Structure and Subunit Arrangement of the A-type ATP Synthase Complex from the Archaeon Methanococcus jannaschii Visualized by Electron Microscopy

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From the *Universität des Saarlandes, Fachrichtung 2.5-Biophysik, D-66421 Homburg, Germany, †Department of Biophysical Chemistry, Groningen Biomolecular Sciences and Biotechnology Institute, University of Groningen Nijenborgh 4, 9747 AG Groningen, The Netherlands, and ‡Institut für Mikrobiologie, Johann Wolfgang Goethe-Universität Frankfurt, D-60439 Frankfurt, Germany

In Archaea, bacteria, and eukarya, ATP provides metabolic energy for energy-dependent processes. It is synthesized by enzymes known as A-type or F-type ATP synthase, which are the smallest rotatory engines in nature (Yoshida, M., Muneyuki, E., and Hisabori, T. (2001) Nat. Rev. Mol. Cell. Biol. 2, 669–677; Imamura, H., Nakano, M., Noji, H., Muneyuki, E., Ohkuma, S., Yoshida, M., and Yokoyama, K. (2003) Proc. Natl. Acad. Sci. U. S. A. 100, 2312–2315). Here, we report the first projected structure of an intact A1A0 ATP synthase from Methanococcus jannaschii as determined by electron microscopy and single particle analysis at a resolution of 1.8 nm. The enzyme with an overall length of 25.9 nm is organized in an A1 headpiece (9.4 × 11.5 nm) and a membrane domain, A0 (6.4 × 10.6 nm), which are linked by a central stalk with a length of ~8 nm. A part of the central stalk is surrounded by a horizontal-situated rod-like structure (“collar”), which interacts with a peripheral stalk extending from the A0 domain up to the top of the A1 portion, and a second structure connecting the collar structure with A1. Superposition of the three-dimensional reconstruction and the solution structure of the A1 complex from Methanosarcina mazei Gö1 have allowed the projections to be interpreted as the A1 headpiece, a central and the peripheral stalk, and the integral A0 domain. Finally, the structural organization of the A1A0 complex is discussed in terms of the structural relationship to the related motors, F1F0 ATP synthase and V1V0 ATPases.

ATP synthases/ATPases are present in every life form and are the most important enzymes for the energy metabolism of the cell (1). They catalyze the formation of ATP at the expense of the transmembrane electrochemical ion gradient. They arose from a common ancestor that underwent structural and functional changes leading to three distinct classes of A1A0, F1F0, and V1V0 ATP synthases/ATPases. The V-type ATPases, found in organelles of eukaryotes, lost their ability to synthesize ATP. Their function is to create steep ion gradients at the expense of ATP hydrolysis (2). Archaea contain ATPases, the A1A0 ATP synthases, that are structurally similar to V1V0 ATPases but synthesize ATP like the F-type ATPases. The genomic sequences available today show that the overall subunit composition of the A1A0 ATP synthases is very similar to the V1V0 ATPases. For example, the A1A0 ATP synthases contain duplicated and even triplicated K subunits (proteolipids) (3, 4). The A1A0 ATP synthase has at least nine subunits (A1B3CDEFIHK), but the actual subunit stoichiometry, especially regarding the proteolipid subunits K in A ATPases, is different in various organisms (12, 6, 4, or as suggested by genomic data, only 1 (5)). The A1A0 ATP synthase is composed of a water-soluble A1 ATPase and an integral membrane subcomplex, A0, ATP is synthesized or hydrolyzed on the A1 headpiece consisting of an A1B3 domain, and the energy that is provided for or released during that process is transmitted to the membrane-bound A0 domain (4). The energy coupling between the two active domains occurs via the so-called stalk part, an assembly proposed to be composed of the subunits C, D, and F (6, 7).

