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# Inactivation of the geranylgeranyl reductase (ChlP) gene in the cyanobacterium *Synechocystis* sp. PCC 6803

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**Abstract**

Geranylgeranyl reductase catalyses the reduction of geranylgeranyl pyrophosphate to phytyl pyrophosphate required for synthesis of chlorophylls, phylloquinone and tocopherols. The gene *chlP* (ORF *sll*1091) encoding the enzyme has been inactivated in the cyanobacterium *Synechocystis* sp. PCC 6803. The resulting *ΔchlP* mutant accumulates exclusively geranylgeranylated chlorophyll *a* instead of its phytylated analogue as well as low amounts of α-tocotrienol instead of α-tocopherol. Whereas the contents of chlorophyll and total carotenoids are decreased, abundance of phycobilisomes is increased in *ΔchlP* cells. The mutant assembles functional photosystems I and II as judged from 77 K fluorescence and electron transport measurements. However, the mutant is unable to grow photoautotrophically due to instability and rapid degradation of the photosystems in the absence of added glucose. We suggest that instability of the photosystems in *ΔchlP* is directly related to accumulation of geranylgeranylated chlorophyll *a*. Increased rigidity of the chlorophyll isoprenoid tail moiety due to three additional C=C bonds is the likely cause of photooxidative stress and reduced stability of photosynthetic pigment–protein complexes assembled with geranylgeranylated chlorophyll *a* in the *ΔchlP* mutant.


*Keywords:* Chlorophyll biosynthesis; Geranylgeranyl reductase; Geranylgeranylated chlorophyll; *Synechocystis* sp. PCC 6803

## 1. Introduction

Chlorophyll (Chl) *a* plays a pivotal role in oxygenic photosynthetic organisms such as plants, green algae and cyanobacteria. Chl *a* is a primary electron donor in the reaction centers (RCs) of photosystem (PS) I ($P_{700}$) and PSII ($P_{680}$). Moreover, Chl *a* constitutes also the primary electron acceptor ($A_0$) in RCI. A Chl *a* derivative—pheophytin *a*—is the primary electron acceptor in RCII. Most Chls in both PSI and PSII, however, act as light-harvesting (antenna) pigments, supplying the RCs with sufficient excitation energy to maintain a high rate of photosynthesis. In cyanobacteria, antenna Chl *a* is associated with the RC-core proteins: PsaA, PsaB of PSI and D1, D2, CP43, CP47 of PSII, respectively. Under certain stress conditions—in particular, iron deficiency—the Chl *a*-binding IsiA protein (CP43′) accumulates in cyanobacteria; for a recent review, see Ref. [1]. IsiA was also found in a PSI *psaFJ-null* mutant of the cyanobacterium *Synechocystis* sp. PCC 6803 (in the following referred to as *Synechocystis*) under iron-replete conditions as a response to oxidative stress [2]. Additionally, one Chl *a* is present in the cytochrome $b_6f$ complex

*Abbreviations:* Chl *a*, (phytylated) chlorophyll *a*; Chl $a_{gg}$, geranylgeranylated Chl *a*; Chlide *a*, chlorophyllide *a*; ChlG, chlorophyll synthase; ChlP, geranylgeranyl reductase; *chlP*, gene encoding ChlP; DCBQ, 2,6-dichloro-*p*-benzoquinone; GGPP, geranylgeranyl pyrophosphate; Km/Km$^r$, kanamycin/kanamycin resistance; OD, optical density; ORF, open reading frame; PBS, phycobilisome; PC, phycocyanin; PPP, phytyl pyrophosphate; PSI, PSII, photosystem I, II; RC, reaction center; WT, wild type

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suggesting that this Chl *a* plays a structural role in assembly and stabilization of the complex [3]. Chl *a* availability affects accumulation of Chl *a*-binding apoproteins of PSI and PSII in higher plants and cyanobacteria [4–6]. Conceivably, the isoprenoid tail moiety of Chl *a* appears to be of particular importance: its absence was shown to prevent, e.g., accumulation of D1 and PsaA [6].

Both the tetrapyrrole and the isoprenoid synthesizing pathways provide the substrates for the final steps of Chl biosynthesis, chlorophyllide (Chlide) and geranylgeranyl-pyrophosphate (GGPP) (Fig. 1). In the last step of Chl *a* biosynthesis, Chlide is esterified with GGPP or phytyl pyrophosphate (PPP) resulting in formation of geranylgeranylated Chl *a* (Chl $a_{gg}$) or phytylated Chl *a*, respectively (for reviews, see Refs. [7,8]). The reaction is catalyzed by Chl synthase (ChlG) (Fig. 1). GGPP has four C=C (double) bonds, three of which (at positions 6, 10, and 14) are reduced by geranylgeranyl reductase (ChlP). ChlP accepts the substrates GGPP as well as Chl $a_{gg}$ yielding PPP or Chl *a*, respectively (Fig. 1, cp. also Ref. [9]).

Phytol is also the lipophilic tail moiety of phylloquinone (vitamin $K_1$) and tocopherols (vitamin E). Phylloquinone acts as secondary electron acceptor ($A_1$) in RCI [10]. Tocopherols are lipophilic antioxidants being synthesized only in photosynthetic organisms [11,12].

