In vivo manipulation of the xanthophyll cycle and the role of zeaxanthin in the protection against photodamage in the green alga Chlorella pyrenoidosa

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In Vivo Manipulation of the Xanthophyll Cycle and the Role of Zeaxanthin in the Protection against Photodamage in the Green Alga Chlorella pyrenoidosa*

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Chlorella pyrenoidosa was grown in steady-state continuous cultures in either high or low light. Samples of these cultures were incubated in darkness (viologanthin state) or in saturating light (zeaxanthin state). These samples were kept in the respective preadapted states throughout the entire photodamage treatment. Photodamage involved exposure to single-turnover flashes fired at a low (non-actinic) frequency. The damage caused by the light stress thus applied was monitored by changes in photosynthetic properties and pigment composition. Cells preadapted in the light resisted photodamage better than those kept in darkness. The low light grown cells were more vulnerable to photodamage than the high light grown cells. Our experimental approach permitted the equilibria between the components that participate in the xanthophyll cycle to be set without addition of inhibitors. Regardless of the total amount of violaxanthin being present, its conversion to antheraxanthin and zeaxanthin is a prerequisite for protection. The protection is most effective for photosystem II. It appeared that antheraxanthin accumulates as a result of photodamaging flashes provided that these are fired in the presence of background light, i.e. with zeaxanthin present. From this, it is newly derived that the xanthophyll cycle operates in full in the light, including epoxidation of zeaxanthin. The latter conversion was also demonstrated in vitro, via nonenzymatic oxygen-dependent turnover of zeaxanthin into violoxanthin.

Dynamic conversion of violoxanthin, antheraxanthin, and zeaxanthin in the so called xanthophyll cycle has been documented in higher plants and algae (reviewed by Hager (1981)). The xanthophyll cycle was first described by Sapozhnikov et al. (1957). Its function was originally suggested to be linked to oxygen evolution (Sapozhnikov, 1972). Alternatively, a role in the electron transfer activity of PS II¹ was proposed (reviewed by Hager (1981)). Another role for the xanthophyll cycle as a protection mechanism against photodamage was first suggested by Krinsky (1971). Chl triplet states can relax via triplet energy transfer to zeaxanthin followed by dissipation of the excited triplet via the trans-cis-isomerization of zeaxanthin, the latter reaction is exothermic. More recently, another energy dissipating process (non-photochemical quenching, qNP) connected with the xanthophyll cycle was introduced by Demmig-Adams (1999). Contrary to the relaxation of Chl triplet states in the former process the qNP has been proposed to be a singlet-singlet exchange between chlorophyll and carotenoids (Owens et al., 1992).

The scheme of reactions that take place in the light involves two de-epoxidation steps through which violoxanthin via the intermediate antheraxanthin becomes zeaxanthin (Hager and Stranksy, 1970). This way the latter compound accumulates in the light. In darkness the reactions are reversed to violoxanthin. All reaction steps have been well characterized, except for the epoxidizing step from zeaxanthin to antheraxanthin in which a “mixed-function oxygenase” (Hager, 1981) was suggested to be involved. The different pH ranges at which the respective enzymes operate give rise to a scheme in which the steady-state concentrations of the components of the xanthophyll cycle are determined by the pH of the lumen. The de-epoxidation reactions yielding the final product zeaxanthin rely on enzymes that become activated at a thylakoid lumen pH of 5.2 and thus operate in the light. The backreactions involve enzymatically catalyzed epoxidation steps that rely on a higher pH of the thylakoid lumen and by consequence operate in darkness (Pfundel and Dilley, 1992; Gilmore and Yamamoto, 1993). Thus, according to these observations, pH transitions between light and dark effect the differences in the presence of violoxanthin and zeaxanthin relative to one another.

Dithiothreitol has been applied as a successful inhibitor of the violoxanthin de-epoxidation steps (Yamamoto and Kamite, 1992). However, additional effects of dithiothreitol under in vivo conditions on several other thiorereoxin-regulated reactions, such as carbon metabolism enzymes (Rowell et al., 1986) or the ATP synthase (Mills, 1986) may obscure the answer to the question whether in addition to the decreased availability of zeaxanthin other inhibitory effects of dithiothreitol are responsible for the observed increased sensitivity to photodamage in the presence of dithiothreitol. In addition, the use of an inhibitor in the study of a cyclic process, excludes the possibility to retrieve information about the dynamic properties of such a cycle.

