Is PsbS the site of non-photochemical quenching in photosynthesis?

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Abstract

The PsbS protein of photosystem II functions in the regulation of photosynthetic light harvesting. Along with a low thylakoid lumen pH and the presence of de-epoxidized xanthophylls, PsbS is necessary for photoprotective thermal dissipation (qE) of excess absorbed light energy in plants, measured as non-photochemical quenching of chlorophyll fluorescence. What is known about PsbS in relation to the hypothesis that this protein is the site of qE is reviewed here.

Key words: Arabidopsis, chlorophyll fluorescence, light harvesting, mutant, non-photochemical quenching, photosynthesis, PsbS, zeaxanthin.

Introduction

Light is necessary for photosynthesis in plants, but the supply of light in natural environments is not constant. Incident light can vary rapidly due to passing clouds or sunflecks, as well as on a daily or seasonal basis. With increasing light intensity, photosynthetic utilization of absorbed light energy reaches saturation, while light absorption continues to increase. This can result in a mismatch between excitation of photosynthetic pigments and a plant’s ability to use the excitation energy for photosynthesis. Under such excess light conditions, how do plants manage to balance the input and utilization of light energy in photosynthesis?

One of the ways in which this balancing act is accomplished is through the regulation of photosynthetic light harvesting. On a time scale of seconds to minutes, non-photochemical quenching (NPQ) processes in photosystem II (PSII) can be induced or disengaged in response to changes in light intensity. The term NPQ reflects the way in which these processes are routinely assayed through measurements of chlorophyll fluorescence (Maxwell and Johnson, 2000; Müller et al., 2001). Under most circumstances, the major component of NPQ is due to a regulatory mechanism, called qE, which results in the thermal dissipation of excess absorbed light energy in the light-harvesting antenna of PSII. qE is induced by a low thylakoid lumen pH (i.e. a high ΔpH) that is generated by photosynthetic electron transport in excess light, so it can be considered as a type of feedback regulation of the light-dependent reactions of photosynthesis (Fig. 1). Because qE involves the de-excitation of singlet excited chlorophyll, it is also sometimes referred to as feedback de-excitation (Kühlheim et al., 2002).

The low thylakoid lumen pH that induces qE has two roles (Fig. 2). One role is the pH-dependent activation of a lumen-localized violaxanthin de-epoxidase (VDE) enzyme that catalyses the conversion of violaxanthin to zeaxanthin via the intermediate antheraxanthin (Demmig-Adams and Adams, 1996). Zeaxanthin and/or antheraxanthin (xanthophylls with a de-epoxidized 3-hydroxy β-ring end group) are necessary for qE in plants (Demmig-Adams, 1990; Demmig-Adams et al., 1990; Gilmore and Yamamoto, 1993; Niyogi et al., 1998). In limiting light, zeaxanthin epoxidase (ZE) converts zeaxanthin back to violaxanthin. Together, these light intensity-dependent interconversions are known as the xanthophyll cycle (Yamamoto et al., 1999).

The second role of low thylakoid lumen pH is in driving protonation of one or more PSII proteins that are involved in qE (Horton and Ruban, 1992). It has been hypothesized that protonation activates a binding site for zeaxanthin in one of the proteins (Gilmore, 1997), and as a result an absorbance change (ΔA₅₃₅) is detectable in leaves and isolated
Holt et al.

NADPH and ATP are used in CO₂ fixation and other assimilatory phyll via energy or electron transfer (Ma et al., 2003; Holt et al., 2004).

qE is a plant trait of major ecophysiological significance (Demmig-Adams et al., 1999). Plants that experience excess light stress in their environment (i.e. sun plants) generally have higher qE capacities and larger xanthophyll cycle pool sizes (violaxanthin+antheraxanthin+zeaxanthin) than plants, growing in shaded environments (Thayer and Björkman, 1990; Demmig-Adams and Adams, 1992, 1994; Johnson et al., 1993; Demmig-Adams, 1998), and the maximum extent of qE is considered to be an important ecophysiological factor for the adaptation of plants to excessive light. Furthermore, mutants that lack qE (see below) are less resistant to light stress (Grañes et al., 2002; Li et al., 2002b) and have decreased ecological fitness in fluctuating light environments (Külheim et al., 2002).

![Fig. 1. Diagram depicting feedback regulation of photosynthetic light harvesting (qE) by one of the products of the light reactions of photosynthesis (ΔpH). The ΔpH is used to drive ATP synthesis, and NADPH and ATP are used in CO₂ fixation and other assimilatory reactions. qE down-regulates photosynthetic light harvesting by de-exciting singlet excited chlorophyll in the PSII antenna and thereby dissipating excess absorbed light energy as heat.](https://example.com/fig1)

The importance of qE as a photosynthetic regulatory process has stimulated tremendous interest in understanding its ecophysiology, genetics, biochemistry, and biophysical mechanism. This paper reviews the role that a specific PSII protein, PsbS, plays in qE.

### A genetic approach revealed a role for PsbS

By isolating and characterizing Arabidopsis thaliana mutants that lack qE, it was shown that qE requires PsbS, in addition to a low lumen pH and the presence of de-epoxidized xanthophylls like zeaxanthin (Li et al., 2000). qE-deficient mutants were isolated by video imaging of chlorophyll fluorescence quenching during exposure of mutagenized Arabidopsis seedlings to excess light (Niyogi et al., 1998; Shikanai et al., 1999; Peterson and Havir, 2000). The npq1 and npq2 (aba1) mutants were defective in VDE and ZE, respectively (Niyogi et al., 1998), whereas npq4 mutants lacked qE and ΔA₅₃₅ but had a normal xanthophyll cycle (Li et al., 2000; Peterson and Havir, 2000). The npq4-1 mutation was mapped to chromosome 1 and ultimately shown to affect the gene encoding PsbS (Li et al., 2000). The npq4-1 mutant had a complete deletion of the psbS gene, so the PsbS protein was missing. Other PSII proteins, however, were present at wild-type levels in the mutant, and light harvesting and photosynthesis appeared to be normal (Li et al., 2000). Characterization of several independently isolated alleles of npq4 with various lesions in the psbS gene (Peterson and Havir, 2001; Grañes et al., 2002; Li et al., 2002c) confirmed that PsbS is necessary for qE in Arabidopsis.

