Insertion of the N-terminal Part of PsaF from *Chlamydomonas reinhardtii* into Photosystem I from *Synechococcus elongatus* Enables Efficient Binding of Algal Plastocyanin and Cytochrome c₆

HIPPLER, Michael, et al.

**Abstract**

A strain of the cyanobacterium *Synechococcus elongatus* was generated that expresses a hybrid version of the photosystem I subunit PsaF consisting of the first 83 amino acids of PsaF from the green alga *Chlamydomonas reinhardtii* fused to the C-terminal portion of PsaF from *S. elongatus*. The corresponding modified gene was introduced into the genome of the psaF-deletion strain FK2 by cointegration with an antibiotic resistance gene. The transformants express a new PsaF subunit similar in size to PsaF from *C. reinhardtii* that is assembled into photosystem I (PSI). Hybrid PSI complexes isolated from these strains show an increase by 2 or 3 orders of magnitude in the rate of P700⁺ reduction by *C. reinhardtii* cytochrome c₂ or plastocyanin in 30% of the complexes as compared with wild type cyanobacterial PSI. The corresponding optimum second-order rate constants (k₂ = 4.0 and 1.7 × 10⁷ m⁻¹ s⁻¹ for cytochrome c₂ and plastocyanin) are similar to those of PSI from *C. reinhardtii*. The remaining complexes are reduced at a slow rate similar to that observed with wild type PSI from *S. elongatus* and the algal donors. At high [...]

**Reference**


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Michael Hippler§§, Friedrich Drepper¶¶, Jean-David Rochaix††, and Ulrich Mühlenshoff‡‡

From the §Department of Molecular Biology and Plant Biology, University of Geneva, 30 Quai Ernest Ansermet, CH-1211 Geneva, Switzerland and the ¶¶Biologisches Institut II, University of Freiburg, Schänzlestraße 1, D-79104 Freiburg, Germany

A strain of the cyanobacterium *Synechococcus elongatus* was generated that expresses a hybrid version of the photosystem I subunit PsaF consisting of the first 83 amino acids of PsaF from the green alga *Chlamydomonas reinhardtii* fused to the C-terminal portion of PsaF from *S. elongatus*. The corresponding modified gene was introduced into the genome of the psaF-deletion strain PK2 by cotransformation with an antibiotic resistance gene. The transformants express a new PsaF subunit similar in size to PsaF from *C. reinhardtii* that is assembled into photosystem I (PSI). Hybrid PSI complexes isolated from these strains show an increase by 2 or 3 orders of magnitude in the rate of P700\(^{+}\) reduction by *C. reinhardtii* cytochrome \( c_6 \) or plastocyanin in 30% of the complexes as compared with wild type cyanobacterial PSI. The corresponding optimum second-order rate constants (\( k_2 = 4 \times 10^{7} M^{-1} s^{-1} \) for cytochrome \( c_6 \) and plastocyanin) are similar to those of PSI from *C. reinhardtii*. The remaining complexes are reduced at a slow rate similar to that observed with wild type PSI from *S. elongatus* and the algal donors. At high concentrations of *C. reinhardtii* cytochrome \( c_6 \), a fast first-order kinetic component (\( t_{1/2} \approx 4 \mu s \)) is revealed, indicative of intramolecular electron transfer within a complex between the hybrid PSI and cytochrome \( c_6 \). This first-order phase is characteristic for P700\(^{+}\) reduction by cytochrome \( c_6 \) or plastocyanin in algae and higher plants. However, a similar fast phase is not detected for plastocyanin. Cross-linking studies show that, in contrast to PSI from wild type *S. elongatus*, the chimeric PsaF of PSI from the transformed strain cross-links to cytochrome \( c_6 \) or plastocyanin with a similar efficiency as PsaF from *C. reinhardtii* PSI. Our data indicate that development of a eukaryotic type of reaction mechanism for binding and electron transfer between PSI and its electron donors required structural changes in both PSI and cytochrome \( c_6 \) or plastocyanin.