The aim of the present study was to evaluate the photoprotective potential of the xanthophyll cycle with different steady-state contents of violoxanthin and zeaxanthin generated in vivo without disturbance of the cellular metabolism by external additions other than light. The data presented indicate that epoxidation of zeaxanthin also proceeds in the light as a result of the photoprotective (excited oxygen quencher activity) proc-
essing of zeaxanthin. This observation reveals that the dy-
amic function of the xanthophyll cycle in vivo is larger than 
would be predictable from existing data. Our approach to 
assess photodamage in a constant background of photoprotection, 
established by introducing continuous background illumina-
tion, may be useful in other areas of photosynthesis research.

MATERIALS AND METHODS

Culture—Two types of steady-state continuous cultures of Chlorella 
pyrenoidosa were used, both were grown in 2-liter chemostats in BG-11
medium (Rippka et al., 1979) at 20°C. One was grown at 30 µE·m·s⁻¹ (low light, LL) the other one at 240 µE·m·s⁻¹ (high light, HL). Circular 
fluorescent tubes (Philips TLE 32W/33) were used for continuous illu-
mination. The set up of the culture system was as in Van Liere and Mur
(1978). Aeration at 60 liter/min provided adequate mixing and CO₂ 
supply. The cultures were maintained at an A₅₇₀ of 0.18–0.20.

Preadaptation and Flash Experiments—Samples from the HL and 
LL cultures were preadapted during 30 min at 50°C in either darkness 
or in the presence of actinic (background) light. The actinic light intensi-
ties for the LL and HL samples were 430 and 600 µE·m⁻²·s⁻¹, respec-
tively. These light conditions were arrived at to be saturating from the
photosynthesis versus irradiance (P/I) curves (see Fig. 1). Preadaptation 
proceeded at room temperature (20°C). This device has been described elsewhere (Dubinsky et al., 1987). The cultures were bubbled with air to ensure a constant partial oxygen 
pressure. Next, while maintaining the conditions of preadaptation (i.e. 
background light or darkness), one group of samples was exposed to one
thousand supersaturating flashes (see below) in order to incite photo-
damaging flash treatment in the continued presence of saturating background light, already perform photosynthesis at a 
maximal rate. This allowed a faster flashing regime with 300-ms 
flash intervals. A General Electric FT 230 flash tube was used at a discharge 
energy of 2 J/flash in the forward direction. Calculated by the 
surface of the incubation chamber this amounts to the supersaturating 
photonflux of approximately 10,000 µE·m⁻²·s⁻¹. The flash tube was 
connected directly to the incubation chamber (i.e. the one used for the 
fluence and fluorescence measurements, cf. below). During the flashes 
aeration was continued. The number of flashes was selected which
yield appreciable photodamage (as judged from changes in the pigment con-
tent and physiological activity presented), while avoiding lethality. All 
flash-treated samples used for the photosynthesis activity assays were 
allowed recovery during 15 min in darkness to equalize the metabolic 
and pigment content of all samples. The pigment content in the samples did 
not change during this 15-min period (especially zeaxanthin 
dissipated, whereas violaxanthin increases, data not shown), the overall 
losses of pigment are not replenished in this short period. Samples for 
pigment analysis were taken immediately after the incubation period 
(with or without flashes) but before the relaxation time introduced in the 
other assays.

P/I Curves and Fluorescence Measurements—After the preadapta-
tion, flash and recovery periods were terminated, the cuvette was 
closed, and P/I curves were recorded according to standard procedures 
(Dubinsky et al., 1987). Fluorescence measurements included two types 
of measurements, A, photochemical quenching was monitored with a pulse-amplitude-modulated chlorophyll fluorescence measuring system 
(Walz, Germany) as described by Schreiber et al. (1986). During the 
measurements the fiber optic light guide was directly placed against 
one side of the oxygen measuring chamber. In this way, oxygen production and photochemical quenching (qP) could be estimated simultaneously. 
qP was estimated every 120 s by firing saturating pulses of 500-ms 
duration (Schott KL-1500 light source, 12,000 µE·m⁻²·s⁻¹).

