDNA)

In a search for genes affecting mitochondrial structure, we analyzed a collection of yeast cells that showed deficiency in growth on nonfermentable carbon sources because mutants with this phenotype are often accompanied by alterations in mitochondrial structure. We focused on genes coding for putative mitochondrial proteins that, so far, do not have an assigned function. Possible candidate strains were checked for mitochondrial morphology by rhodamine staining and then by expression of matrix-targeted GFP. We identified a mutant that showed alterations in the typical mitochondrial network. In the strain lacking the open reading frame FCJ1 (AIM28/FMP13/YKR016w), abnormally large spherical mitochondria were observed. These were mostly located in the periphery of the cell and formed atypical networks (Fig. 1 A). In addition, mitochondria occasionally appeared hollow. For further characterization, we determined the percentage of rho0/rho− cells. Depending on the cell density and the growth medium used, this value varied from 15 to 40% for the mutant cells. The respiratory rates of isolated mitochondria from such cells in state III (+ADP) and state IV (−ADP) and the maximal uncoupled rates were reduced by 30% as compared with wild type (Table I). The membrane potential, ∆ψ, of the mutant mitochondria was also reduced compared with wild type, although to a lesser extent (Table I). The respiratory control ratio (state III/state IV rates) in the mutant was not altered, indicating that the respiratory chain and the ATP synthase were still well coupled. Taking all of these observations into account, compromised respiration in the mutant cells was rather caused by a secondary loss of mtDNA than by primary deficiencies of enzymatic activities involved in oxidative phosphorylation.

Fcj1 is located in the mitochondrial IM facing the intermembrane space with its large hydrophilic domain

The FCJ1 (AIM28/FMP13/YKR016w) gene encodes a protein of 540 aa residues. In silico analysis by the MitoProt II program (Claros and Vincens, 1996) yielded a high probability for...
**Figure 1.** Fc1 is required for normal mitochondrial morphology. (A) Wild-type (WT) and Δfc1 cells expressing mitochondria-targeted GFP were grown on nonfermentable medium and visualized by fluorescence microscopy. (B) Domain structure of Fc1 depicting the mitochondrial-targeting sequence (MTS), the transmembrane segment (TM), the coiled-coiled domain, and the conserved C-terminal domain (CTD) with corresponding positions of amino acid residues. (C) Subcellular fractionation of wild-type cells: mitochondria (Mito), microsomes (ER), and cytosol. Equal amounts of protein (50 µg) were analyzed by Western blotting with the indicated marker proteins: Tim44 (Mito), Erp1 (ER), and Hxk1 (Cytosol). (D) Submitochondrial localization of Fc1. Wild-type mitochondria and mitoplasts generated by hypotonic swelling (SW) were treated with PK, a specific proteolytic fragment of Oxa1. (E) Membrane association of Fc1. Wild-type mitochondria were extracted with NaCl or Na carbonate. Membrane-bound (P) and soluble (S) fractions were loaded and analyzed by Western blotting using the indicated marker proteins. DLD, d-lactate dehydrogenase. (F) Homotypic interaction of Fc1. Mitochondria from cells expressing a His-tagged (Fc1-His6) or a TAP-tagged variant of Fc1 (Fc1-TAP) or both were subjected to TAP affinity chromatography. Total (T), 10%, bound (B), 100%, and unbound (UB), 10% material was analyzed by Western blotting with the indicated antibodies. Tom40 and TAP-tagged Fc1 were detected simultaneously using rabbit antibodies against Tom40. Bars, 1 µm.
mitochondria solubilized in Triton X-100 did not lead to co-oligomeric Fcj1 complex. Collectively, Fcj1 is a protein engaged on the detection of the TAP tag or the His tag, respectively shifted to a molecular mass of 220 kD, as determined by size exclusion chromatography (SEC). Moreover, the complex retained its size after affinity purification, which is consistent with the formation of a stable homo-oligomeric complex (Fig. S2 B). The size would suggest a trimeric complex; however, a dimeric or tetrameric complex seems possible as well. We also analyzed the size of the Fcj1 complex after TAP from mitochondria harboring Fcj1-His6 and Fcj1-TAP. The size of the Fcj1-TAP–Fcj1-His6 complex was shifted to a molecular mass of ~220 kD depending on the detection of the TAP tag or the His tag, respectively (Fig. S2 C). This increase in molecular mass is consistent with the presence of one or more subunits of Fcj1 containing the 20-kD TAP tag, further strengthening the view of a homo-oligomeric Fcj1 complex. Collectively, Fcj1 is a protein engaged in homotypic interactions that is anchored to the mitochondrial IM with its major part exposed to the intermembrane space.

**Fcj1 is enriched at CJs**

We determined the distribution of Fcj1 over the various subdomains of the IM using quantitative immuno-EM. Cryosections of chemically fixed wild-type cells were immunodecorated with antibodies against Fcj1 and visualized by immunogold. Low concentrations of antibodies were used to keep the level of unspecific immunodecoration low. The specificity of the Fcj1 antibody was confirmed by Western blotting as well as by immunogold labeling of wild-type and ∆fcj1 cells (Fig. S3, A and B). Gold particles present in a large number of sections of wild-type cells were projected on a model, as described previously (Vogel et al., 2006), representing OM, IBM, CM, and a CJ (Fig. 2, A and B). Fcj1 was most prominently clustered in close proximity to the CJ (Fig. 2, A and B), a region which, so far, was rather characterized by a quite low density of numerous other mitochondrial proteins (for comparison see Vogel et al. [2006]). A region nearly lacking gold particles was observed in the CM adjacent to the CJ region (Fig. 2 B). This necklike region represents the narrow tubular segment of the CM, exhibiting a relatively high positive membrane curvature. The curvature here is opposite to the one at the base of CJs. Fcj1 was present to some extent in the remainder of the CM, including the cristae tips and in the IBM distant from the CJ region. The term cristae tip refers to its appearance in electron micrographs of mitochondrial sections. Depending on the section plane, they represent the highly positively curved rims of lamellar-like CM sheets. To evaluate these findings in a quantitative way, a sliding window was moved along the IM of our model starting from the bottom, counting only gold particles that were located within 14-nm distance from the IM (Fig. 2, C and D). This was performed for Fcj1 and as a control for Cox2, a subunit of cytochrome c oxidase, as well as for Su e and Su g of F1F0 (Fig. 2, C and D; raw data for Cox2 and Su e and Su g were taken from Vogel et al. [2006]). With Fcj1, the highest number of gold particles was observed in the region corresponding to the CJ (Fig. 2, C and D, gray boxes). The number of gold particles representing Cox2 was very low in the CJ and IBM region and increased in the CM (Fig. 2 C; Vogel et al., 2006). Su e and Su g of F1F0 were not enriched in the CJ region.
but rather appeared accumulated in the cristae tips (Fig. 2 D). Collectively, the enrichment of Fcj1 at CJs was unique and not observed for any of the proteins analyzed previously (Fig. 2, C and D; Vogel et al., 2006). The presence of Fcj1 in lower amounts in the planar parts of the cristae, where the levels of Su e and Su g are also intermediate, could reflect a balance of function in these regions; in part, they could also be caused by the topological complexity of bent cristae and perhaps, to a lesser degree, by background signals. Altogether, our data demonstrate that Fcj1 is the only protein identified so far specifically enriched at CJs at sites where the amounts of Su e and Su g are relatively low.