One of several minor differences found in the otherwise remarkably conserved electron transfer chains of oxygenic photosynthesis of cyanobacteria, algae, and land plants concerns the type of electron carrier proteins used to transfer electrons from the cytochrome \( b_{6}/f \) complex to photosystem I and the way they interact with PSI\(^{1}\) (1, 2). All cyanobacteria investigated utilize a cytochrome \( c_6 \) as a soluble periplasmic electron carrier. In several cases, e.g. *Synechococcus elongatus*, cytochrome \( c_6 \) is the only electron carrier in the periplasma and is constitutively expressed (1–3). Other cyanobacteria like *Anabaena* sp. PCC 7119 and *Synechocystis* sp. PCC 6803 and most algae examined, however, use both cytochrome \( c_6 \) and the copper-containing plastocyanin as alternative periplasmic electron carrier proteins (4–8). In these organisms, they are differentially expressed depending mostly on the relative availabilty of copper and iron in the culture medium (5, 8). In contrast, plastocyanin is expressed constitutively in photosynthetic land plants that lack cytochrome \( c_6 \). Thus, in the evolution of oxygen-evolving organisms a tendency to replace the originally used \( c \)-type cytochrome by plastocyanin is clearly discernible.

The PSI complex functions as a light-driven oxidoreductase that transfers electrons from cytochrome \( c_6 \) or plastocyanin to ferredoxin or flavodoxin (see Refs. 9 and 10 for a review). According to the established atomic structure of PSI from *S. elongatus*, the primary donor of PSI, P700, is located within the highly conserved reaction center core close to the periplasmic surface of the photosynthetic membrane (9, 11, 12). Two horizontal helixes I and I\(^{'}\), attributed to the PSI core subunits PsaA and PsaB, are thought to form a recognition site for binding of the periplasmic electron carriers (11, 12). However, despite the high degree of structural conservation of the PSI core subunits in all oxygen-evolving organisms, the mechanism of interaction between plastocyanin or cytochrome and PSI varies in different species.

In higher plants, electron transfer from plastocyanin to P700\(^{+}\) is a biphasic process that includes a first-order kinetic component with a half-life of about 12 \( \mu \)s which is attributed to electron transfer from plastocyanin to P700\(^{+}\) within a stable complex between plastocyanin and PSI formed prior to the photooxidation of P700 (13–15). Biochemical studies indicate that the PsaF subunit of PSI is involved in the formation of this complex (16–18). Similar first-order kinetic components with half-lives of about 3 \( \mu \)s are observed for the reduction of P700\(^{+}\) by both plastocyanin and cytochrome \( c_6 \) in the green alga *Chlamydomonas reinhardtii* (19). Electron transfer from both donors to PSI from a *psaF*-deficient mutant of *C. reinhardtii*...
was introduced at codons 24 and 25 of the psaF gene encoding the entire mature PsaF is fused in frame to the C. reinhardtii psaF gene were identified by either immunoblot analysis of photosynthetic membranes isolated from small scale cultures using anti-C. reinhardtii (20) or anti-S. elongatus PsaF antibodies or by Southern blot analysis of genomic DNA as described (32).

Isolation of Protein Components from S. elongatus and C. reinhardtii—Photosystem I complexes were extracted from PSII-depleted membranes by 0.6% w/v β-dodecyl maltoside and purified by centrifugation in sucrose gradients as described (33, 34). PSII from C. reinhardtii was isolated as described (19), and plastocyanin and cytochrome c551 were isolated from C. reinhardtii following the protocol of Ref. 6 with modifications described in Ref. 19. Cytochrome c551 from S. elongatus was isolated essentially as described in Ref. 35. Plastocyanin and cytochrome c551 concentrations were determined spectroscopically using absorption coefficients of ε370 nm = 4.93 mm\(^{-1}\) cm\(^{-1}\) and ε552 nm = 20 mm\(^{-1}\) cm\(^{-1}\), respectively (19).

Analytical Methods, Cross-linking Procedures, and Immunoblot Analysis—For the fast immunoblot analysis of photosynthetic membranes, 3.5-ml cultures of S. elongatus were grown to OD680 = 1, harvested by centrifugation, washed once in 1 ml of HMC buffer (20 mM Hepes, pH 7.8, 10 mM CaCl\(_2\), 5 mM MgCl\(_2\), 0.5 mM NaN\(_3\)), resuspended in 50 ml of HMC buffer, and frozen. The thawed suspension was incubated with 2 mg/ml lysozyme for 30 min at 48 °C and frozen. Cells were then lysed by the addition of 10 volumes of MCM (MMCC minus mannitol), and the photosynthetic membranes were recovered by centrifugation in a microcentrifuge at 4 °C for 10 min at maximum speed. Membranes were washed once in 500 μM of MLM supplemented with 0.1% sulfoethyl 10, pelleted by centrifugation, and resuspended in SDS loading buffer at a concentration of approximately 0.25 mg of chlorophyll/ml.