B, relative energy transfer efficiency from carotenoids to Chl was 
measured by comparing the fluorescence yield after excitation with 
broad blue and orange light. The former excites both carotenoids and 
chlorophyll, the latter chlorophyll only. Data were normalized on the 
emission resulting from the chlorophyll excitation in the orange. These 
measurements were done with a Perkin-Elmer 1000 spectrofluorom-
eter, emission wavelength 685 nm, slit width “M.” Before the measure-
ments, the samples were preadapted for 30 min in darkness or dark adapted conditions as de-
scribed above. Samples were treated with 3-(3,4-dichlorophenyl)-1,1-
dimethyleurea (10 µM) during 1 min, either in the dark or light analogous 
the preadaptation conditions, immediately before the assay. Excitation 
was done with orange light through a 628-nm interference filter (Schott) 
and with blue light through a 2-mm BG28 cut-off filter (Schott). 

Data shown are the average of three separate experiments. Differ-
ences between comparable data points in the three experiments were 
below 10% of each of the numeric values given.

RESULTS

Changes in photosynthetic activity (O₂ production) and photo-
chemical quenching (qP) after exposure of C. pyrenoidosa 
cells to control or photodamaging conditions are shown in Fig. 1. 
Control samples of LL and HL Chlorella cells behave differ-
ently. The LL cells have a lower maximal photosynthesis 
activity/Chl than the HL ones. The LL cells show a stronger qP 
decrease than the HL cells. The rate of O₂ evolution decreases at higher irradiances of the LL cells. Using preadaptation the 
light/darkness, HL cells show an appreciable loss of oxygen evolution and qP at increasing 
actinic light intensities over the course of the P/I curve 
determination.

The observed differences of the photosynthetic activities 
were related to changes in the pigment composition of the samples. Table I depicts the pigment analysis of the HL and LL 
cultured cells. The data reflect that in the LL cells the total Chl 
to carotenoid ratio is at least twice that of the HL cells, the Chl 
to summed xanthophyll cycle components ratio is 3-fold higher. 

The dark or light preadaptation conditions are mainly restricted to 
the three xanthophyll cycle pig-
ments. The violaxanthin content decreases in the light and the 
zeuganthin content increases. This way, variable pool sizes of 
the xanthophyll cycle components were established before ex-
posure to potentially photodamaging conditions.

The exposure to photodamaging flashes induced extensive
FIG. 1. Samples of cells from the HL (left) and LL (right) cultures were monitored for oxygen production activity and photochemical quenching in a range of actinic light intensities. The two top frames (A and B) display oxygen production versus light intensity profiles (P/E curves). The two lower frames show the changes in the relative photochemical quenching. Details on these measurements and preadaptation procedures are provided under "Materials and Methods." Activities are expressed as milligrams of oxygen/mg of Chl and hour or relative units for qP. Four different incubation conditions were chosen: +, control cells incubated in the presence of actinic background light; (C), control cells preincubated in darkness; A, light-preadapted cells exposed to flashes with background light present; L, dark preadapted cells exposed to flashes without background light (lowest line).

TABLE I

Pigment content of Chlorella cells from LL and HL cultures prior to exposure to photodamage in the presence or absence of background light

The different incubation conditions are equivalent to the ones used in Fig. 1. Pigment contents were estimated by HPLC. Results are expressed in mol % of Chl a. Details are given under "Materials and Methods" and in the text. Chl a content (used as 100% values in Tables I and II) were: 1.08 ± 0.01 nmol for LL and 1.21 ± 0.01 nmol for HL grown cells, respectively.