**Deletion of Fcj1 leads to loss of CJs and altered cristae morphology**

The morphology of mitochondrial IMs was studied by EM and tomographic reconstruction from sections of yeast cells prepared by the Tokuyasu method (Tokuyasu, 1989). In wild-type cells, mitochondria showed a large number of CJs, and the IM and OM were often in very close proximity at the bases of CJs (Fig. 3, A and B; Table II; and Video 1). In Δfcj1 cells, mitochondria were increased in size and contained numerous internal cristae with no apparent CJs (Fig. 3, C and D; Table II; and Video 2). These CMs were arranged mainly as parallel, concentric, stacked vesicular structures. The lumen of the vesicular structures was identified as intracristal space (Fig. S3 C). In a further approach, rapidly frozen hydrated spheroplasted yeast cells were subjected to cryosectioning and cryo-EM tomography. In addition, isolated mitochondria were analyzed by cryo-EM tomography. Both procedures led to high resolution structures of CJs in wild-type cells (Fig. 4, A and B; Fig. S4, A–C; and Video 3) and revealed the absence of CJs in Δfcj1 mitochondria (Fig. 4 C, Fig. S4 D, and Video 4).

The narrow matrix space between adjacent CMs in mitochondrial Δfcj1 cells contained particles of uniform size and shape that were arranged in a zipperlike pattern (Fig. 4, D–G; and Videos 4 and 5). Top views reveal the distribution and organization of these complexes as short linear assemblies or as two
To provide further evidence that the zipperlike structures represent oligomers of F\(_1\)F\(_\text{O}\), we deleted Su\(_e\) or Su\(_g\) of F\(_1\)F\(_\text{O}\). Loss of these subunits is known to impair dimerization/oligomerization of F\(_1\)F\(_\text{O}\) (Arnold et al., 1998). Indeed, neither in \(\Delta\text{fcj1}/\Delta\text{su}\_e\) (Fig. 5 A) nor in \(\Delta\text{fcj1}/\Delta\text{su}\_g\) mitochondria (not depicted) were the putative F1 particles arranged in a zipperlike manner. Rather, they were distributed randomly over the IM, which is in contrast to what was observed with \(\Delta\text{fcj1}\) mitochondria parallel lines with a square-like or a hexagonal arrangement (Fig. 4, D–G). The dimensions and relative distances of these structures corresponded very well to those of the F\(_1\) part of the F\(_1\)F\(_\text{O}\)-ATP synthase (~10 × 10 × 10 nm). These highly abundant structures have been assigned to dimers or oligomers of F\(_1\)F\(_\text{O}\) in numerous other studies (Allen et al., 1989; Dudkina et al., 2005, 2006; Minauro-Sam miguel et al., 2005; Buzhynskyy et al., 2007; Strauss et al., 2008).

Table II. Analysis of electron micrographs of cells with disturbed IM organization upon deletion of Fcj1, Su e, or Su g

<table>
<thead>
<tr>
<th>Strain</th>
<th>Number of mitochondrial sections</th>
<th>Number of CJs</th>
<th>Number of CJs per mitochondrial section</th>
<th>Percentage of CJs connected to one or more CJs</th>
<th>Number of cristae tips</th>
<th>Number of cristae tips per mitochondrial section</th>
</tr>
</thead>
<tbody>
<tr>
<td>WT</td>
<td>65</td>
<td>120</td>
<td>1.8</td>
<td>0</td>
<td>245</td>
<td>3.8</td>
</tr>
<tr>
<td>(\Delta\text{fcj1})</td>
<td>75</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>731</td>
<td>9.7</td>
</tr>
<tr>
<td>(\Delta\text{su}_e)</td>
<td>58</td>
<td>170</td>
<td>2.9</td>
<td>84.1</td>
<td>12</td>
<td>0.2</td>
</tr>
<tr>
<td>(\Delta\text{su}_g)</td>
<td>64</td>
<td>163</td>
<td>2.5</td>
<td>81.0</td>
<td>10</td>
<td>0.2</td>
</tr>
</tbody>
</table>

WT, wild type. The numbers of CJs and cristae tips per mitochondrial section were determined from electron micrographs of chemically fixed whole cells of the indicated strains grown at 30°C on complete liquid media containing 2% (vol/vol) lactate.
from wild-type yeast was an oligomeric arrangement of this complex previously observed (Buzhynskyy et al., 2007; Strauss et al., 2008). Collectively, the lack of Fcj1 correlates, on the one hand, with the absence of CJs and, on the other hand, with the appearance of regular arrangements of large protein complexes characteristic of F1FO supercomplexes.