Cytochrome c551 and plastocyanin were chemically cross-linked to photosystem I essentially as described (19); PSI particles at a concentration of 0.1 mg of chlorophyll/ml in 30 mM Hepes, pH 7.5, 3 mM MgCl\(_2\), and 1 mM ascorbate were incubated in the presence of 20 μM plastocyanin or cytochrome c551 with 5 mM N-ethyl-3-(3-dimaminopropyl)carbodiimide and 10 mM N-hydroxysuccinimide for 45 min in darkness. The reaction was terminated by addition of ammonium acetate to a final concentration of 0.2 M and diluted 4-fold. PSI complexes were sedimented by centrifugation at 200,000 × g for 45 min and resuspended in 20 mM Hepes, pH 7.5, 0.05% Triton X-100. Analytical SDS-polyacrylamide gel electrophoresis was carried out using 15 or 16.5% (w/v) polyacrylamide gels (36). For immunoblot analysis, PSI complexes equivalent to 4 μg of chlorophyll and membrane preparations equivalent to 10 μg of chlorophyll were analyzed. Western blots and antibody incubations were carried out essentially as described (36). Immunodection reactions were performed using anti-rabbit IgG antibodies linked to horseradish peroxidase followed by enhanced chemiluminescence detection (ECL, Amersham Pharmacia Biotech).

Flash-absorption Spectroscopy—Flash-induced absorption changes at 817 nm were measured at 296 K on a single beam spectrophotometer essentially as described (15). Flash excitation was performed using a frequency-doubled Nd:YAG laser (5 ns full width at half maximum). The measuring light was provided by a luminescence diode (Hitachi HE6404SG, 40 milliwatts, 30 nm full width at half maximum), filtered through an 817-nm interference filter (9 nm full width at half maximum), and focused through a spot with an optical path length of 1 cm that contained 200 μl of sample. For flash-absorption experiments, PSI reaction centers were excited in the presence or absence of cytochrome c551 or plastocyanin at a standard concentration of 50 μM chlorophyll in 30 mM Mops, pH 7.0, supplemented with 0.05% β-dodecyl

2 U. Mühlenhoff, unpublished.
RESULTS

Vector Construction—To generate an S. elongatus strain carrying the psaF gene from C. reinhardtii, integrative vectors were introduced into the S. elongatus strain FK2 that carries a psaF gene interrupted by a kanamycin resistance cassette and the cleavage site of the signal peptidase is indicated by an arrow. For DNA sequences see Refs. 29 and 30. The Sm′/Sp′ gene cassette was obtained from pHP45 (31); the Km′ gene originated from pRL161 (32). Restriction sites in brackets were lost during construction. For details of the cloning procedures see “Experimental Procedures.”

Characterization of the Mutant H53 Expressing a Chimeric PsaF Subunit—Following the electroporation of the psaF-deletion strain FK2 from S. elongatus in the presence of the plasmid pFBalCRF3, streptomycin-resistant transformants with the desired Km′/Sm′ phenotype were selected by replica plating on solid media, and those expressing the chimeric C. reinhardtii-S. elongatus PsaF protein were screened by immunoblot analysis using anti-C. reinhardtii-PsaF antibodies (not