Naturally, Chl $a_{gg}$ occurs in detectable quantities only transiently in etioplasts of higher plants during greening [13,14]. It is generally not detectable in the mature photosynthetic apparatus of plants, green algae and cyanobacteria. The photosynthetic purple bacterium, *Rhodospirillum rubrum*, accumulates geranylgeranylated bacteriochlorophyll *a* (BChl $a_{gg}$). The RC of this species, however, contains phytylated bacteriopheophytin at the H site [15]. Previously characterized mutants of the green alga *Scendesmus obliquus* and the purple bacterium *Rhodobacter capsulatus* accumulating Chl $a_{gg}$ and BChl $a_{gg}$, respectively, were shown to be impaired in photosynthetic performance [16,17].

Transgenic *Nicotiana tabaccum* lines expressing antisense *chlP*-RNA showed reduced Chl and tocopherol contents and accumulated considerable levels of Chl $a_{gg}$, Chl $b_{gg}$ and α-tocotrienol in their leaves [18–20]. These transgenic plants, however, did not completely substitute Chls *a* and *b* by geranylgeranylated counterparts. Nevertheless, increased light sensitivity and impaired growth were observed [18–20]. The specific roles of tocopherols in protection of thylakoid membranes from photooxidation and stabilization of the photosynthetic apparatus remain still elusive. The effects brought about by substitution of Chl *a* by Chl $a_{gg}$, however, indicate pivotal functions of the phytyl tail moiety in photosynthesis that cannot be substituted for completely by a geranylgeranyl residue.

The present study is aimed at contributing to a better understanding of the role of the isoprenoid chain, in particular the phytyl chain of Chl *a*, in the structure and function of the photosynthetic apparatus. The *chlP* gene (ORF *sll*1091) encoding geranylgeranyl reductase (ChlP) [21] was inactivated in *Synechocystis*. The resulting *ΔchlP* mutant was used to study the effects of the exclusive accumulation of Chl $a_{gg}$ (instead of its phytylated analogue) on assembly, stability and function of the photosynthetic apparatus.

## 2. Materials and methods

### 2.1. Strains and growth conditions

*Synechocystis* wild-type (WT) and *ΔchlP* mutant cells were grown in BG11 medium [22] supplemented with 10

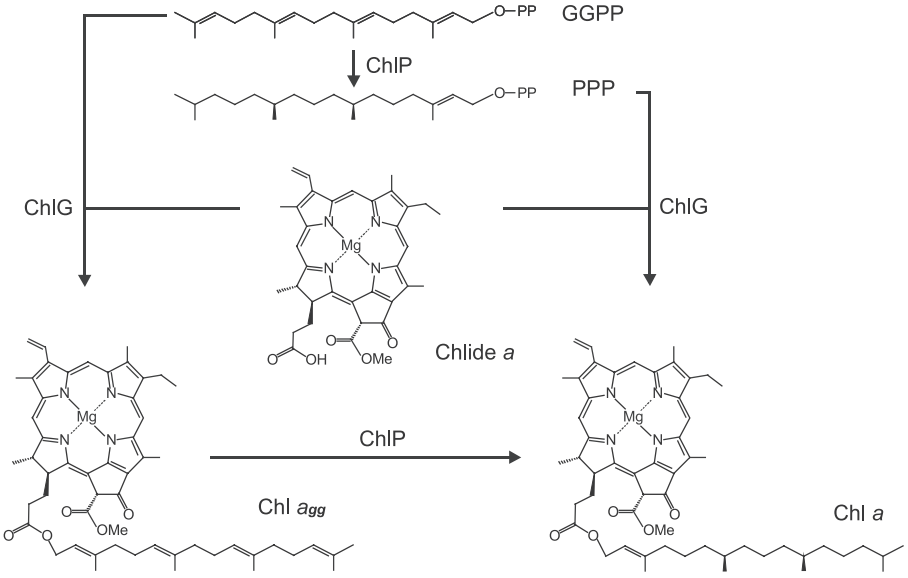


Fig. 1. The last steps of chlorophyll *a* biosynthesis. GGPP, geranylgeranyl pyrophosphate; PPP, phytyl pyrophosphate; Chl $a_{gg}$, geranylgeranylated Chl *a*; Chl *a*, phytylated Chl *a*; ChlP, geranylgeranyl reductase; ChlG, Chl synthase.

mM glucose at 40 μmol photons $m^{-2}$ $s^{-1}$ (moderate light intensity) unless otherwise indicated. The *ΔchlP* mutant was propagated at low light intensity (2–4 μmol photons $m^{-2}$ $s^{-1}$). For growth on plates, 1.0% (w/v) bacto agar (Difco) was added to BG11. Additionally, the medium was supplemented with kanamycin (Km, 50 μg $ml^{-1}$) in the case of the *ΔchlP* mutant. Growth was monitored by optical density (OD) measurements at 750 nm using an Ultrospec II spectrophotometer (LKB Biochrom).