Insight in the molecular structure of the A-type ATP synthases comes from small-angle x-ray scattering data of the A1 ATPase from Methanosarcina mazei Gö1 whose A1 domain is made up of the five different subunits, A1B3CDE (8). The data have shown that the hydrated A1 ATPase is rather elongated with a headpiece of 10 × 9.4 nm in dimension and a stalk of ~8.4 nm in length. A comparison of the central stalk of this A1 complex with bacterial F1 and eukaryotic V1 ATPase indicates different lengths of the stalk domain (8, 9). Image processing of electron micrographs of negatively stained A1 ATPase from M. mazei Gö1 (7) has revealed that the headpiece consists of a pseudohexagonal arrangement of six masses surrounding a seventh mass. These barrel-shaped masses of ~3.2 and 2.8 nm in diameter and 7.5 and 5.0 nm in length, which consist of the major subunits A and B, are arranged in an alternating manner (7). The hexagonal barrel of subunits A and B encloses a cavity of ~2.3 nm in the middle in which part of the central stalk is asymmetrically located. The stalk protrudes from the bottom side of the headpiece forming an angle of ~20° with the vertical axis of the molecule. At the upper end of the hexagonal barrel, extensions can be observed that are assumed to belong to the N termini of subunit A (7). Further insights into the topology of the A1 ATPase were obtained by differential protease sensitivity (8) and cross-linking studies (6, 7). These studies...
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RESULTs

Subunit Composition and Electron Microscopy—A characteristic gel of the preparation of the \( A_1A_0 \) ATP synthase from \( M. jannaschii \) is presented in Fig. 1A showing the nine subunits, F, H, I, and K, with apparent molecular masses of 66, 51, 45, 25, 23, 11, 10, 77, and 21 kDa, respectively. A typical electron microscopy raw image of the enzyme yields monodisperse particles with almost no contamination by smaller particles that could represent dissociated complexes or fragments (Fig. 1B). A total of 17,238 such molecular images were subjected to image processing. Fig. 2 demonstrates different class sums of the \( A_1A_0 \) ATP synthase projections obtained after several steps of reference-free translational/rotational alignment, multivariate statistical analysis, and multireference alignment. All of the projections reveal a tripartite structure consisting of a headpiece, a membrane-embedded domain, and a connecting stalk region. The classes can be grouped in respect

\* W. Keegstra, unpublished data.
to the number of visible stalks: one group showing one peripheral stalk besides the central stalk (Fig. 2, frames A1–4; 12,555 particles) and a second group with two peripheral stalks on both the left and right side (Fig. 2, frames B1–4; 4,683 particles). To obtain more homogeneous classes, both data sets, including either two or three stalks, were analyzed separately as described under “Experimental Procedures.” Fig. 3 shows averages of each refined data set at a resolution of 1.8 nm (Fig. 3, A–C). In all of the averages, the A1A0 ATP synthase from *M. jannaschii* has a total length of 25.9 nm. The dimensions of the A1 headpiece, the central stalk domain, and the membrane portion, A0, are 9.4 × 11.5, 8.0 × 3.9, and 6.4 × 10.6 nm, respectively. The A1 headpiece has a rather spherical mass that is clearly separated from the stalk domain at its base (Fig. 3B). The stalk domain is formed by a central stalk and either one (Fig. 3A) or two peripheral stalks (Fig. 3B). This observation might be explained either by some of the complexes being disrupted or by these classes containing complexes in different orientation. The central stalk can be divided into an asymmetric upper part and a collar-like structure located above the A0 domain. In the collar, several distinct densities could be resolved. At both ends of this domain, two of such densities are connected to the peripheral stalks (Fig. 3B), which go all the way up to the A1 headpiece. One of these stalks appears to be in close contact with two areas of the A1 headpiece with one located at the outside and the second located on top of the A0B3 headpiece (Fig. 3, B and C). This peripheral stalk shows a clear connection to the A0 portion via the collar structure (Fig. 3, B and C). By comparison, the second peripheral stalk is attached to the top of the A1 headpiece (Fig. 3C) and extended slightly down from the collar domain (Fig. 3B). A corresponding weak density rises up from the A0 (Fig. 3B). Whereas the peripheral stalk(s) seems to be connected to the outside of the A0 domain, the central stalk is attached to the center of the membrane-embedded A0, which appears as a rather symmetric flattened sphere and slightly tilted in most of the projections, especially in Fig. 2, frame B3.