As shown in Fig. 1 (bottom) and Fig. 2, the integrative vector FBalCRF3 carries a gene encoding a hybrid PsaF protein that contains the cyanobacterial signal sequence (up to codon Asp-24 of S. elongatus psaF), the N-terminal domain of PsaF from C. reinhardtii (30) (i.e. between codons Asp-63/Ile-64 to codon His-145), and the hydrophobic C-terminal part of the cyanobacterial subunit (starting with codon Ala-60 of S. elongatus psaF) which is assumed to anchor the protein to the hydrophobic core of PSI. A streptomycin/spectinomycin resistance gene cassette was inserted at the HpaI site located 165 base pairs downstream of psaF, well downstream of the transcribed region of the psaF/psaJ operon (see “Experimental Procedures” for details of the construction). In addition to FBalCRF3, a vector, pCRSEF/3, was constructed in which the complete region of the psaF gene from S. elongatus encoding the entire mature PsaF subunit was replaced by the corresponding part of psaF from C. reinhardtii (see “Experimental Procedures”). However, following the introduction of this vector into S. elongatus, C. reinhardtii PsaF was not recovered in PSI although it was verified by Southern blot analysis that the gene was cotransformed together with the antibiotic resistance marker and inserted correctly into the genome (not shown).
shown, see “Experimental Procedures”). The organization of the psaF/psaJ locus of one of these strains, H53, was investigated by Southern blot analysis shown in Fig. 3. First, upon hybridization with a 500-base pair fragment from a C. reinhardtii psaF cDNA clone carrying part of the gene encoding the mature PsaF, a single 6.3-kb genomic EcoRV restriction fragment is detected that is not present in S. elongatus nor in strain FK2 (Fig. 3A). The same DNA fragment is detected in H53 DNA after hybridization with a probe carrying the Smr/Spr genes inserted into pFBalCRF/3 (Fig. 3B). Taken together, these blots indicate that the region of the psaF gene of C. reinhardtii has been inserted with the antibiotic marker gene into the genome of S. elongatus. Furthermore, when the blots were probed with the ClaI/XhoI fragment carrying the psaF, psaJ, and rpl9 genes, only single EcoRV fragments of /H11011 13 and 14.5 kb are observed in DNA from wild type and strain FK2. The size difference is due to the presence of the Kmr marker gene in FK2 (Fig. 3C, see Fig. 1). For strain H53, however, two EcoRV fragments of /H11011 8.0 and 6.3 kb are detected, indicating that a new EcoRV site has been introduced into the psaF/psaJ locus of H53. Since the Smr/Spr marker genes do not contain an EcoRV site, the existence of a new EcoRV restriction site together with the Smr/Spr genes at the psaF/psaJ gene locus indicates that the entire part of the psaF gene that originates from C. reinhardtii has been introduced into strain H53, because C. reinhardtii psaF is flanked by a new EcoRV site and the Smr/Spr genes in the integrative vector pFBalCRF/3 (Fig. 1). Finally, when the blots were probed with a fragment carrying the Km’ marker present in strain FK2, no hybridization signal was observed in DNA from strain H53 (Fig. 3D). This result indicates that H53 represents a fully segregated mutant in which the original psaF/psaJ gene locus that carried a kanamycin resistance gene has been completely replaced by the new psaF gene at the psaF/psaJ gene locus in all copies of the polyploid genome. Essentially the same conclusion was obtained by a similar Southern blot analysis that was carried out using EcoRI-restricted DNA (not shown).

The expression pattern of the psaF genes in S. elongatus wild type and strains FK2 and H53 was monitored by Western blot analysis of photosynthetic membranes and isolated photosystem I complexes using anti-C. reinhardtii-PsaF antibodies (Fig. 4). This antibody recognizes the cyanobacterial PsaF subunit in membranes and PSI preparations of wild type S. elongatus. As expected from the deduced sequences, the apparent mass of the cyanobacterial PsaF subunit is approximately 15 kDa, approximately 3 kDa smaller than its algal counterpart (Fig. 4, lanes 1, 4, and 5). In strain FK2, the corresponding subunit is absent (Fig. 4, lanes 2 and 6). However, in membranes and PSI from strain H53 a new version of the PsaF protein is detected which exceeds the original cyanobacterial PsaF subunit by 2.5 kDa in mass and is only slightly smaller than PsaF from C. reinhardtii (Fig. 4, lanes 3 and 7). Thus, the modified psaF gene of strain H53 is expressed, and the hybrid PsaF protein is assembled
into the cyanobacterial photosystem I complex. In addition, the fact that the protein is very similar in size to the mature algal PsaF subunit indicates that the protein is exported across the membranes and processed correctly by the tran-
sition of plasmid pHP45 encoding the part for the mature PsaF; C. reinhardtii from strain FK2; lane 5, PSI from strain H53. Membrane samples equivalent to 4 mg of chlorophyll were separated by SDS-polyacrylamide gel electrophoresis and transferred to nitrocellulose membrane. The blot was probed with the following biotinylated DNA probes: A, PCR fragment of a psaF cDNA clone from C. reinhardtii encoding the part for the mature PsaF; B, the Smal fragment of plasmid pH45I containing the Smr/Syp genes; C, ClaI/BglII fragment containing psaF/psaJ from S. elongatus; D, HindII fragment of plasmid pRL161 carrying Kmr gene. Bars to the left indicate the positions of the HindIII restriction fragments.