**Fcj1 has a direct role in determining the number and the architecture of CJs**

To further study the role of Fcj1 in the formation of CJs, we used overexpression and down-regulation of Fcj1. Fcj1 was expressed from a plasmid in wild-type yeast cells under control of a doxycycline-repressible promoter. Wild-type cells containing the empty plasmid were also analyzed. Upon five- to 10-fold overexpression of Fcj1, the number of CJs per cell was increased two- to threefold as compared with control cells. The branching
Down-regulation of Fcj1 led to a progressive decrease of the number of CJs as well as of cristae branches (Fig. 6, C and D). These alterations of cristae morphology occurred already at the early time points (13.5 and 23 h). Mitochondria with the characteristics of the $\Delta fcj1$ phenotype with continuous concentric stacks of IM appeared at later time points (37.5 and 47.5 h).

Figure 5. Zipperlike structures observed in $\Delta fcj1$ mitochondria depend on the presence of dimer-specific Su e and Su g of F1F0–ATP synthase. Cryo-EM tomograms of isolated mitochondria of indicated strains. (A) Top views of putative F1F0–ATP synthases in $\Delta fcj1/\Delta su g$ mitochondria (left) and a surface-rendered representation (right) are shown. (B) Top views of putative F1F0–ATP synthases in $\Delta fcj1$ mitochondria (left; magnified view of boxed area in Fig. 4 E) and a surface-rendered representation (right) are shown. (C) Frequency distribution of F1–F1 distances. The center to center distance of an F1 particle to its nearest neighbor was determined for cryo-EM tomograms of isolated mitochondria of the indicated strains ($n = 102$ for both strains). Bars, 50 nm.

of cristae, which is very rarely observed in wild-type cells, was increased $\sim$17-fold in cells overexpressing Fcj1 (Fig. 6 A). Moreover, the diameter of CJs appeared enlarged and showed a higher variation when Fcj1 was overexpressed (Fig. 6, A and B). Thus, Fcj1 overexpression promotes the formation of additional CJs and alters the molecular architecture of CJs.

Down-regulation of Fcj1 led to a progressive decrease of the number of CJs as well as of cristae branches (Fig. 6, C and D). These alterations of cristae morphology occurred already at the early time points (13.5 and 23 h). Mitochondria with the characteristics of the $\Delta fcj1$ phenotype with continuous concentric stacks of IM appeared at later time points (37.5 and 47.5 h).
Therefore, we asked whether protein levels of Su\(e\) or Su\(g\) were altered in \(\Delta fcj1\) cells and also whether levels of Fcj1 were altered in \(\Delta su\ e\) or \(\Delta su\ g\) cells. In the absence of Fcj1, similar levels of Su\(e\) or Su\(g\) were observed (Fig. 7 A). Thus, altered cristae morphology in \(\Delta fcj1\) mutant cells was not caused by a change in the levels of Su\(e\) or Su\(g\). Likewise, Fcj1 levels were unaffected in \(\Delta su\ e\) and \(\Delta su\ g\) mutant cells, suggesting that Fcj1 is not responsible for the altered cristae morphology described for these mutants (Paumard et al., 2002). In addition, deletion of Fcj1 had no effect on the levels of several nuclear as well as mitochondrial encoded proteins that are involved in mitochondrial cristae formation.

The incomplete disappearance of CJs is attributed to the incomplete down-regulation of Fcj1 (Fig. 6 C). The formation of rho\(^0\)/rho\(^-\) cells was not observed in the course of the experiment, excluding the possibility that our observations are caused by a secondary loss of mtDNA. In summary, these observations strongly suggest a direct involvement of Fcj1 in CJ formation.

Unchanged levels of Su\(e\) or Su\(g\) of the F\(_1\)F\(_0\)-ATP synthase in \(\Delta fcj1\) cells

Mutant strains lacking Su\(e\) or Su\(g\) of the F\(_1\)F\(_0\)-ATP synthase were reported to have altered cristae morphology (Paumard et al., 2002). Therefore, we asked whether protein levels of Su\(e\) or Su\(g\) were altered in \(\Delta fcj1\) cells and also whether levels of Fcj1 were altered in \(\Delta su\ e\) or \(\Delta su\ g\) cells. In the absence of Fcj1, similar levels of Su\(e\) or Su\(g\) were observed (Fig. 7 A). Thus, altered cristae morphology in \(\Delta fcj1\) mutant cells was not caused by a change in the levels of Su\(e\) or Su\(g\). Likewise, Fcj1 levels were unaffected in \(\Delta su\ e\) and \(\Delta su\ g\) mutant cells, suggesting that Fcj1 is not responsible for the altered cristae morphology described for these mutants (Paumard et al., 2002). In addition, deletion of Fcj1 had no effect on the levels of several nuclear as well as mitochondrial encoded proteins that are involved in mitochondrial cristae formation.

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functions such as mitochondrial protein import, mitochondrial fusion and fission machineries, and oxidative phosphorylation (Fig. 7 A). Notably, levels of proteins involved in determining mitochondrial morphology such as Mgm1, Fzo1, Fis1, and Dnm1 were not affected. Consistent with this, mitochondria in Δfcj1 cells formed a tubular, albeit altered, network. The formation of the short isoform of Mgm1 (s-Mgm1) was also not impaired. This further supports our conclusion that mitochondrial energy production and protein import are functional in cells lacking Fcj1 as both processes are required for the formation of s-Mgm1 (Herlan et al., 2004).

Fcj1 impairs oligomerization of the F₁Fₒ-ATP synthase

In view of the presence of a zipperlike arrangement of F₁ particles in Δfcj1 mitochondria, we asked whether Fcj1 affects oligomerization of F₁Fₒ. First, we determined whether solubilization of F₁Fₒ with a mild detergent depends on the level of Fcj1. Mitochondria isolated from wild-type cells, cells overexpressing Fcj1, and cells lacking Fcj1 were solubilized with digitonin. The proportion of nonsolubilized F₁Fₒ-ATP synthase subunits (F₁β and Atp4) was highest in mitochondria lacking Fcj1, lower in wild type, and lowest in cells overexpressing Fcj1 (Fig. 7 B). The solubilization of other IM proteins such as Dld1 and Aac2 did not show such a dependence on the level of Fcj1. The nonsolubilized fraction of the F₁Fₒ-ATP synthase could subsequently be solubilized with Triton X-100. Apparently, F₁Fₒ forms a high molecular mass complex that is less easily dissociated by digitonin in mitochondria lacking Fcj1.