### 2.2. Mutant construction

A DNA fragment carrying a segment of the *chlP* coding region was amplified by PCR from genomic DNA of the *Synechocystis* WT strain using the primers CGGGAA CGGGCGGAGAAACTGGG (F) and CACATACGGGCG-GATTTGGCGGC (R) (Fig. 2A). The PCR product was cloned into the pGEM-T Easy vector (Promega, Mannheim, Germany). A Km resistance ($Km^r$) cassette was cut with *Hin*cII from the pUC4K plasmid (Pharmacia) and inserted into the *Eco*72I site of the cloned *chlP* fragment. For cloning and subcloning of plasmids, *Escherichia coli* strain JM109 [23] was used. The resulting plasmid construct was used to transform *Synechocystis* WT cells to $Km^r$ by homologous recombination. Transformants, in which the $Km^r$ cassette interrupts the WT gene (cp. Fig. 2A), were segregated by restreaking on plates containing 10 mM glucose and increasing concentrations of Km (from 20 to 100 μg $ml^{-1}$). Low light conditions were applied during segregation to avoid generation of suppressor mutations. Complete segregation of the *Synechocystis* mutant was confirmed by PCR (Fig 2B). The homozygous mutant with a disrupted *chlP*-gene has been designated *ΔchlP*.

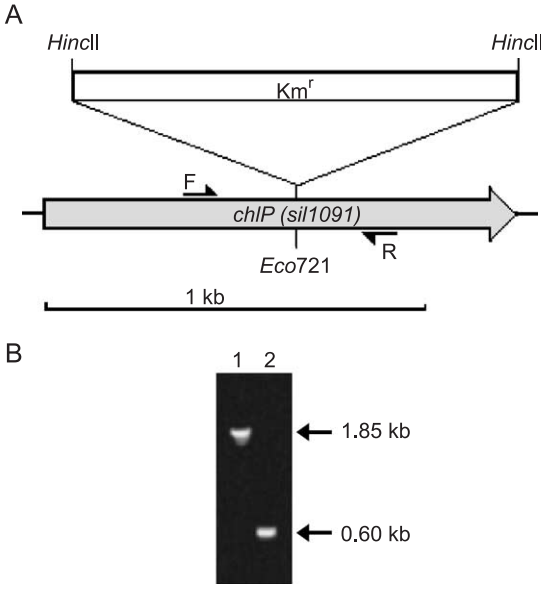


Fig. 2. Insertional inactivation of the *chlP* gene in *Synechocystis* sp. PCC 6803. (A) Scheme of the insertion of the kanamycin resistance ($Km^r$) cassette into the *Eco*72I site of the *chlP* gene. Arrows indicate the positions of the forward (F) and reverse (R) primers used for genomic PCR. (B) PCR products amplified from the *ΔchlP* mutant (lane 1) and WT (lane 2).

### 2.3. Pigment and tocopherol analyses

Pigments were extracted from whole cells with 90% methanol. Concentrations of Chls and carotenoids were determined according to Ref. [24]. Pigments were separated by HPLC on a Waters chromatography system (600 E gradient module, 717 autosampler, 996 diode array detector) using a Waters Spherisorb ODS2 Analytical Column (5-μm particle size; 4.6×250 mm). Gradients consisted of acetonitrile/water/triethyl amine (900:100:1, solvent A) and ethyl acetate (solvent B) with 100% A for 16 min, 66.7% A/33.3% B for 6 min, 59.7% A/40.3% B for 12 min, 33.3% A/66.7% B for 0.2 min, 100% B for 2.5 min, and 100% A for 4.3 min. The flow rate was 1 ml $min^{-1}$. Pigments were identified by their specific retention times and absorption spectra and quantified by comparison with authentic standards using photodiode-array detection at 440 nm.

Tocopherols were extracted from whole cells with 90% methanol and separated by HPLC on a Nova Park $C_{18}$ column (4-μm particle size; 3.9×150 mm) at 1 ml $min^{-1}$ with the following gradient: 30% methanol and 10% 0.1 M ammonium acetate, pH 5.2 (solvent A) and 100% methanol (solvent B): 6% A/94% B for 7 min, 1% A/99% B for 13 min, and 6% A/94% B for 5 min. Tocopherols were identified by fluorescence detection ($\lambda_{ex}$=295 nm, $\lambda_{em}$=325 nm) and comparison to authentic standards (Roth, Germany).

### 2.4. Absorption and 77 K fluorescence emission spectra

Absorption spectra of whole cells in BG11 medium were recorded on an Ultrospec II spectrophotometer. 77 K fluorescence emission spectra were obtained using a Fluorolog FL-112 spectrofluorimeter with a model 1680 emission double monochromator (Jobin-Yvon, Longjumeau, France). Cells were resuspended in 25 mM HEPES–NaOH, pH 7.0 containing 67% glycerol to an OD=1.0 at 750 nm corresponding to Chl *a* concentrations of 2.6 and 1.9 μg $ml^{-1}$, for WT and the *ΔchlP* mutant, respectively, for excitation at 435 nm (Chl *a*). In experiments with phycobilisome (PBS) excitation (at 590 nm) glycerol was omitted.

### 2.5. Oxygen evolution measurements

Photosynthetic activity was measured as oxygen evolution from intact cells at 30 °C under saturating white light (3000 μmol photons $m^{-2}$ $s^{-1}$) using a Clark-type electrode essentially as described [25]. Cells were resuspended in BG11 medium buffered with 25 mM HEPES–NaOH, pH 7.0 containing 10 mM glucose to an OD=1.5 at 750 nm. Whole-chain electron transport rates were measured in the presence of 10 mM $NaHCO_3$. PSII-mediated electron transport was measured in the presence of 10 mM $NaHCO_3$,

1 mM $K_3Fe(CN)_6$ and varying concentrations of 2,6-dichloro-*p*-benzoquinone (DCBQ).