Localization of the Subunits Inside the A1A0 ATP Synthase—A known three-dimensional reconstruction of the asymmetrical A1 complex from *M. mazei* G61 (7) determined from tilt pairs of negatively stained molecules was superimposed on the projection of the A1A0 ATP synthase from *M. jannaschii* (Fig. 4, panel C) by rotating the A1 subcomplex in 5° steps through 360°. One of the projections of the A1 from *M. mazei* G61 is well accommodated within the A1 headpiece, composed of the A0B3D subassembly (7) and the upper central stalk, which is only partially (35%) solved in the three-dimensional reconstruction of the A1 ATPase from *M. mazei* G61 (7). In this projection, one of the catalytic A subunits is on the right of the A0 domain, implying that the peripheral stalk on the right may be close to this major A subunit. Nevertheless, from the superposition of the A1 profile with the A0 part in the A1A0 ATP synthase images, it is clear that the cap at the top of the A1 headpiece (Figs. 3B and 4C) does not belong to the A0B3D subassembly. To further examine the composition of the central stalk, the projection of the A1A0 ATP synthase from *M. jannaschii* was compared with the solution structure of the A0B3CDF complex of the A1 ATPase from *M. mazei* G61 deduced from solution x-ray scattering data (8). The central stalk of the hydrated A0B3CDF complex, which consists of the subunits C, F, and a part of subunit D, is 8.4 nm in length (8) and fits well to the dimensions (8 nm) of the elongated central stalk of the negative-stained A1A0 ATP synthase, indicating that the central stalk is made up by the subunits C, D (partly), and F.

**DISCUSSION**

The A1A0 ATP synthase has been described as a chimeric enzyme combining the structural and functional features of F0F1 ATP synthases and V1V0 ATPases (4). Single particle analysis resulted in the visualization of projections of the A1A0 ATP synthase from *M. jannaschii* consisting of an A1 headpiece and an A0 domain linked by a central stalk and two peripheral stalks. The A1 headpiece fits well with the projection of the recently determined three-dimensional reconstruction with the A1 complex from *M. mazei* G61 composed of the hexagonal A0B3 domain surrounding a cavity in which the central stalk subunit D is located (7, 8). The subunit is displaced toward an A-B-A triplet (7), allowing the rearrangements of the central D sub-
and the related Thermus thermophilus A1A0 ATP synthase from A3B3CDF complex derived from small-angle x-ray scattering data.

The black arrow points at the groove of the A1 headpiece. The side view of the A1 complex (gold: C) and the envelope of the hydrated A1B3CDF complex derived from small-angle x-ray scattering data (green: D) from *M. mazei* Go1 are superimposed on the projection of the A1A0 ATP synthase from *M. jannaschii*, respectively.

The comparison of the A1A0 ATP synthase with the recently determined envelope of the hydrated A1A0 ATPase from *M. jannaschii* Go1 (6, 7) and the recently determined Thermus thermophilus A1A0V1 ATPase (21). A key feature from the superposition of the A1 complex from *M. mazei* Go1 and the A1A0 ATP synthase is the close fit at the top of the A1 headpiece showing the knoblike structures. These knobs, also found in the related V-type ATPase (22–25) but absent in the F-type ATP synthases (26–28), are formed by the N-terminal non-homologous inserts (80–90 amino acids) of the three catalytic A subunits, which alternate with the nucleotide-binding B subunits (7, 29). They point out that the cap at the very top of the A1A0 molecule (Fig. 4C) is not formed by a subunit belonging to the soluble A1 domain (see below).

The comparison of the A1A0 ATP synthase with the recently determined envelope of the *M. mazei* Go1 A1B3CDF complex in solution (8) yields that there is no significant shrinkage of the A1A0 molecule through the negative staining procedure. The central stalk is rather elongated (−8 nm) and in close contact with A0. As described recently, the central stalk of the *M. mazei* Go1 A1B3CDF complex accommodates subunits C, F, and partly D (7, 8). The cross-linking data of this complex indicate that subunit F is in close neighborhood to one of the nucleotide-binding B subunits (Fig. 5) and that F, together with the central stalk subunits C and D, undergoes significant structural rearrangements depending on nucleotide binding (6, 7).

Such nucleotide-dependent alterations of stalk subunits C, D, and F will facilitate the mechanistic linkage of ATP synthesis/ hydrolysis in the A1B3 hexamer to ion pumping in the A0 part via the central CDF stalk domain. The length and the shape of the central stalk of the A1 part resemble those of the related V1 ATPase (8, 9). In contrast, the central stalk of the complete bacterial F1ATPase is substantially shorter (4.0–4.5 nm) (9, 30).