We then examined the supramolecular organization of F₁Fₒ by blue native PAGE (BN-PAGE) and in-gel visualization of its ATPase activity. Formation of monomers, dimers, and putative tetramers of F₁Fₒ was observed in mitochondria of all strains (Fig. 7 C). Higher order oligomers were observed in Δfcj1 mitochondria even at high digitonin concentrations, only at very low concentrations in wild-type mitochondria, and not when Fcj1 was overexpressed. These high molecular mass complexes of F₁Fₒ represent a small subpopulation of the soluble fraction. They were very stable even at high digitonin to protein ratios when Fcj1 was lacking but not when Fcj1 was present. Overexpression of Fcj1 impaired the formation of these higher oligomers markedly and also decreased the amount of the tetrameric forms (Fig. 7 C and Fig. S5 A). The amount of dimers and monomers was not affected significantly. Likewise, the abundance of higher oligomers of F₁Fₒ when determined by SEC was dependent on the presence of Fcj1 (Fig. 7 D). The majority of Fcj1 was recovered in the fractions corresponding to the higher oligomeric forms of F₁Fₒ (>2 MD), showing that Fcj1 is present in a high molecular mass complex. Thus, the size of F₁Fₒ oligomers was considerably larger upon solubilization with digitonin as compared with solubilization with Triton X-100 (Fig. S2). Collectively, various lines of evidence, including biochemical data as well as EM tomography, show that Fcj1 affects the stability of F₁Fₒ oligomers in an adverse manner but obviously does not influence that of the dimers of this complex.

Fcj1 acts in an antagonistic manner to Su e and Su g of the F₁Fₒ-ATP synthase

The observed effect of Fcj1 on the stability of oligomeric forms of F₁Fₒ suggested a functional link between these proteins. Su e and Su g are known to be required for dimerization/oligomerization of F₁Fₒ and are required for normal cristae morphology. To determine whether there exists a genetic interaction between these subunits and Fcj1, we determined the doubling times on a nonfermentable carbon source of each single and corresponding double deletion strain. The strain lacking Fcj1 was most severely impaired in growth on a nonfermentable carbon source, showing a 1.75-fold longer doubling time as compared with wild type (Fig. 8 A). Additional deletion of either Su e or Su g of F₁Fₒ led to an efficient suppression of the growth defect of the Δfcj1 strain. These double deletion strains had significantly shorter doubling times than the Δfcj1 strain. This was further confirmed by drop dilution growth tests (Fig. 8 B). In conclusion, these data demonstrate a genetic interaction of Fcj1 with Su e/Su g of F₁Fₒ, placing all proteins in the same pathway. The latter subunits are promoting the assembly of F₁Fₒ-ATP synthase oligomers, whereas Fcj1 has the opposite effect. In the double deletion strains (Δfcj1/Δsu e and Δfcj1/Δsu g), the formation of F₁Fₒ-ATP synthase oligomers was not observed (Fig. S5 B). Dimers were present to a very low extent, resembling the phenotype of single deletions of Su e or Su g. This is consistent with the view that dimers are the building blocks for oligomerization of F₁Fₒ, as previously suggested (Paumard et al., 2002; Wittig et al., 2008). Collectively, Fcj1 interacts functionally with Su e and Su g in an antagonistic mode that appears crucial for the formation of CJs.

Deletion of Su e and Su g leads to alterations of the IM structure of mitochondria

To relate the oligomeric states of F₁Fₒ to the structure of cristae, we determined the number of cristae tips and the number of CJs in the deletion mutants of Su e and Su g and compared them with the numbers in wild-type and Δfcj1 cells. Cristae tips per mitochondrial section were ~2.5-fold more abundant in sections of Δfcj1 cells than in wild type (Table II). Mitochondria of strains lacking Su e or Su g were reported to contain onion-like structures and extended CMs (Paumard et al., 2002), but it was not investigated whether formation of CJs is affected. Therefore, we performed a quantitative analysis of CJs in these strains. Next to onion-like structures, we observed CJs in these strains, and the numbers of CJs per mitochondrial section were modestly increased compared with those in the corresponding wild type (Table II). Thus, Su e and Su g are not essential for CJ formation. However, CJs often appeared in pairs and were connected via CMs crossing a mitochondrial section, which is a structure rarely observed in wild type (Fig. 8, C and D; and Table II). In line with this observation, the number of cristae tips per mitochondrial section observed in Δsu e and Δsu g mitochondria was extremely low, ~20 times lower than in wild type (Table II). Moreover, branching of cristae was found in 27% and 9% of mitochondrial sections of Δsu e and Δsu g strains, respectively, but not in sections of the corresponding wild-type strain (Fig. 8, C and D). Furthermore, the mean diameters of CJs in Δsu e and Δsu g cells were increased, although to a smaller extent.
than in cells with overexpressed Fcj1, and showed a high variation (Fig. 8 E and not depicted). In wild-type cells, a slightly lower mean CJ diameter was measured when compared with the wild-type control shown in Fig. 6 B. We attribute this to different growth media (selective minimal vs. complete media) and strain backgrounds (W303 vs. BY4742; Table S2). We also investigated the ultrastructure of mitochondria of the double deletion strains Δfcj1/su e and Δfcj1/su g. These mitochondria were characterized by the presence of internal, concentric or vesicle-like CMs and the virtual absence of CJs (Fig. S5, C and D). In conclusion, Su e and Su g, on the one hand, promote the formation of cristae tips, and Fcj1, on the other hand, is necessary for formation of CJs. These two types of mitochondrial membrane proteins modulate the oligomeric state of F1F0, in an antagonistic manner. This suggests that the architecture of the cristae with its elements of the cristae endings, connections with the IBM, and perhaps also the planar arrangement of cristae sheets are controlled by the local concentrations of these two types of antagonistic proteins.