<table>
<thead>
<tr>
<th>Pigment</th>
<th>High light grown</th>
<th>Low light grown</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Darkness</td>
<td>Light</td>
</tr>
<tr>
<td>Neoxanthin</td>
<td>18.2</td>
<td>17.1</td>
</tr>
<tr>
<td>Violaxanthin</td>
<td>34.4</td>
<td>17.5</td>
</tr>
<tr>
<td>Antheraxanthin</td>
<td>2.6</td>
<td>4.2</td>
</tr>
<tr>
<td>Zeaxanthin</td>
<td>8.5</td>
<td>21.2</td>
</tr>
<tr>
<td>Lutein</td>
<td>37.5</td>
<td>38.1</td>
</tr>
<tr>
<td>Chl b</td>
<td>34.2</td>
<td>33.9</td>
</tr>
<tr>
<td>Chl a</td>
<td>100.0</td>
<td>100.0</td>
</tr>
<tr>
<td>β-Carotene</td>
<td>20.1</td>
<td>22.8</td>
</tr>
</tbody>
</table>

Calculated ratios and sums

- Chl a/Chl b: 2.92/2.95
- Σ Xanthophyll cycle pigments: 43.3/42.9
- Σ Carotenoids: 122.1/120.9
- Chl/carotenoids: 1.10/1.11
- Chl/xanthophyll cycle pigments: 3.10/3.12

These changes in the pigment composition (Table II). Relative to the data displayed in Table I, the overall picture depicts photodamage of most pigments, including Chl a, lutein, and β-carotene, with the marked exception of the antheraxanthin content in the light preadapted samples. The neoxanthin content decreases in the LL cells only. In general, the damage is small in the light-preadapted HL cells and somewhat more pronounced in the dark-preadapted HL cells. Noticeable damage is induced in the dark preadapted cells of the LL culture. As opposed to the HL grown cells, in which the total of xanthophyll cycle components becomes reduced by 17% in the dark-flashed group, the loss in the analogous LL experiment amounts to 66% (Table II). Antheraxanthin is the predominantly disappearing compound in the dark-flashed HL cells with reference to the just dark-incubated HL control cells. In the absence of zeaxanthin, β-carotene is a target for breakdown, as can be seen most clearly in a comparison of the LL dark-adapted and dark-flashed samples. Lutein appears to be relatively little involved in the protection.

TABLE II

Pigment content of Chlorella cells from LL and HL cultures, preadapted as in Table I after exposure to photodamaging strong light flashes

Results are expressed in mol % of Chl a of the controls in Table I.

<table>
<thead>
<tr>
<th>Pigment</th>
<th>High light grown cells</th>
<th>Low light grown cells</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Dark flashed</td>
<td>Light flashed</td>
</tr>
<tr>
<td>Neoxanthin</td>
<td>19.2</td>
<td>17.0</td>
</tr>
<tr>
<td>Violaxanthin</td>
<td>32.1</td>
<td>16.8</td>
</tr>
<tr>
<td>Antheraxanthin</td>
<td>0.5</td>
<td>5.9</td>
</tr>
<tr>
<td>Zeaxanthin</td>
<td>3.2</td>
<td>18.2</td>
</tr>
<tr>
<td>Chl b</td>
<td>36.7</td>
<td>34.3</td>
</tr>
<tr>
<td>Chl a</td>
<td>93.2</td>
<td>88.8</td>
</tr>
<tr>
<td>β-Carotene</td>
<td>19.2</td>
<td>21.8</td>
</tr>
</tbody>
</table>

Calculated ratios and sums

- Chl a/Chl b: 2.89/3.00
- Σ Xanthophyll cycle pigments: 35.8/40.9
- Σ Carotenoids: 110.9/114.0
- Chl/carotenoids: 1.13/1.15
- Chl/xanthophyll cycle pigments: 3.50/3.22

To define the site where the actual photodamaging process occurs and especially to locate the site at which the xanthophyll cycle provides protection against photodamage, the electron transfer capacity of the total electron transfer chain (PS II and PS I) was compared to the capacity of PS I alone (Table III). Full chain electron transfer rates in the samples that had received the strong flashes in the presence of background light appeared to remain nearly unaltered. The samples that were exposed to the flashes in the absence of background light displayed more than 20% photodamage (both HL and LL), comparable to the data given in Fig. 1. As opposed to the full chain data, PS I capacity appeared to diminish even when the strong flashes were administered in the presence of background light. The inhibition was stronger in the LL samples. However, in the dark-flashed samples and in comparison to the full chain, the damage to PS I appeared relatively low. Compared to the full chain electron transfer rate numbers, the PS I change in the light-flashed samples is already big. The increased damage observed for the full chain rates in the dark-flashed sample does not correspond to a similar decrease in the PS I sample. The protective function of the xanthophyll cycle therefore ap-
The effect of photodamaging conditions on the light energy transfer capacity of PS II plus PS I measured separately Results are given in μmol of oxygen per mg of Chl α and hour. Assay conditions are given under "Materials and Methods." The control cells were preadapted in light, otherwise sample preparation and exposure to photodamaging conditions were as in Fig. 1. Experiments were performed three times with independently flushed samples, standard deviations are indicated by ±.