The question that now arises is, which subunits of the A1A0 ATP synthase contribute to the A0 domain, the peripheral stalks, and the additional mass on top of A1. The A1A0 ATP synthase as isolated has nine subunits (A–I, K). Five of them form the A1 part and are assembled in the stoichiometry A1B3CDF (see above). The I and K subunits form the membrane domain, A0 (11, 12). Subunit I (70 kDa) is very similar to subunit a of V1V0 ATPases with a hydrophilic N-terminal and a hydrophobic C-terminal domain. The C terminus of subunit I is predicted to have seven transmembrane helices and is assumed to be functionally similar to subunit a of the V1V0 ATPases and F1F0 ATP synthases (3). The N-terminal domain is predicted to be highly α-helical and assumed to be the functional homolog of the soluble domain of peripheral stalk subunit b of F1F0 ATP synthases. Because only one of the peripheral stalks is clearly attached to the outside of the A0 domain, we conclude that the hydrophilic N terminus of subunit I emerges from the membrane-embedded A0 part and may go up along the side of A1 until the top of the A1 headpiece (Fig. 5). Whether the N-terminal domain might partly contribute to the cap on the top of the A1A0 molecule can only be speculated. In the presented average, the peripheral stalk (right) has a kinked structure in the lower part, giving this domain the flexibility to wrap around the A1 headpiece and ending up as the cap on the top (Fig. 3, B and C). Insertion and deletion of altered length in the so-called “tether” domain of the peripheral stalk subunit b of the Escherichia coli F1F0 ATP synthase, which is located above the membrane service, can be tolerated by the enzyme, indicating that this related connecting stalk has an inherent flexible structure (31). It has been suggested for the F1F0 ATP synthases that flexibility of the domain might allow reorientation of the stalk to act as a stator for rotation in one direction during ATP synthesis and in the opposite direction during ATP hydrolysis (31, 32).

Subunit K is a homolog of the F-type subunit c with two transmembrane helices. It consists of fused tandem repeats of sequences corresponding to the F-type subunit. *M. jannaschii* has a subunit K with six membrane-spanning helices (27 kDa) but with only two active carboxylates per monomer (12), which are involved in ion conduction along the membrane. As in the case of the F-type ATP synthases (33, 34) and V-type ATPases (35), the K subunits (or c in the F- and V-type ATPases) are thought to form a ring, which belongs to the rotary element inside the A1A0 ATP synthase. As shown in Fig. 4, the bottom of the central CDF-stalk domain spans the upper center of the A0 domain, facilitating the direct contact of the rotary ele-
ments, which consists of an ensemble made from the central stalk (CDP domain) and a ring of hydrophobic K subunits in the A0 membrane domain (21).

The second peripheral stalk appears to be connected to the collar domain and goes up to the A1 headpiece. Probable candidates for this stalk are the remaining A1A0-hydrophilic subunits H (12 kDa) and E (25 kDa) with the latter predicted to be highly α-helical (12). The modest contact area of this peripheral stalk with the A1 headpiece, which is also evident in electron micrographs of the related bacterial V1V0 ATPase from *Caloramator fervidus* (36), might be caused partially by stain accumulation. The top view projection of the rotated A1 complex (Fig. 4, panel D) shows a groove at the top of the A3B3-hexamer in close neighborhood to this peripheral stalk. Such a groove-like feature may form a binding domain for the peripheral connection in the A1 headpiece. In general, the positions of the peripheral stalks of the A1A0 ATP synthase as deduced from side views cannot be directly verified from top view projections, because such projection are not present in significant numbers if intact A1A0 molecules are prepared.

In summary, the first two dimensional projection maps of the A1A0 ATP synthase from *M. jannaschii* presented provides the structural basis toward a fuller understanding of the mechanistic events occurring in this class of enzymes. The reconstruction at a 1.8-nm resolution shows similarities and diversities between the structural modules to the evolutionary-linked F1F0 ATP synthases and V1V0 ATPases, such as the catalytic A1/F1/V1 headpiece and the central stalk domain. Although the existence of one (26, 37) or two (27) peripheral stalk(s) in the F1F0 ATP synthase is uncertain, these classes of ATPases/synthases might need at least one peripheral stalk acting as a stator that prevents the major hexameric arranged subunits (α3β3 or A3B3) from following the rotation of the central stalk domain. Whether the visualized second peripheral stalk in the V1V0 ATPase and in the presented A1A0 ATP synthase might act as a regulatory domain in the A-type ATP synthase as described for the plant V ATPase (25) can now be addressed.

REFERENCES