Discussion
This study addresses the question of how the complex structure of cristae in mitochondria is determined on a molecular basis. In this study, we report on proteins that, in conjunction with
Figure 8. Functional link between Fcj1 and the F₁F₀-ATP synthase. (A and B) Genetic interaction of Fcj1 with Su e and Su g. (A) Generation times of the indicated strains (BY4742) grown in complete liquid lactate media during exponential growth at 30°C (n = 4). Error bars show standard deviations. Statistically significant differences (*, P < 0.05) according to a t test are indicated. (B) Growth of indicated strains tested by drop dilution in 1:10 steps on YPD and YLac media.

C and D show electron microscopy images of cells with Su g or Su e, respectively.

E illustrates the distribution of CJ diameters comparing wild type (WT) and Δsu e strains.
F_{1}F_{0}–ATP synthase, determine cristae architecture. The IM protein Fcj1 plays an essential role in the formation of CJs and cristae shape. Su e and Su g of F_{1}F_{0}, whose depletion was previously shown to lead to onion-like cristae (Paumand et al., 2002), have an influence on cristae structure, which is opposing that of Fcj1. We present a model of how these components determine the structure of the various parts of cristae, which is based on our results as discussed in this study (Fig. 9, A and B).

Fcj1 is anchored to the IM by a single N-terminal transmembrane segment, exposing the major part of the protein to the intermembrane space. It undergoes homotypic interactions and is quite abundant with an estimated number of 5,730 molecules per cell (Ghaenmghahi et al., 2003). Yet, it is much less abundant than the major constituent of the IM, the F_{1}F_{0}–ATP synthase with an estimated number of 41,500 and 164,000 molecules for the Flα and F1β subunits, respectively (Ghaenmghahi et al., 2003). The mammalian protein mitofilin shares very low sequence similarity with Fcj1; however, it is likely to represent an orthologue on the basis of its depletion phenotype (John et al., 2005). Fcj1 is present at high levels at the base of CJs but is also present in other parts of cristae, although to a lesser extent. Deletion of Fcj1 leads to a loss of CJs. Overexpression results in an increase in the number of CJs and to internal branching of cristae, suggesting a direct role of Fcj1 in the formation of junctions. Fcj1 has a regulatory influence on the oligomeric state of F_{1}F_{0}. Deletion of Fcj1 leads to an increase in the level of F_{1}F_{0} supercomplexes. This effect is also apparent upon morphological analysis of mitochondria lacking Fcj1. Cryo-EM revealed the formation of extensive F_{1}F_{0} supercomplex structures in the matrix space between cristae of this strain. Consistent with these observations, overexpression of Fcj1 leads to a reduction of the level of F_{1}F_{0} supercomplexes.

Manipulation of the levels of the F_{1}F_{0} Su e and Su g yielded equally intriguing results. As previously documented, depletion of these subunits leads to accumulation of concentric cristae structures (Paumand et al., 2002). Deletion of either Su e or Su g has been reported to strongly favor the dissociation of the F_{1}F_{0} into monomers (Arnold et al., 1998). Remarkably, this has no effect on the enzymatic activity of the ATP synthase. In this study, we show that these mitochondria contain CJs but exhibit a virtual absence of cristae tips. This goes along with a strongly increased number of bridgelike cristae that extend across whole sections of mitochondria, ending on both sides in CJs. Moreover, branching of cristae is observed in these mitochondria, much like in Fcj1-overexpressing cells. Thus, branching of cristae may represent internal CJs that emerge within a planar region of the cristae, a region in which CJs are normally absent.

In summary, our data show opposing functions of Fcj1 in relation to F_{1}F_{0} Su e and Su g. Fcj1 is obviously critical for formation of CJs, whereas formation of cristae tips requires Su e and Su g. This is in line with the specific enrichment of these components within the respective regions of the IM, as revealed by quantitative immunogold labeling. It appears to be their relative distribution that determines cristae structure in mitochondria.

Building on our results, we propose a working hypothesis for the molecular basis of the generation of CJs and cristae tips. In the mitochondria of most species and organs, the following structural elements can be discriminated (Fig. 9, A and B). The cristae sheets are made up of two leaves of IM arranged in close apposition, leaving a narrow intermembrane space in between. These sheets are delimited by tips or rims, in which the lipid bilayer is bending over, showing a strong positive curvature. At their base, the cristae are connected to the IBM, which forms a kind of second envelope tightly apposed to the OM. These connections, the CJs, have a rather complex 3D architecture. At the base where they open out into the IBM, the membrane exhibits negative curvature. It is followed by a narrow tubular neck region with highly positive curvature. This structure widens out into the planes of the cristae, a region in which both negative and positive curvatures are present.

According to our model, Fcj1 directly or indirectly interferes with the formation of higher oligomers and thereby favors negative membrane bending. By this mechanism, the presence of Fcj1 affects the building of the bases of CJs. However, in the regions where the formation of higher oligomeric forms of F_{1}F_{0} is not disturbed, these oligomers impose a positive curvature on the membrane and thereby favor the formation of cristae tips. The idea of F_{1}F_{0} oligomers introducing a positive curvature to the IM and leading to tip formation has also been put forward in a recent study (Strauss et al., 2008). Our findings attribute this effect to the action of Su e and Su g. As we show in this study, they are both enriched in the rim region, and their absence leads to a virtual absence of cristae tips. However, their lower abundance in CJs supports negative curvature. Interestingly, Fcj1 is present in very low amounts in cristae necks, the IM region connecting the base of CJ with the cristae sheets. This membrane has an extremely high positive curvature. Thus, we suggest that the ratios of Fcj1 to Su e/Su g are decisive in shaping cristae. The sheets of cristae appear to contain both Fcj1 and Su e/Su g, and this may determine their planar shape. A balanced distribution of these antagonistic components may also be necessary for the dynamics and fission/fusion of cristae. A dynamic nature of cristae was proposed previously (for reviews see Mannella et al., 2001; Mannella, 2006b) based on EM tomography studies of isolated mitochondria showing that cristae morphology apparently is reversibly changing under various physiological conditions (for reviews see Mannella et al., 2001; Mannella, 2006b; Zick et al., 2009).