**Fig. 3.** Southern analysis of genomic DNA from wild type and mutant strains of S. elongatus. Lane 1, wild type DNA; lane 2, DNA from strain FK2; lane 3, DNA from strain H53. DNA samples were restricted by EcoRV separated on a 0.8% agarose gel and transferred to nylon membranes. The blots were probed with the following biotinylated DNA probes: A, PCR fragment of a psaF cDNA clone from C. reinhardtii encoding the part for the mature PsaF; B, the Smal fragment of plasmid pH45I containing the Smr/Syp genes; C, ClaI/BglII fragment containing psaF/psaJ from S. elongatus; D, HindII fragment of plasmid pRL161 carrying Kmr gene. Bars to the left indicate the positions of the HindIII restriction fragments.

**Fig. 4.** Immunoblot analysis of membranes and photosystem I preparations from wild type S. elongatus and strains FK2 and H53 probed with antibodies against PsaF from C. reinhardtii. Lane 1, S. elongatus wild type membranes; lane 2, membranes from strain FK2; lane 3, membranes from strain H53; lane 4, C. reinhardtii PSI; lane 5, S. elongatus wild type PSI; lane 6, PSI from strain FK2; lane 7, PSI from strain H53. Membrane samples equivalent to 10 μg of chlorophyll and PSI preparations equivalent to 4 mg of chlorophyll were separated by SDS-polyacrylamide gel electrophoresis and transferred to nitrocellulose membrane. The blot was probed with an anti-C. reinhardtii-PsaF antiseraum and developed by luminol detection. Bars to the left indicate the position of recombinant molecular mass marker proteins (Sigma) whose molecular masses (in kDa) are indicated.