## 3. Results and discussion

### 3.1. Mutant construction and growth characteristics

A segment of the *chlP* coding region was amplified by PCR from *Synechocystis* WT genomic DNA (Fig. 2A). A $Km^r$ cassette was inserted into the *Eco*72I site of the cloned *chlP* fragment. The resulting plasmid construct was used to transform WT cells to $Km^r$ through homologous recombination. Segregation of the transformants was achieved by adding increasing concentrations of Km (from 20 to 100 μg $ml^{-1}$) and verified by PCR (Fig. 2B) yielding the homozygous *ΔchlP* mutant strain.

The *ΔchlP* mutant is incapable of photoautotrophic growth (Table 1). In the presence of 10 mM glucose in the medium (photomixotrophic conditions), the doubling time of *ΔchlP* is approximately equal to that of WT under 2–4 or 40 μmol photons $m^{-2}$ $s^{-1}$ illumination (Table 1). However, the mutant did not grow at light intensities above 100 μmol photons $m^{-2}$ $s^{-1}$, not even when it was supplemented with glucose.

### 3.2. Pigment and tocopherol contents

Cultures of the *ΔchlP* mutant grown under moderate or low light conditions were more bluish in color than the WT. The difference in coloration is corroborated by whole cell absorption spectra (Fig. 3). Whereas peaks at 440 and 680 nm (corresponding to Chl) are reduced in *ΔchlP*, a peak centered at 625 nm corresponding to phycocyanin (PC)—the major component of phycobilisomes (PBS)—is increased (Fig. 3).

Spectrophotometric quantitation of pigments following extraction with methanol consistently revealed a 26% decrease of Chl content and a 22% decrease of total carotenoid content in the mutant as compared to WT (Table 1). With the exception of a slight relative increase in myxoxanthophyll,

Table 1
Growth rates and pigment composition in *Synechocystis* sp. PCC 6803 WT and *ΔchlP* mutant cells

| | WT | *ΔchlP* |
|---|---|---|
| Photoautotrophic growth, doubling time [h] | | |
| 2–4 μmol photons $m^{-2}$ $s^{-1}$ | 47.1±3.1 | No growth |
| 40 μmol photons $m^{-2}$ $s^{-1}$ | 11.2±1.1 | No growth |
| Photomixotrophic growth, doubling time [h] | | |
| 2–4 μmol photons $m^{-2}$ $s^{-1}$ | 17.3±1.8 | 16.0±1.4 |
| 40 μmol photons $m^{-2}$ $s^{-1}$ | 9.4±0.9 | 9.2±0.7 |
| 100 μmol photons $m^{-2}$ $s^{-1}$ | 8.8±0.6 | No growth |
| Chlorophyll content [μg $ml^{-1}$ $OD_{750}^{-1}$][a] | 2.61±0.27 | 1.93±0.18 |
| Total carotenoid content [μg $ml^{-1}$ $OD_{750}^{-1}$][a] | 0.69±0.06 | 0.54±0.04 |

[a] Pigments were extracted from cells grown photomixotrophically at a light intensity of 40 μmol photons $m^{-2}$ $s^{-1}$.

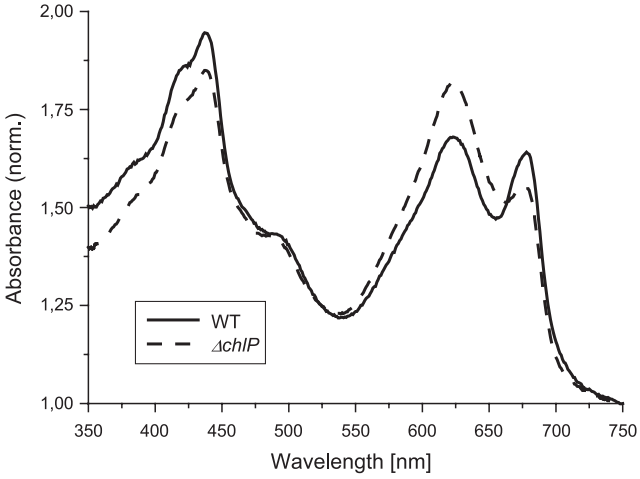


Fig. 3. Absorption spectra of whole cells of *Synechocystis* sp. PCC 6803 WT (solid line) and *ΔchlP* mutant (dashed line). Spectra were normalized to 1.0 at 750 nm. This procedure facilitates comparison on a per cell basis.

carotenoid composition was not significantly altered in *ΔchlP* (Fig. 4). HPLC analyses indicated that *exclusively* Chl $a_{gg}$ accumulates in *ΔchlP* mutant cells (Fig. 4B).

A possible contribution of Chlide *a* to Chl absorption in the mutant was assessed after removal of Chl $a_{gg}$ with *n*-hexane. No Chlide was detectable in the mutant extracts by spectrophotometry. Thus, the 440- and 680-nm peaks in the *ΔchlP* absorption spectrum indeed entirely correspond to Chl $a_{gg}$.