Altogether, our hypothesis can explain all of the findings presented in this study and in other studies (Paumand et al., 2002; Strauss et al., 2008). It does not exclude that other components such as prohibitins or OPA1 or others yet to be identified also contribute to CJ and cristae tip formation (for reviews
seen by EM but long enough for diffusion of newly inserted proteins and lipids. Several other explanations may seem equally possible. In any case, it will be a great challenge to find out how mitochondria can survive the virtual complete absence of CJs and still maintain mitochondrial function and inheritance.

Materials and methods

Strains and growth conditions

The strains and plasmids used are listed in Tables S2 and S3. Culturing of yeast strains was performed using standard methods (Sherman et al., 1986) at 30°C on complete liquid media containing 2% (vol/vol) lactate. Strains containing plasmids (Table S2) were grown on selective liquid media supplemented with 400 mg/l of 5-fluoroorotic acid. Yeast cells were streaked onto plates as indicated and incubated at 30°C. Growth was observed after 2 to 4 days.
Fractionation of yeast cells

Yeast total cell extracts were prepared by alkaline lysis as previously described (Herlan et al., 2003). Cellular subfractionation of yeast cells was performed as previously described (Rowley et al., 1994). To extract peripherally bound membrane proteins, 10 mg/ml of mitochondria was swollen by dilution to a final concentration of 1 mg/ml in 20 mM Hepes/KOH, pH 7.4. After the addition of an equal volume of freshly prepared 0.2 M Na carbonate solution or 2 M NaCl solution, samples were incubated for 30 min at 4°C and centrifuged at 92,000 g for 30 min at 4°C. Equal fractions of membrane-associated and soluble proteins were analyzed by SDS-PAGE and immunoblotting. Spheroplasts of yeast cells, preparation of mitochondria, generation of mitoplasts, and PTK treatment were performed according to standard procedures (Sirenenberg et al., 1996).

Recombinant DNA techniques

The yeast strain FCJ1 [W303 background] was obtained by genomic integration of the PCR product synthesized from the plasmid pBADHIS3Mx6 (Wadsworth et al., 2001). To amplify the primers FCJ1-HIS3 upstream and FCJ1-HIS3 reverse, the deletion of FCJ1 was verified by PCR using the primers FCJ1 upstream and FCJ1 downstream. pCM189-FCJ1 was generated by amplifying FCJ1-YKR016w by PCR from yeast genomic DNA using Pyrococcus furiosus polymerase (Agilent Technologies) and FCJ1 forward and reverse expression FCJ1 reverse primers (Table S4) and cloning into the pCM189 yeast overexpression vector using BamHI–NotI restriction sites. For the generation of pFX242-FCJ1-His6 or pFX242-FCJ1-His12, the primers FCJ1 upstream and FCJ1-His6 reverse or FCJ1 upstream and FCJ1-His12 reverse, respectively, were used, and the PCR products were cloned into pFX242 using BamHI–XhoI restriction sites. Constructs or empty plasmids (Table S3) were transformed into the wild-type or the FCJ1 strain to allow growth of all strains in the same selective media.

Antibody production

Antisera against FCJ1 were raised in rabbits against a synthetic peptide comprising of amino acid residues 214–226 of FCJ1 (CNGYEN-SKREFEK) coupled to activated ovalbumin (Pineda, 2000).
Cryopreparation of isolated mitochondria

Cryopreparation was performed essentially as previously described (Dubochet et al., 1988). Freshly prepared mitochondria were resuspended in isotonic Hepes buffer (10 mM Hepes, pH 7.4, 1 mM EDTA, and 600 mM sorbitol) at a protein concentration of 10 mg/ml. 3–5 µl of this mitochondrial suspension was applied onto an EM grid (R2/2; Quantifoil; or custom made) and mounted in a plunger equipped with a custom-made humidifying device (Cyrklaff et al., 1990). After adding 2–5 µl of fiducial marker solution (3-nm protein A–gold [Sigma–Aldrich] in isotonic Hepes buffer), excess liquid was removed, and the grids were rapidly frozen in liquid ethane slush and stored in liquid nitrogen.

Cryo-EM of vitreous sections

Sample vitrification, cryosectioning, and imaging were performed as described previously (Al-Amoudi et al., 2004). In brief, spheroplasted yeast cells mixed with fiducial markers in isotonic buffer were soaked in 20% dextan (50–100 kD), sucked in 300-µm diameter copper tubes and high pressure frozen at >2,000 bars using EMPTACT (Leica). Vitreous samples were cryosectioned in the microtome (Ultraplast UCT; Leica) with nominal thickness of sections of 120 nm and a final thickness of ~200 nm as the result of specimen compression using either a 35° cryodiamond knife (Diament) or a 45° glass knife with a clearance angle of 6°.

Electron tomography

Cryohydrated samples were mounted in a 70° tilt cryospecimen holder (model 626; Gatan GmbH) and examined in a cryoelectron microscope (CM 300; Philips) equipped with a field emission gun, a postcolumn energy filter (GIF 2000; Gatan GmbH), and a slow-scan charge-coupled device camera (Gatan GmbH) with 2,048 × 2,048 pixels. Low electron-dose series (4,000–5,000 electrons/µm²) of typically 60–70 images were recorded using the Digital Micrograph package [Gatan GmbH in tilt ranges between ±60° and ±70°, with 2° tilt intervals, at nominal magnifications of 40,000 [0.82 nm/pixel] or 52,000 [0.68 nm/pixel], and with an objective lens defocus of 6–10 µm. Chemically preserved material was imaged under similar conditions, but the areas selected for recording of tomographic tilt series were preirradiated with electron doses of >10,000 electrons/µm². Images of tilt series were aligned using fiducial markers and merged in 3D reconstructions as well as for displaying the results in figures.