<table>
<thead>
<tr>
<th>Growth</th>
<th>PS I + PS II</th>
<th>PS I</th>
</tr>
</thead>
<tbody>
<tr>
<td>Control</td>
<td>11.6 ± 0.9</td>
<td>25.5 ± 1.9</td>
</tr>
<tr>
<td>LL</td>
<td>9.6 ± 0.7</td>
<td>20.1 ± 1.2</td>
</tr>
<tr>
<td>Light flashed</td>
<td>11.5 ± 0.5 (99.2)</td>
<td>24.2 ± 0.9 (94.9)</td>
</tr>
<tr>
<td>LL</td>
<td>9.5 ± 0.5 (98.6)</td>
<td>17.7 ± 1.2 (88.1)</td>
</tr>
<tr>
<td>Dark flashed</td>
<td>9.2 ± 0.5 (79.3)</td>
<td>23.1 ± 0.5 (90.6)</td>
</tr>
<tr>
<td>LL</td>
<td>7.1 ± 0.8 (73.9)</td>
<td>16.1 ± 2.6 (80.1)</td>
</tr>
</tbody>
</table>

pears to be predominantly effective for PS II.

The observed changes in the relative abundance of the carotenoids may exert effects on the light energy transfer efficiency of PS II. If so, a lower light energy conductance would give rise to a lesser fluorescence output from PS II in the presence of 3-(3,4-dichlorophenyl)-1,1-dimethylurea. To eliminate effects of sample geometry, fluorescence excitation was done with broad blue as well as 628-nm orange light. The latter excites chlorophylls only, the former both chlorophylls and carotenoids. Normalizing on fluorescence yield in the orange by using ratio’s equals any changes in fluorescence yield of Chl related, for example, to qNP. In HL and LL cultures, the lower fluorescence ratio observed in the dark-preadapted samples indicates that the light energy transfer efficiency from carotenoids to chlorophylls remains higher in darkness than following preadaptation in the light (Table IV). The difference in the efficiency of energy transfer carotenoids → chlorophyll between the dark and light adapted samples is more pronounced in the HL cells.

The results presented in Table II indicate that the formation of the monooxepoxide antheraxanthin can only in part be accounted for by conversion of violaxanthin, in addition, the disappearance of zeaxanthin appears to add to antheraxanthin formation as well. The apparent two reactions by which antheraxanthin can be formed addresses the question on the nature of the protective function. In order to investigate the involvement of nonenzymatic processes, the breakdown of zeaxanthin under in vitro conditions was examined. The HPLC chromatograms shown in Fig. 2 indicate that when isolated zeaxanthin (retention time 13.4 min) was exposed to damaging conditions (10,000 μE·m⁻²·s⁻¹) and air (50 °C) degradation occurred. With oxygen present, formation of violaxanthin (retention time of 8.6 min) became evident. The identity of the other "breakdown products" with retention times between 16 and 17 min has not yet been extensively determined. The cis peak in the UV region in the absorbance spectra (data not shown) indicated that these may be the different cis-isomers of zeaxanthin. A similar experiment with zeaxanthin was performed in the presence of the singlet oxygen-generating agent cosrene, in just room light and at room temperature. Violaxanthin was formed, other zeaxanthin conversion products were nearly absent (data not shown). The in vitro conversion reactions of zeaxanthin support our view on the actual process of singlet oxygen quenching as part of a dynamic xanthophyll cycle in the light: zeaxanthin is recycled into violaxanthin in the light. In vivo, antheraxanthin is formed this way as well, either by monooxepoxidation of zeaxanthin or by the normal viola- to anther-