**Fig. 5.** Flash-induced absorption changes measured at 817 nm with isolated photosystem I complexes from wild type S. elongatus and from the mutant strains FK2 and H53. Kinetic traces were recorded in the presence of cytochrome c6 from S. elongatus (S.e.) (A), cytochrome c6 from C. reinhardtii (C.r.) (B), and plastocyanin from C. reinhardtii (C). The concentrations of reduced donor protein were 10 μM. MgCl2 was present at 1 mM (A), or 10 mM (B and C). Transients obtained with PSI from wild type S. elongatus (WT) are displayed on dotted lines, and those obtained with PSI from the mutant strains FK2 and H53 are shown on continuous lines. The vertical dashed lines separate regions recorded on different time scales. In order to be directly comparable, the kinetic traces of the mutant PSI were normalized to the same initial amplitude as for wild type PSI. (The differences in amplitude were <10%.) Residuals for fits of the traces of P700 reduction from wild type S. elongatus and strain H53 by cytochrome c6 from S. elongatus with one (dotted trace) or two exponential components (solid trace) are shown in the panels directly below A. Results of fits: S. elongatus H53 PSI, two components, t1/2 = 7.2 ms (30%) and t1/2 = 27 ms (70%) (solid trace); wild type PSI, one component, t1/2 = 20 ms (for details see text.)
from wild type *S. elongatus* and the mutant strains FK2 and H53 induced by a laser flash in the presence of 10 μM cytochrome *c* from *S. elongatus* (A), and 10 μM cytochrome *c* (B) or 10 μM plastocyanin from *C. reinhardtii* (C). In the presence of *S. elongatus* cytochrome *c* electron transfer is monophasic for photosystem I from wild type *S. elongatus* with a half-life of ~20 ms (Fig. 5A), and at first glance, the introduction of the hybrid PsaF in PSI from H53 causes only a small increase of the apparent rate of P700− reduction (see below for a more detailed analysis). Cytochrome *c* and plastocyanin from *C. reinhardtii*, however, react much slower with PSI isolated from wild type *S. elongatus* or the PsaF deletion strain FK2, and the kinetic traces can be fitted to monophasic decays (Fig. 5, B and C). For *C. reinhardtii* cytochrome *c* electron transfer to the cyanobacterial PSI is about four times slower (t1/2 ~ 80 ms) than with the cyanobacterial cytochrome, and the electron transfer from plastocyanin shows a half-life of ~1 s, which is ~50 times slower than for cytochrome *c* from *S. elongatus*. In contrast, the electron transfer to the chimeric PSI from *S. elongatus* strain H53 by cytochrome *c* and plastocyanin from *C. reinhardtii* shows a faster and a slower component, accounting for about 30 and 70% of the total amplitude, respectively (Fig. 5, B and C). The rates of both phases depend on the donor concentrations, indicating second-order processes. The fast component of these biphasic decays has a half-life of 2.1 and 6.5 ms for cytochrome *c* and plastocyanin (at 10 μM each), respectively, whereas the slow kinetic component with both electron transfer donors is about 2 orders of magnitude slower than the fast phase and similar to those observed for PSI from wild type *S. elongatus*. A similar ratio of 30–70% between the fast and slow phase is also observed for P700− reduction by *C. reinhardtii* within a stable, preformed complex (19); second, an intermediate component (t1/2 = 154 μs) with a half-time that decreases with increasing concentration of reduced donor protein typically for second-order reactions between soluble reactants (see also Fig. 5). The amplitudes of the first- and second-order phases contribute to about 15 and 25% of the entire signal, respectively. The third, very slow component (t1/2 = 70 ms) with an amplitude of ~65% of the total signal is attributed to PSI lacking a chimeric PsaF. In contrast, the absorbance transients of P700− reduction in H53 PSI show only two kinetic components at plastocyanin concentrations up to 500 μM that are both concentration-dependent (Fig. 6B). The slower component (t1/2 = 49 ms at 300 μM plastocyanin) most likely reflects the reduction of PSI complexes without a functional hybrid PsaF and plastocyanin, whereas the faster component (t1/2 = 96 μs at 300 μM plastocyanin) is attributed to the reaction of plastocyanin with PSI containing the chimeric PsaF. No fast first-order component can be detected with plastocyanin (Fig. 6B). Thus, the presence of the hybrid PsaF subunit in the cyanobacterial PSI is not sufficient to generate a tight complex between plastocyanin and PSI although its presence is sufficient for complex formation with cytochrome *c* from *C. reinhardtii*. Whereas the introduction of the hybrid PsaF into the cyanobacterial PSI has a strong effect on the binding of the algal donors, the effects observed with the cyanobacterial cytochrome *c* are minor (see Fig. 5). However, upon analyzing the transient signals in more detail, it appears that although the kinetics of P700− reduction by *S. elongatus* cytochrome *c* are monophasic for PSI from wild type *S. elongatus* (see lower panel of residuals in Fig. 5A) and the PsaF deletion mutant (not shown), they are biphasic in the presence of the hybrid PsaF (upper panel of residuals in Fig. 5A). Therefore, in order to analyze a possible interaction between the hybrid PsaF and the cyanobacterial cytochrome *c* in more detail, P700− reduction was monitored under a wide range of salt concentrations. Fig. 7 shows the effect of the ionic strength on the rate of the kinetic components for cytochrome *c* from *S. elongatus* (open symbols) and *C. reinhardtii* (closed symbols). At low ionic strength (<1 mM MgCl2) the kinetics of P700− reduction by *S. elongatus* cyto-
concentrations found for the faster phase of P700 phases for cytochrome comparison to those observed between the corresponding two components is rather small (factor C. reinhardtii the hybrid PSI by C. reinhardtii cytochrome c₆ (4 × 10⁻⁷ M⁻¹ s⁻¹ at 3–10 mM MgCl₂). In addition, the general shape of the salt dependence of this component is very similar for the algal and the cyanobacterial cytochrome and reminiscent of the one observed for C. reinhardtii photosystem I (19). On the other hand, the salt dependence of the slower phase of P700⁺ reduction of PSI from S. elongatus H53 by S. elongatus cyt c₆ (open triangles, 70% relative amplitude) is similar to the one observed for PSI from the wild type (open rectangles) and the psaF-deletion strain FK2 (not shown), and those observed for the slow phase in the presence of C. reinhardtii cytochrome c₆ (closed triangles) is similar to the one observed for PSI from the C. reinhardtii psaF-deletion strain b3f (19). Thus, the salt dependences of the slow phases (70% relative amplitude) corroborate the attribution of these phases to the reduction of those PSI complexes from strain H53 that lack a functional hybrid PsAF subunit. The existence of a new, faster kinetic component for P700⁺ reduction of the hybrid PSI by cytochrome c₆ from S. elongatus with a salt dependence reminiscent of the one observed for C. reinhardtii cyt c₆ shows that the cyanobacterial cytochrome is affected by the introduction of a eukaryotic PsAF. However, the difference between the rate of the faster and slower components is rather small (factor <4) in comparison to those observed between the corresponding two phases for cytochrome c₆ from C. reinhardtii (factor ~200) which is fully adapted to use the eukaryotic PsAF subunit efficiently.