Online supplemental material

Fig. S1 shows that FCI1 ([AIM28/FMP13/YKR016W] has very low sequence similarity to mitoflin. Fig. S2 shows that oligomeric protein complexes containing FCI1 are the result of FCI1 self-interaction. Fig. S3 shows the specificity of FCI1–directed antibodies and immuno-EM in ΔFCI1 cells. Fig. S4 shows that the deletion of FCI1 leads to altered cristae morphology. Fig. S5 shows the analysis of double deletion strains ΔFsj1/Δsuw e and ΔFsj1/Δsuw g and of a strain overexpressing FCI1. Videos 1 and 2 show EM tomograms of chemically fixed wild-type and ΔFsj1 S. cerevisiae cells, respectively. Video 3 shows a cryo-EM tomogram of isolated wild type S. cerevisiae mitochondrion. Videos 4 and 5 show cryo-EM tomograms of isolated ΔFsj1 S. cerevisiae mitochondrion. Table S1 shows the quantitative analysis of wild-type and ΔFsj1 cells. Tables S2–S4 show the plasmids, and oligonucleotides, respectively, used in this study. Online supplemental material is available at http://www.jcb.org/cgi/content/full/jcb.200811099/DC1.

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Accepted: 18 May 2009

References


Published June 15, 2009
Figure S1. **FCJ1 (AIM28/FMP13/YKR016W)** has very low sequence similarity to mitofilin. Amino acid sequences of mitofilin-related proteins Fc1 ([S. cerevisiae [S.c.]]), Q7SD8 ([Neurospora crassa [N.c.]]), Q22505 ([Caenorhabditis elegans [C.e.]]), mouse IMMT (Q8CAQ8; [Mus musculus [M.m.]]), and human IMMT (Q16891; [Homo sapiens [H.s.]]). were aligned using CLUSTALW (Thompson, J.D., D.G. Higgins, and T.J. Gibson. 1994. *Nucleic Acids Res.* 22:4673–4680) at the Pôle BioInformatique Lyonnais server (http://npsa-pbil.ibcp.fr). Amino acid residues are indicated as identical (asterisk; red), very similar (colon; green), and weakly similar (period; blue). Gaps are indicated by dashes. A conserved C-terminal domain is indicated by a box. The position of the single predicted transmembrane segment present in all species is underlined and highlighted in gray. Putative coiled-coil domains are highlighted in yellow.
Figure S2. Oligomeric protein complexes containing Fc1 are caused by Fc1 self-interaction. (A) Nickel nitritetriacetic acid pull-down of Fc1 from solubilized mitochondria. A His-tagged variant of Fc1 (Fc1-His12) and wild-type (WT) control were subjected to nickel nitritetriacetic acid affinity purification. Bound material was analyzed by SDS-PAGE and Coomassie staining. Protein bands corresponding to Fc1 and a degradation fragment of Fc1 (f) were identified by immunoblotting (not depicted). Nonspecific protein bands are indicated by an asterisk. (B and C) Homo-oligomeric nature of the Fc1 complex. (B) Mitochondria from cells expressing Fc1-His12 were isolated and either directly subjected to SEC on a Superose 6 column (closed squares) or nickel nitritetriacetic acid (Ni-NTA) pull-down was performed, and the bound material was subjected to SEC (open triangles; gray). (C) Mitochondria from cells expressing both Fc1 and Fc1-TAP were solubilized and subjected to TAP affinity purification. Bound material was subjected to SEC. Analysis of SEC fractions was performed by SDS-PAGE and Western blotting with the indicated antibodies both against the His-tagged (open squares) and the TAP-tagged (closed triangles) versions of Fc1. Bands were quantified by densitometry, setting the peak fraction to 100%. For comparison, the size distribution of the Fc1 complex determined in B is included as a reference (gray). The peak fractions of protein size markers are indicated by arrows.
Figure S3. **Specificity of Fcj1-directed antibodies and immuno-EM in Δfcj1 cells.** (A) Western blotting. Equal amounts of wild-type (WT) and Δfcj1 mitochondria (30 µg) were analyzed by Western blotting with antibodies against Fcj1 and Aac2. (B) Quantification of immuno-EM. After immunogold labeling of Fcj1, wild-type and Δfcj1 cells were screened for the presence of gold particles. The number of gold particles per mitochondrial area unit in wild-type sections was set as 100%. m, number of mitochondrial sections. (C) Matrix-targeted GFP (mtGFP) was expressed in Δfcj1 cells and labeled with immunogold using antibodies against GFP to distinguish between the matrix and intermembrane space. The majority of gold particles appears outside and between cristae stacks, indicating that these structures enclose the intracristal space rather than the matrix space. Bar, 100 nm.
Figure S4. **Deletion of Fcj1 leads to altered cristae morphology.** (A–D) Cryo-EM tomograms of cryohydrated sections of spheroplasted yeast cells. (A) Wild-type yeast cell with two cryosectioned mitochondria. (B) CJ of wild-type mitochondrion magnified from the boxed area in A. (C) An enlargement of the boxed area in B (left) and a surface-rendered view (right) are shown. (D) ΔFcj1 cell with cryosectioned mitochondrion showing cristae stacks. Bars, 100 nm.
Figure S5. Analysis of double deletion strains Δfcj1/Δsu e and Δfcj1/Δsu g and of a strain overexpressing Fcj1. (A and B) Equal amounts (400 µg) of wild-type (WT) and Fcj1-overexpressing mitochondria (Fcj1↑; A) or of wild-type, Δsu e, Δfcj1/Δsu e, Δsu g, and Δfcj1/Δsu g mitochondria (B) were solubilized at the indicated ratios of digitonin/protein (Dig/Prot; g/g) and analyzed by BN-PAGE and by in-gel F1FO–ATPase activity. (C and D) Electron micrographs of Δfcj1/Δsu g (C) and Δfcj1/Δsu e (D) mitochondria in chemically fixed yeast cells. Cells were cultivated on a nonfermentable carbon source before fixation. Bars, 100 nm.
Table S1. **Quantitative analysis of wild-type and Δfcj1 cells**

<table>
<thead>
<tr>
<th>Stereological parameter used for comparison</th>
<th>Wild type</th>
<th>Δfcj1</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ratio of membrane length IM/OM</td>
<td>1.57 ± 0.25 (m = 5)</td>
<td>3.29 ± 0.64 (m = 12)</td>
</tr>
<tr>
<td>Ratio of mitochondrial volume/cell volume</td>
<td>0.21 ± 0.06 (m = 16)</td>
<td>0.26 ± 0.08 (m = 17)</td>
</tr>
<tr>
<td>Ratio of mitochondrial area per mitochondrion relative to wild type</td>
<td>1 (m = 38)</td>
<td>2.0 (m = 31)</td>
</tr>
</tbody>
</table>

m, number of mitochondria or mitochondrial sections. Electron micrographs of the indicated cells after chemical fixation (Tokuyasu method) were analyzed by standard stereological tools (Griffiths, G. 1993. Fine Structure Immunocytochemistry. Springer-Verlag, Berlin. 459 pp.) for membrane length and the mitochondrial area per section. The assessment of mitochondrial volumes was performed by analyzing images obtained after confocal fluorescence microscopy of strains expressing mitochondrial GFP (see Materials and methods). Mean values ± standard deviations are given.