The contents of tocopherols were also determined in WT and *ΔchlP* mutant. Whereas the WT accumulates exclusively α-tocopherol, *ΔchlP* contains only α-tocotrienol instead (Fig. 5). The amount of tocotrienol in the mutant, however, does not reach the WT vitamin E contents, suggesting less efficient prenylation of homogentisate with GGPP by the respective prenyltransferase, consistent with in vitro experiments [26].

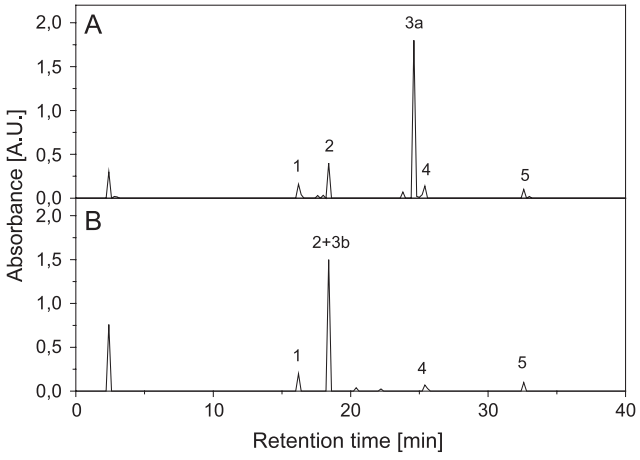


Fig. 4. HPLC analysis of pigment extracts from WT and *ΔchlP* cells of *Synechocystis* sp. PCC 6803. Absorbance was measured at 440 nm. Peaks: 1, myxoxanthophyll; 2, zeaxanthin; 3a, phytylated chlorophyll *a*; 3b, geranylgeranylated chlorophyll *a*; 4, echinenone; 5, β-carotene.

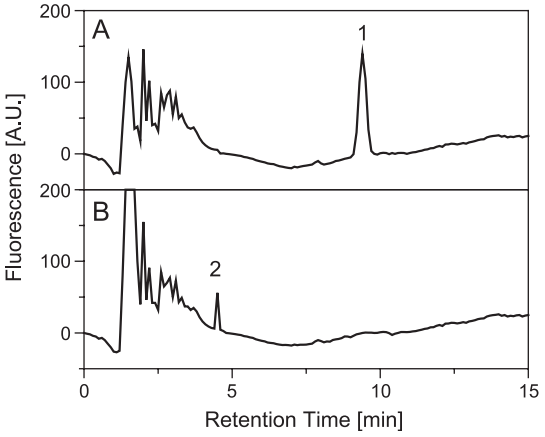


Fig. 5. HPLC analysis of vitamin E contents in WT and *ΔchlP* cells of *Synechocystis* sp. PCC 6803. Fluorescence was excited at 295 nm and measured at 325 nm. Peaks: 1, α-tocopherol; 2, α-tocotrienol.

### 3.3. 77 K fluorescence emission spectra

Consequences of the substitution of Chl *a* by Chl $a_{gg}$ on assembly, stoichiometry, and structure of PSI and PSII were assessed using 77 K fluorescence emission spectroscopy. Excitation of Chl at 435 nm elicits fluorescence emission with prominent maxima at 685, 695 and 725 nm in WT (Fig. 6A). The former two maxima represent emission from the PSII core antenna complexes, CP43 and CP47, respectively. A certain proportion of the 685-nm peak has to be assigned also to the long-wavelength terminal emitter of PBS [27]. It has been shown previously that accumulation of the IsiA protein (CP43′) as a result of iron deficiency and/or photooxidative stress may cause an increase in the 685-nm emission, too [1,2]. The dominant emission peak at 725 nm derives from PSI [2,25,27,28]. Minor peaks at about 650 and 665 nm originate from the PBS components, PC and allophycocyanin, respectively [29].

The 77 K fluorescence spectrum of the *ΔchlP* mutant is characterized by a considerable reduction of the PSI peak being consistent with the decreased cellular Chl content. Moreover, the maximum of this peak in the mutant is blue-shifted by 2 nm as compared to WT, possibly indicating a somehow perturbed association of Chls $a_{gg}$ with the respective apoprotein(s) affecting the structure of PSI in the *ΔchlP* mutant. A slight blue-shift of PSI emission has also been observed upon accumulation of the IsiA protein in *Synechocystis* [2]. Additionally, the mutant spectrum reveals an enhanced fluorescence at 685 nm. The latter might be due to an altered CP43-to-CP47 ratio, or to compromised excitation energy transfer from CP43 to CP47. Another explanation might be that the enhanced 685-nm peak in the *ΔchlP* fluorescence spectrum is due to increased emission from the terminal emitter of the PBS. This is conceivable since the amount of PBS is enlarged in mutant cells as judged from the absorption spectra (cp. Fig. 3). The notion is supported by the 77 K fluorescence emission spectra obtained upon excitation at 590 nm (the short-wavelength edge of the PBS absorption band, Fig. 6B). Glycerol was not added to the samples to avoid decoupling of PBS from the photosystems. The WT spectrum obtained upon 590-nm excitation exhibits four maxima corresponding to emission from PC (at about 655 nm), allophycocyanin (shoulder at about 665 nm), the terminal emitter/CP43/IsiA (at 685 nm), and PSI (at 725 nm) (Fig 6B, cp. also Refs. [2,27–29]). The respective spectrum of the *ΔchlP* mutant reveals a dramatic increase of the 685-nm peak. The estimated ratio of the 685-nm peak to the 665-nm peak is approximately 9. This value is consistent with 685 nm-to-665 nm fluorescence ratios of 6–10 as observed for isolated PBS [30]. Hence, the data suggest that also the increase of the 685-nm peak in the