PSI from S. elongatus H53 Cross-links to Plastocyanin and Cytochrome c₆—The interactions of isolated PSI particles from C. reinhardtii, S. elongatus wild type, and strain H53 with plastocyanin and cytochrome c₆ from C. reinhardtii and S. elongatus were examined by immunoblot analysis of cross-linked complexes generated in the absence of donor protein (lanes 1) or in the presence of either plastocyanin (Pc, lanes 2) or cytochrome c₆ from C. reinhardtii (Cyt. Cr, lane 3) or cytochrome c₆ from S. elongatus (Cyt. S sp, lane 4) were analyzed. Samples corresponding to 2 μg of chlorophyll were loaded on each lane, fractionated by SDS–polyacrylamide gel electrophoresis, electrotransferred to nitrocellulose membrane, and probed with antibodies against C. reinhardtii efficiency of cross-linking to PSI from C. reinhardtii or S. elongatus H53 is in low comparison with plastocyanin or cytochrome c₆ from C. reinhardtii.

**DISCUSSION**

Comparison of the PsAF subunits of PSI from eukaryotic and prokaryotic photosynthetic organisms has revealed that the former contain a basic region near their N-terminal end which is absent in cyanobacteria. This region has been postulated to form an amphipathic helix whose positively charged face interacts electrostatically with acidic patches of plastocyanin (26). Studies by site-directed mutagenesis of the psaF gene from C. reinhardtii have confirmed this hypothesis and have further shown that this region forms a recognition site for the binding of plastocyanin and cytochrome c₆. In particular, Lys-16 to Lys-23 of PsAF appears to play a crucial role in the electrostatic interaction with both electron donor proteins (37).

In this study we have used a complementary approach to study the function of the N-terminal region of the eukaryotic PsAF by inserting this sequence into a cyanobacterial PsAF protein. We have thereby shown that it is possible to express a chimeric algal-cyanobacterial PsAF protein in a psaF-deficient strain of S. elongatus and to incorporate it into its PSI complex. This report thus demonstrates that site-directed mutagenesis of non-essential photosynthetic genes can be performed in S. elongatus, the cyanobacterium from which the crystallographic structure of PSI was determined (11, 12). The organization of the psaF/psaJ operon of S. elongatus strain analyzed in this work corresponds to a combination of a eukaryotic psaF with a cyanobacterial psaJ gene that is very similar to the psaF/psaJ operon of *Cyanophora paradoxa* and *P. purpurea* (38, 39) indicating that the basic N-terminal domain of PsAF was already present very early in the evolution of algae and land plants (1) (see Fig. 2).

The introduction of the N-terminal basic patch of PsAF from C. reinhardtii into the cyanobacterial subunit clearly improves the binding of plastocyanin or cytochrome c₆ from C. reinhardtii to cyanobacterial PSI. The electron transfer rates are increased by 2 and 3 orders of magnitude, and the second-order rate constants (₃ = 4.0 and 1.7 × 10⁻⁷ M⁻¹ s⁻¹ for cytochrome
c₆ and plastocyanin, respectively) are similar to the values found for electron transfer to PSI from wild type C. reinhardtii (19). In addition, a first-fast order electron transfer occurs between cytochrome c₆ from C. reinhardtii and the hybrid PSI indicating that the N-terminal domain of the eukaryotic PsaF subunit is required and sufficient for complex formation between cytochrome c₆ and PSI. Finally, the electron donors from C. reinhardtii can be cross-linked almost equally well to PSI complexes from S. elongatus H53 and C. reinhardtii, demonstrating that the basic N-terminal part of PsaF which is unique to eukaryotes is important for binding of the electron donors from C. reinhardtii and even from cyanobacteria. Surprisingly, however, no fast first-order kinetic component is detected for P700⁺ reduction by C. reinhardtii plastocyanin, indicating that although the electron transfer to the cyanobacterial PSI is drastically improved by the N-terminal domain of PsaF, its interaction cannot be stabilized and thus cannot lead to the formation of an intermolecular electron transfer complex. This indicates that, besides the N-terminal region of PsaF, additional structural differences must exist between PSI from S. elongatus and C. reinhardtii which affect the docking of plastocyanin to PSI. Site-directed mutagenesis of plastocyanin (26, 40–42) suggests that the binding of plastocyanin to PSI involves long range electrostatic interactions between PsaF and plastocyanin and a docking mechanism which brings the flat hydrophobic surface of plastocyanin in close contact to the PSI core proteins. The absence of complex formation with plastocyanin could indicate that the electrostatic interaction with PsaF is incompletely restored in the chimeric PSI due to a slight misalignment of the hybrid PsaF within PSI. Alternatively, a second recognition site is different in PSI from cyanobacteria, most likely the hydrophobic contact surface on the PsaA or PsaB subunits. However, gross structural alterations of the hybrid PsaF are not likely since the intermolecular electron transfer with a half-life of 4 μs observed in the complex with algal cytochrome c₆ is the same as within the eukaryotic complex. This is indicative of a similar orientation within both electron transfer complexes, since the half-life of electron transfer is very sensitive to changes in distance between two redox partners (43).