Table S2. **Strains**

<table>
<thead>
<tr>
<th>Name</th>
<th>Description</th>
<th>Background/genotype</th>
<th>Plasmids</th>
<th>Source</th>
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<tbody>
<tr>
<td>BY4741</td>
<td>WT</td>
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<td>EUROSCARF</td>
</tr>
<tr>
<td>Δfcj1</td>
<td>Δfcj1</td>
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</tr>
<tr>
<td>Δsu e</td>
<td>Δsu e</td>
<td>BY4742</td>
<td>NA</td>
<td>Open Biosystems</td>
</tr>
<tr>
<td>Δsu g</td>
<td>Δsu g</td>
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<td>NA</td>
<td>Open Biosystems</td>
</tr>
<tr>
<td>Δfcj1/Δsu e</td>
<td>Δfcj1/Δsu e</td>
<td>BY4742</td>
<td>NA</td>
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</tr>
<tr>
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<td>Δfcj1/Δsu g</td>
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<tr>
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<td>Open Biosystems</td>
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<td>Fcj1-His6</td>
<td>W303</td>
<td>This study</td>
</tr>
<tr>
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<td>Fcj1-His6</td>
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<td>This study</td>
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<td>Δfcj1 + pCM189-Fcj1</td>
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<tr>
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<tr>
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<td>Fcj1† overexpression experiments</td>
<td>W303</td>
<td>pCM189-Fcj1</td>
<td>This study</td>
</tr>
</tbody>
</table>

EUROSCARF, European Saccharomyces Cerevisiae Archive for Functional Analysis; NA, not applicable; WT, wild type.

Table S3. **Plasmids**

<table>
<thead>
<tr>
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<th>Description</th>
<th>Vector</th>
<th>Source</th>
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<tr>
<td>pYX242</td>
<td>Yeast expression vector containing constitutive TPI promoter</td>
<td>NA</td>
<td>EMD</td>
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<tr>
<td>pCM189</td>
<td>Yeast expression vector containing doxycycline-regulatable promoter system</td>
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<td>Garí et al., 1997</td>
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<tr>
<td>pVT100-mtGFP</td>
<td>Expression of mitochondrial matrix-targeted GFP</td>
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<td>Westermann and Neupert, 2000</td>
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<td>pYX242</td>
<td>This study</td>
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<tr>
<td>pYX242-Fcj1-His6</td>
<td>Expression of C-terminally His-tagged Fcj1</td>
<td>pYX242</td>
<td>This study</td>
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mtGFP, mitochondrial GFP; NA, not applicable.

References


Table S4. **Oligonucleotides**

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<tr>
<td>Fcj1 forward</td>
<td>5'-CCCCCATGGCAATGCGAAGAACTACTGCTTCAGC-3'</td>
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<tr>
<td>Overexpression Fcj1 reverse</td>
<td>5'-CCCCCGGCGGCGGCCTCACACAGTGTCCTTCAGTTC-3'</td>
</tr>
<tr>
<td>Fcj1-His6 reverse</td>
<td>5'-CCCCCTCGAGTCAGTGATGGTGATGGTGATGCAACGTCCTTATTTCACAGTCTTC-3'</td>
</tr>
<tr>
<td>Fcj1-His6 upstream</td>
<td>5'-AAAAGGAATAGAAGCGATGAAAGAATCCTATATCAGTCGAGTCGAGTCGAC-3'</td>
</tr>
<tr>
<td>Fcj1-His6 reverse</td>
<td>5'-TTGGGAGTGAATAGCGATCCTTCTTCTTCTTGTATATTCTTATCAGAATTTGGAGTCGAC-3'</td>
</tr>
<tr>
<td>Fcj1 upstream</td>
<td>5'-GTTAATTTCTGATTCC-3'</td>
</tr>
<tr>
<td>Fcj1 downstream</td>
<td>5'-TCCTTTATAAAAGCGCTTC-3'</td>
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</table>
Video 1. **EM tomogram of chemically fixed wild-type S. cerevisiae cell.** Successive xy slices through the tomogram are shown moving along the tomographic z axis. The top right mitochondrion was used for surface rendering and is shown in Fig. 3 (A and B). The video is shown at 30 frames/s.

Video 2. **EM tomogram of chemically fixed Δfcj1 S. cerevisiae cell.** Successive xy slices through the tomogram are shown moving along the tomographic z axis. A single slice of mitochondrion was used for surface rendering and is shown in Fig. 3 (C and D). The video is shown at 30 frames/s.

Video 3. **Cryo-EM tomogram of isolated wild-type S. cerevisiae mitochondrion.** Successive xy slices through a tomogram represented in Fig. 4 A are shown moving along the tomographic z axis. The video is shown at 30 frames/s.

Video 4. **Cryo-EM tomogram of isolated Δfcj1 S. cerevisiae mitochondrion.** Successive xy slices through a tomogram represented in Fig. 4 C are shown moving along the tomographic z axis. Details are shown in Figs. 4 (D–G) and 5 B. See also Video 5. Zipperlike structures typical of the F₁ parts of F₁F₀–ATP synthases are visible. The video is shown at 30 frames/s.

Video 5. **Cryo-EM tomogram of isolated Δfcj1 S. cerevisiae mitochondrion.** Successive xy slices through a tomogram represented in Fig. 4 D are shown moving along the tomographic z axis. This represents an enlargement slightly below the boxed area in Fig. 4 C. Zipperlike structures typical of the F₁ parts of F₁F₀–ATP synthases are visible. The video is shown at 30 frames/s.