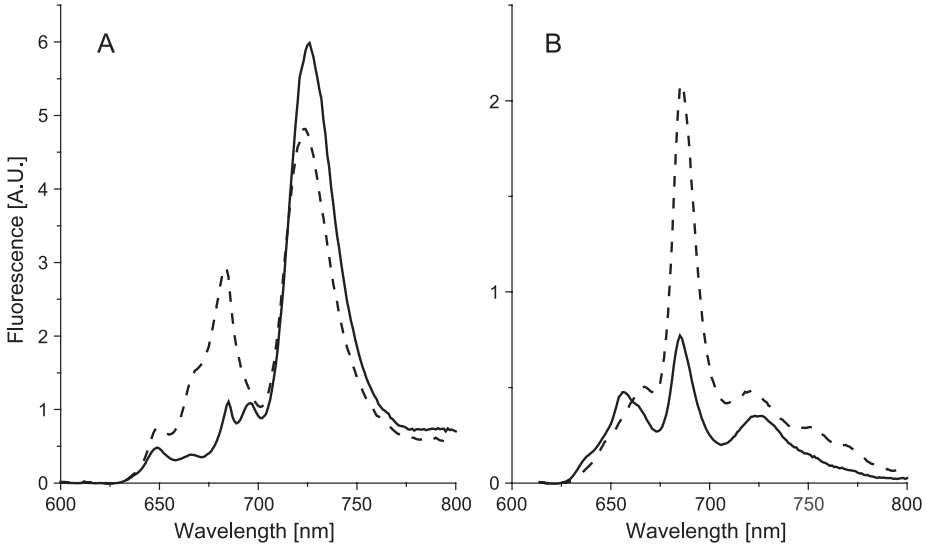


Fig. 6. 77 K fluorescence emission spectra of whole cells of *Synechocystis* sp. PCC 6803 WT (solid line) and *ΔchlP* mutant (dashed line). Cells were grown photomixotrophically under moderate (40 μmol photons $m^{-2}$ $s^{-1}$) light conditions. Cells were suspended in 67% glycerol/25 mM HEPES–NaOH (pH 7.0) for excitation at 435 nm (A). Glycerol was omitted for excitation at 590 nm (B).

*ΔchlP* spectrum recorded upon Chl excitation is likely due to the PBS terminal emitter. Possibly, a proportion of the PBS is not tightly coupled energetically to the photosystems in the *ΔchlP* mutant. Alternatively, at least a fraction of the increased 685-nm emission peak may derive from the IsiA (CP43′) protein which has been shown to accumulate in cyanobacteria in response to a variety of stress conditions [1,2]. The latter would also be consistent with the observed blue-shift of the main PSI emission maximum [2].

### 3.4. Electron transport

The 77 K fluorescence emission spectra obtained upon Chl excitation indicate the presence of PSI and PSII in *ΔchlP* cells. Functional characterization of PSI and PSII was substantiated by measuring electron transport as oxygen evolution under light-saturated conditions. The rate of electron transport across the whole chain (from $H_2O$ to $CO_2$) appeared to be increased by 34% in *ΔchlP* cells in comparison to WT, indicating the presence of fully functional PSI and PSII in the mutant (Table 2).

PSII-mediated electron transport was measured in the presence of the artificial electron acceptors, DCBQ and 1 mM $K_3Fe(CN)_6$. In WT cells the 0.5 mM DCBQ-mediated oxygen evolution rate was about 38% higher than the whole chain rate. In contrast, under the same conditions *ΔchlP* evolved oxygen at an essentially lower rate, even less than the corresponding whole chain rate (Table 2).

The latter observation suggests an inhibitory effect of DCBQ on PSII in the mutant. Therefore, oxygen evolution was determined in mutant and WT cells in dependence on increasing concentrations of DCBQ (from 0.2 to 1.0 mM). Maximum oxygen evolution was achieved in WT at 0.5 mM DCBQ (Table 2). In contrast, increasing DCBQ concentrations were accompanied by a significant decline in oxygen evolution in the *ΔchlP* mutant (Table 2). At 1.0 mM DCBQ oxygen evolution of mutant cells was only about 20% of the whole chain rate. The origin of the inhibitory effect of DCBQ is presently unclear and requires further study. One possible explanation might be that quinone electron acceptors (such as DCBQ) can act as nonphotochemical quenchers of Chl excited states—in particular in structurally altered PSII antenna systems [31], thus reducing excitation density available for photochemistry in the *ΔchlP* mutant.

In addition to increased electron transport capacity, the mutant shows enhanced respiration as judged by an elevated oxygen uptake rate in the dark when supplemented with glucose (data not shown). Considering the similarity of the *ΔchlP* and WT growth rates under moderate light conditions, these data suggest the existence of additional energy-consumptive processes in the mutant.