The new N-terminal domain of PsaF in the hybrid photosystem I also influences the interaction with cytochrome c₆ from S. elongatus, but the effects are apparently more subtle. In contrast to its algal counterpart, this protein reacts very efficiently with S. elongatus PSI regardless of the presence of a cyanobacterial type PsaF (Fig. 5). However, the salt dependence of the faster of the two second-order kinetic components observed for P700⁺ reduction of the hybrid PSI by cytochrome c₆ from S. elongatus qualitatively resembles the one observed for cytochrome c₆ from C. reinhardtii (Fig. 7), and the cyanobacterial protein cross-links to the eukaryotic PsaF subunit, although less efficiently than its algal counterpart (Fig. 8). In addition, the presence of the eukaryotic PsaF subunit results in a 4-fold rate increase in the rate of P700⁺ reduction by S. elongatus cytochrome c₆ at optimal salt concentrations. This suggests that the introduction of the new basic domain on PsaF during evolution resulted in a small immediate improvement of the reaction between cyanobacterial cytochrome c₆ and PSI. However, the rates observed for cytochrome c₆ from C. reinhardtii are still 4–5 times faster than those of the cyanobacterial cytochrome, a clear indication that during the evolution from cyanobacteria to algae further structural changes must have been introduced into cytochrome c₆ in order to develop an efficient interaction with the basic domain of PsaF. In this context, the slow P700⁺ reduction rates that are observed with cytochrome c₆ in the PsaF-less complex from C. reinhardtii but not from cyanobacteria also show that during evolution the PsaF subunit has become an essential component in the binding of cytochrome to PSI.

This essential role of the N-terminal domain of eukaryotic PsaF is even more pronounced in the case of the binding of plastocyanin to PSI in C. reinhardtii (19). The extremely poor rates of electron transfer between plastocyanin and the cyanobacterial PSI (10 times slower than with algal cyt c₆) indicates that, during evolution, the eukaryotic plastocyanin most likely lost essential structural elements required for the recognition of cyanobacterial PSI. These are still present to some extent in algal cytochromes. With regard to its binding mechanism to PSI, cytochrome c₆ from C. reinhardtii thus appears to represent an evolutionary intermediate between cytochrome c₆ from S. elongatus and plastocyanin from C. reinhardtii, since it interacts efficiently with the positively charged patch of a eukaryotic PsaF and still partially retains the ability to interact with the recognition site for the periplasmatic electron donors of a cyanobacterial PSI. In this context, it is noteworthy that cyanobacterial cytochromes contain a single arginine residue at the otherwise hydrophobic surface that contacts PSI. This residue is conserved in algal cytochromes and in cyanobacterial plastocyanin but is absent in eukaryotic plastocyanin and may thus play an important role in the interaction between PSI and the periplasmic electron donors in cyanobacteria.

Taken together, our data indicate that during the evolution from cyanobacteria to algae and land plants, the reaction pathway from the periplasmic electron donor proteins to photosystem I changed and required structural changes in both PSI and cytochrome c₆ or plastocyanin. For PSI, these were (i) the introduction of the positively charged N-terminal recognition site of PsaF to bind plastocyanin and cytochrome efficiently and to locate them in the vicinity to P700⁺, and (ii) structural change(s) that most likely occurred on the PSI subunits PsaA or PsaB. In addition, changes were required on cytochrome c₆ and plastocyanin in order to adapt to the new mechanism. For cytochrome c₆ from C. reinhardtii, the presence of an algal type PsaF subunit suffices to establish tight complex formation with PSI, whereas for plastocyanin both changes are required. In this respect, the algal cytochrome c₆ appears to be an evolutionary intermediate between a cyanobacterial cytochrome c₆ and an algal/land plant plastocyanin.

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REFERENCES


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