DISCUSSION

The two different types of cultures (i.e., LL and HL grown) allowed assays with different contents of xanthophyll cycle pigments present, i.e., relatively abundant in HL cells and low in LL cells as in Thayer and Björkman (1990). Applying or omitting actinic background light appeared to be a useful approach to allow or avoid the conversion of violaxanthin to zeaxanthin (Blas et al. (1959) and Yamamoto et al. (1962)). In earlier studies diithiothreitol was used to study the role of zeaxanthin in the prevention of photodamage. Those experiments precluded the possibility of studies on a dynamically operating cycle. Our approach involved preadaptation of the cells in either darkness or light to install a stable pH in the thylakoid lumen. To this end, the light intensity was chosen to just reach the P₅₀ max condition (Fig. 1), while avoiding the occurrence of appreciable photodamage (Table I). The lumen pH has been associated with the equilibria of the xanthophyll cycle (Rees et al., 1989; Pfundel and Dilley, 1953). By the preadaptation step, the ratio of the xanthophyll cycle pigments was fixed in a given state before the photodamaging flashes were given. The flashes were administered at a low frequency in order to prevent the build up of a proton gradient for the dark-preadapted cells as much as possible. Obviously, if there had been a substantial acidification of the thylakoid lumen analogy with the samples prepared in the presence of actinic background light would have given a diminished breakdown of pigments through the installment of the xanthophyll cycle in the protective mode.

Regardless of the growth conditions and the preincubations, the flashed light induces general photodamage of nearly all
pigments, be it to different extents. A clear exception is the increase for antheraxanthin in the samples that were flashed in the presence of actinic background light. This increase is of great interest in the understanding of the physiological function of the xanthophyll cycle. Comparison of the pigment distribution in between HL with background light only (Table I) and HL flashed with background light present (Table II), shows that the decrease of the violaxanthin content is less than the actual increase of antheraxanthin. The only feasible explanation for this observation is epoxidation of zeaxanthin. We conclude that epoxidation of zeaxanthin under photodamaging conditions in the light also contributes to antheraxanthin formation. Interestingly, earlier work (Hager, 1981; Pfändel and Dilley, 1993) established the regulatory function of the light-dependent proton gradient formation for the xanthophyll cycle. From that work can be concluded that epoxidation occurs only after relaxation of the proton gradient, i.e. in darkness. Given the conditions in our experiment, changes of the content of antheraxanthin, other than at the expense of violaxanthin, would not be expected (see above). It is concluded that in addition to the "mixed oxidase" function operating in high lumen pH, i.e. darkness (Hager, 1981), a nonenzymatic epoxidation reaction occurs in the light as well, in accordance with Fig. 2.

Control experiments in which purified zeaxanthin was treated with light plus heat in the presence of air indeed gave rise to the formation of the (di-)epoxy compound antheraxanthin. This is comparable to the earlier report on the oxidative degradation of antheraxanthin for which in vitro treatment with heat and oxygen has been shown to facilitate the formation of violaxanthin (Thomas and Goodwin, 1965). A recent report describes that oxidative degradation of β-carotene yields mono- and diepoxides (Liebler and Kennedy, 1992). This explains our observation that, regardless of the continued presence of a stable proton gradient, formation of antheraxanthin in the light is possible via a nonenzymatic epoxidation of zeaxanthin. The nonenzymatic epoxidation of zeaxanthin results from its function as a photoprotective pigment, i.e. in quenching of singlet oxygen in a particular case. Thus in the light a complete cycle is active. This includes enzymatic reutilization of nonenzymatically epoxidized zeaxanthin (i.e. recycled violaxanthin).

Our work shows that the quenching of excited oxygen by zeaxanthin involves an epoxidation reaction which effectively results in recycling to antheraxanthin and probably violaxanthin as made likely in the in vitro assay. This means that after reaction of zeaxanthin with singlet oxygen, the zeaxanthin is not lost from the cycle but is actually converted into the epoxy compounds antheraxanthin and violaxanthin, through which in the presence of the appropriate acidification of the lumen in the light zeaxanthin can be made again. Table III showed that the xanthophyll cycle was most effective in relation to PSII the site at which singlet oxygen generation is most likely to occur.