Table 2
Electron transport rates in *Synechocystis* sp. PCC 6803 WT and *ΔchlP* mutant cells

| Oxygen evolution rates [μmol $O_2$ $h^{-1}$ $OD_{750}^{-1}$] | WT | *ΔchlP* |
|---|---|---|
| Whole chain[a] | 576[b] | 774 |
| 0.2 mM DCBQ[c] | 778 | 463 |
| 0.5 mM DCBQ | 795 | 293 |
| 0.8 mM DCBQ | 694 | 174 |
| 1.0 mM DCBQ | 645 | 146 |

[a] In the presence of 10 mM $NaHCO_3$.
[b] S.D. were about ±10%.
[c] In the presence of 10 mM $NaHCO_3$, DCBQ and 1.0 mM $K_3Fe(CN)_6$.

### 3.5. Instability of the photosystems in the ΔchlP mutant

A previously described mutant of *R. capsulatus* accumulating BChl $a_{gg}$ (instead of BChl *a*) showed compromised photosynthetic performance due to instability of components of the photosynthetic apparatus [17]. A similar impact can also be asserted for Chl $a_{gg}$ accumulation in the *ΔchlP* mutant. To test this hypothesis, *ΔchlP* mutant and WT cultures were depleted of exogenous glucose supply. Cells grown photomixotrophically were gently harvested by centrifugation and transferred to a glucose-free medium. Growth of the cultures was assessed as OD at 750 nm. The cellular PS content was monitored by absorption and 77 K fluorescence spectroscopy (not shown) and parallel measurements of Chl content (Fig. 7B). To account for a possible additional impact of illumination, Chl degradation was compared in light and in darkness.

Following transfer to photoautotrophic conditions, the *ΔchlP* mutant continued growth for only 1 day (Fig. 7A). Thereafter growth ceased completely in the mutant, in contrast to WT. Both strains, *ΔchlP* and WT, exhibited no growth in the dark. The Chl content (Fig. 7B) of the dark-incubated WT did not show significant alterations, indicating stability of PSI and PSII. In contrast, a continuous decline of Chl content was observed in *ΔchlP* cultures during dark incubation. This observation can be explained with progressive degradation of the mutant's photosystems (Fig. 7B). Light was found to promote the degradation process in *ΔchlP* (Fig. 7B). The latter observation is corroborated by a rapid Chl depletion observed in glucose-supplemented mutant cultures under enhanced illumination (500 μmol photons $m^{-2}$ $s^{-1}$; data not shown).

The observed instability of the photosystems in the *ΔchlP* mutant is most likely due to impaired binding of Chl $a_{gg}$ to the respective apoproteins due to reduced flexibility of the isoprenoid chain. Three additional C=C bonds will hinder rotation of carbon atoms at six positions, thereby limiting the number of possible conformations of the isoprenoid tail. It has been shown previously that the phytyl tail moiety was required for the stable assembly of the D1 and PsaA complexes [6]. Additionally, perturbed binding of Chl $a_{gg}$ to the apoproteins—in particular of accessory light-harvesting pigments—may lead to impairment of excitation energy transfer to the RCs and, hence, to longer excited state life-times, inevitably giving rise to enhanced generation of long-lived Chl triplet excited states.

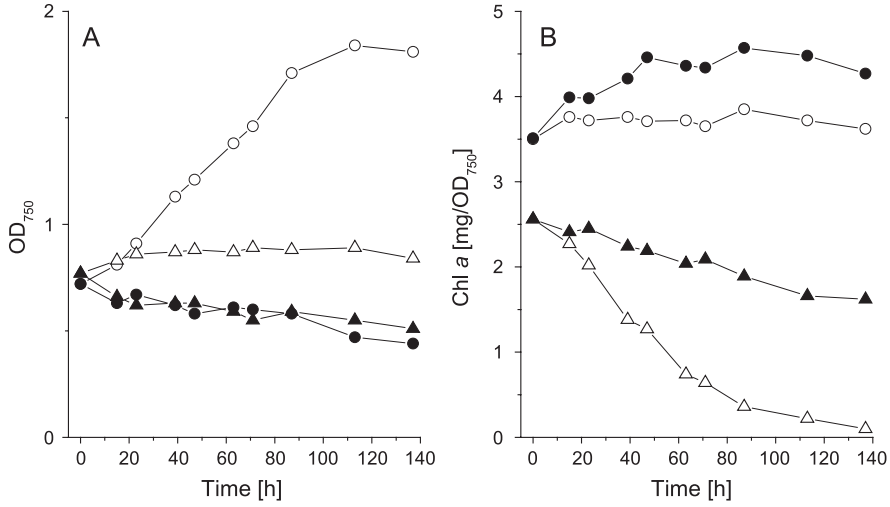


Fig. 7. Growth (A) and Chl content (B) in cells of *Synechocystis* sp. PCC 6803 WT (circles) and *ΔchlP* mutant (triangles). Cultures were cultivated under moderate (40 μmol photons $m^{-2}$ $s^{-1}$) light conditions (open symbols) or in the dark (full symbols) in the absence of glucose.