The position of the steady state of all the processes involved determine the actual distribution of viola-, anthera-, and zeaxanthin in a given sample. This way, the xanthophyll cycle has a real dynamic function in the photoprotective process (Fig. 3). The net decrease of xanthophyll cycle components over the course of exposure to photodamaging conditions is due to the limited number of times that zeaxanthin, in its function as quencher of excited chlorophyll triplet states, is able to withstand trans-cis-trans transitions. In this, according to Krinsky (1971), zeaxanthin has to become damaged during the quenching at a statistical rate of 1000 quenching events per degradation.

In addition to the chemical modifications associated with the operation of the xanthophyll cycle, a change of the energy transfer efficiency in the carotenoid absorbance region related to the state of the xanthophyll cycle and the amount of the xanthophyll cycle pigments as well, was observed (Table IV). The difference in the molecular absorbance coefficient between zeaxanthin and violaxanthin cannot be the only reason for this appreciable change. This points to differences in the transfer efficiency between violaxanthin and zeaxanthin to Chl. An explanation for these differences is the number of conjugated double bonds: 9 in violaxanthin and 11 in zeaxanthin. With an increasing number of conjugated double bonds the energy level of the excited states becomes lower, i.e. the zeaxanthin excited states (1Aگ، 1B) lies below that of violaxanthin by which the possibility of an energy transfer to the S1 of Chl a from zeaxanthin becomes increasingly unfavorable (Owens et al., 1992). Violaxanthin has been shown to act as light-harvesting pigment (Owens et al., 1987). This implies that the energy level of the first excited state of violaxanthin is higher than the one of the final Chl acceptor.

Three ways in which the xanthophyll cycle provides protection against photodamage are qNP (singlet transfer), decreased light harvesting capacity (singlet transfer), and photosensitizer-quenching reactions (triplet related). These processes are cooperative: if a carotenoid has a protective func-
In Vivo Manipulation of the Xanthophyll Cycle

In conclusion, the xanthophyll cycle provides a dynamic tool for Chl a and b containing organisms and possibly also for brown algae with the diatoxanthin/diadinorxanthin conversion: tailor made photosensitizer quenching without loss of light harvesting efficiency under changing light conditions.

REFERENCES


It also has a shadowing effect in the blue region of Chl absorbance and the possibility to quench excited chlorophylls (both singlet and triplet). This effect is important, not only with reference to the more % numbers presented in Tables I and II, but more so because of the about 3.5 times higher molar absorbance coefficient of a carotenoid in comparison to Chl. In other words, in cases of excessive irradiation the shadowing effect is useful, but it should be reversed at less than optimal irradiance, which indeed occurs through the enzymatic epoxidation steps in darkness.

The advantages of the xanthophyll cycle are clear, its dynamically adjustable sun/shade function. It excludes the need for a constantly present shadowing pool of carotenoids, the chemical trans-cis-trans heat release involved in triplet Chl a photosensitizer quenching strongly reduces the need for de novo synthesis to replace photodamaged molecules. To this, the observation in the present study that singlet oxygen quenching provides a means for recycling of zeaxanthin to violaxanthin in the light further extends the functional role of the xanthophyll cycle. The equilibria of the system can rapidly switch from a protective (shadowing, Chl triplet, and singlet quenching (Demming-Adams, 1990)) to a light harvesting (singlet transfer from violaxanthin to Chl) function.

As stated by Hager (1981), the xanthophyll cycle is present in higher plants and green algae but is absent in phycobilisome containing organisms. This remarkable difference may be related to another way of discarding excess excitation energy in cyanobacteria via decoupling of the phycobilisome antennae (Mullineaux et al., 1990). Otherwise, the spectral region of light harvesting in phycobiliprotein containing organisms is largely shifted outside the carotenoid region. This way, light harvesting in cyanobacteria in the blue spectral region is circumvented through which the capacity losses by shadowing carotenoids are in principle negligible in comparison to Chl a and b containing organisms. Cyanobacteria indeed contain a high carotenoid over Chl ratio, to provide for a shading and a photosensitizer quenching function. Likely, these two functions are confined to the cytoplasmic and thylakoid membranes, respectively. The apparent need for an appreciably higher poolsize of carotenoids acting as photosensitizer quenching pigments may be explained by the lack of a recycling system.