The latter are known to react readily with oxygen ultimately leading to photodamage of pigment–protein complexes and photosynthetic membranes. Accumulation of the IsiA protein (as suggested by the increased 685-nm fluorescence and the shift of the PSI emission peak) may be indicative of photooxidative stress in the mutant [1,2]. Correct assembly of Chls with the apoprotein may also be essential for efficient photoprotection (by carotenoids and/or other antioxidants). Alterations in antioxidant (e.g., vitamin E) contents—although most probably not being the primary cause—may further exacerbate the observed instability of the photosystems (see also below).

An enhanced rate of photosystem turnover in the mutant cells is a likely consequence of their instability. Glucose requirement and more intense respiration are indicative for intensive metabolic activity that is required to maintain the observed steady-state levels of otherwise degraded photosystems in the *ΔchlP* mutant.

### 3.6. Complementation

To exclude contributions of secondary mutations to the *ΔchlP* phenotype, the WT *chlP* copy was reintroduced into the mutant. The mutant was transformed with a 0.60-kb *chlP* segment to oust the $Km^r$ cassette by homologous recombination and restore the WT *chlP* gene activity. The resultant transformants were selected and restreaked on plates under standard photoautotrophic conditions. After a month of photoautotrophic propagation transformants had lost the resistance to Km and complete segregation of the WT *chlP* copy was confirmed by PCR (data not shown). The transformants regained the ability to synthesize phytylated Chl *a* and tocopherols and exhibited color, absorption spectra and oxygen evolution rates characteristic of WT (data not shown). Hence, the phenotype of the *ΔchlP* mutant is entirely caused by inactivation of the *chlP* gene.

It should be noted that attempts to obtain spontaneous suppressor mutations restoring photoautotrophic capability were unsuccessful so far. The latter indicates that (i) the adverse effects of Chl $a_{gg}$ accumulation on photosynthetic growth cannot be completely compensated by any other physiological mechanism; and (ii) in *Synechocystis* ChlP function is coded for exclusively by ORF *sll*1091.

## 4. Concluding remarks

The current study was conducted to investigate the impact of substitution of (phytylated) Chl *a* by its geranygeranylated counterpart on assembly, stability and performance of the photosynthetic apparatus. ChlP activity, which provides the phytyl moiety for Chl (as well as for phylloquinone and tocopherol) synthesis, is exclusively encoded by ORF *sll*1091 in *Synechocystis*. To discern the effects of Chl $a_{gg}$ accumulation and tocopherol or phylloquinone deficiency, the *ΔchlP* strain was also compared to respective deficient mutants. In our laboratories tocopherol and phylloquinone deficient mutants with disrupted homogentisate phytyl transferase (*hpt*, ORF *slr*1736) and 1,4-dihydroxy-2-naphthoic acid phytyl transferase (*menA*, ORF *slr*1518) genes, respectively, have been constructed, too. These mutants show phenotypes similar to previously described analogous *Synechocystis* mutants [10,26,32]. Tocopherols are apparently not essential for photosynthesis and photoautotrophic growth in *Synechocystis* (Ref. [26] and own unpublished results). Even tolerance to high light is not affected in tocopherol-deficient *Synechocystis* mutants [26]. Consequently, *ΔchlP* has to be compared in particular to the phylloquinone-deficient mutant *ΔmenA*. Two phenotypic similarities were observed between *ΔchlP* and *ΔmenA*: (i) a reduced cellular Chl content consistent with a decreased PSI level; and (ii) inability to grow under illumination exceeding 100 μmol photons $m^{-2}$ $s^{-1}$ [10].

However, differences do also exist: in contrast to *ΔchlP*, the *ΔmenA* mutant grows photoautrophically under moderate illumination [10]. Whereas photomixotrophic growth (under moderate light) is not affected in *ΔchlP*, the *ΔmenA* mutant exhibited about twofold increased doubling times as compared to WT under the same conditions [10]. Contrasting Chl $a_{gg}$ and phylloquinone-related contributions to the *ΔchlP* phenotype requires further investigations—in particular regarding individual electron transfer steps in which phytylated electron carriers (in WT) are substituted by geranylgeranylated ones (in the *ΔchlP* mutant). These intricate investigations are currently under way in our labs. In this regard, it is worth to note that overall linear electron transport appears not to be affected directly by the *ΔchlP* mutation, although several components of the electron transport chain in both PSI and PSII are natively phytylated in WT.

The observed enlarged amount of PBS might be a compensatory response to account for impaired light-harvesting (excitation energy transfer) capacity of Chl $a_{gg}$ containing antenna complexes in the *ΔchlP* mutant (see above). However, the instability of certain Chl-binding proteins in the *ΔchlP* mutant apparently compromises coupling of PBS to the photosystems.

Very recently, rice mutants with alterations in hydrogenation of the Chl alcohol side chain have been isolated [33]. One of these mutants showed preferential accumulation of Chls $a_{gg}$ and $b_{gg}$. The mutant was lethal despite a high photosynthetic activity measured as oxygen evolution. These authors concluded that accumulation of geranylgeranylated Chls leads to impaired photoprotection as well as instability of the photosystems [33].

In conclusion, the *ΔchlP* mutant is a useful system for further studies of the aspects of Chl–apoprotein interactions, photosystem biogenesis and function as well as regulation of photosynthetic and respiratory activities.

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