### A working hypothesis for the role of PsbS

The PsbS protein had been identified previously as an integral component of PSII in other plants through biochemical approaches (Ljungberg et al., 1984; Ghanotakis et al., 1984).
sequencing of the spinach psbS gene (Kim et al., 1992; Wedel et al., 1992) had revealed similarity to chlorophyll- and xanthophyll-binding proteins that are members of the light-harvesting complex (LHC) protein superfamily (Green and Pichersky, 1994; Jansson, 1999), and pigment binding by isolated PsbS had been reported (Funk et al., 1994, 1995b). This information, coupled with the npq4 mutant characterization, led to the hypothesis that PsbS might be the site of qE in PSII (Li et al., 2000). Based on this working hypothesis, several predictions could be made.

If PsbS is the site of qE, then (i) other PSII antenna proteins should not be required for qE, except perhaps for the pigment–protein complex from which excitation energy is transferred to the quenching site in PsbS. (ii) PsbS should bind both zeaxanthin and chlorophyll, the pigments that are necessary for qE. (iii) Protonation of PsbS at low thylakoid lumen pH should be necessary for qE. (iv) More quenching sites would mean more quenching, so qE capacity should depend to some extent on the amount of PsbS. In the following sections, the experiments that have been performed to test these predictions will be considered.

Where is PsbS?

PsbS was discovered more than 20 years ago as a 22 kDa protein in isolated PSII preparations (Berthold et al., 1981), but its exact location within PSII is still unknown. In order for PsbS to function as the site of qE, the presumed pigments bound to PsbS would have to be coupled excitationally to one or more chlorophylls in the PSII light-harvesting antenna system. Early biochemical studies showed that PsbS could be co-immunoprecipitated with the (non-pigmented) 33 kDa and 23 kDa subunits of the oxygen-evolving complex in PSII (Ljungberg et al., 1984), suggesting a close association with the PSII reaction centre core. However, PsbS is still present in etiolated plants (Funk et al., 1995a) and in mutants that lack PSII (Dominici et al., 2002), indicating that it might be a more peripheral subunit of PSII. Selective extraction of PsbS was shown to disrupt interaction between the peripheral LHCII and the reaction centre, consistent with a location at the interface between these subcomplexes (Kim et al., 1994). A similar conclusion was reached in some studies of PSII supercomplexes, in which PsbS was found to be more closely associated with the reaction centre than with an LHCII fraction (Dominici et al., 2002; Thidholm et al., 2002). Homodimers of PsbS have been described recently, and a dimer-to-monomer transition seems to be triggered by low pH or high light (Bergantino et al., 2003). The dimeric form of PsbS was shown to cofractionate more with the PSII reaction centre, whereas the monomer was also associated with an LHC fraction, and LHC proteins could be co-immunoprecipitated with PsbS (Bergantino et al., 2003). Investigation of qE in chlorophyll b-less mutants and antisense plants that lack various LHC proteins (Lokstein et al., 1993; Andersson et al., 2001, 2003), however, have shown that no single LHC protein seems to be necessary for qE (unlike the situation in algae such as Chlamydomonas), which casts some doubt on the functional significance of an association between PsbS and a specific LHC protein. Considering all of these results, it seems likely that PsbS is located somewhere between the PSII reaction centre core and the peripheral LHCII (Fig. 2), with the functional association possibly occurring between PsbS and the PSII core antenna.

Electron microscopic studies of plant PSII–LHCII supercomplexes have revealed the positions of most peripheral antenna and core subunits of PSII (Hankamer et al., 2001, 2003), but this approach has not thus far been successful in revealing the specific location of PsbS. It turns out that PsbS was not present in these supercomplexes (Nield et al., 2000), because it was removed by the β-dodecylmaltoside detergent that was used to solubilize the supercomplexes (Harrer et al., 1998; Nield et al., 2000). It was recently found that extraction of PSII particles with α-dodecylmaltoside results in the retention of PsbS in supercomplexes (Dominici et al., 2002), so there is hope that a home for PsbS will be found soon.

Does PsbS actually bind pigments?

Although the initial biochemical studies of PsbS did not provide any hint of pigment binding (Ljungberg et al., 1986; Bowly and Yocum, 1993), the finding that PsbS is a member of the LHC protein superfamily suggested this as a strong possibility (Kim et al., 1992; Wedel et al., 1992). However, PsbS is considered to be a distant relative of the well-known chlorophyll- and xanthophyll-binding members of this superfamily (Green and Durnford, 1996; Jansson, 1999), and it differs from all others in having four transmembrane domains instead of the usual three (Kim et al., 1994) (Fig. 3). Inspection of the predicted amino acid sequence of PsbS shows little conservation of the residues that provide binding sites for chlorophylls in the LHC proteins that are known to function in light harvesting (Kühlbrandt et al., 1994; Bassi et al., 1999; Croce et al., 1999; Liu et al., 2004). The only ligands that appear to be conserved in LHCII and PsbS are the two charge-compensated glutamates (Funk et al., 1995b) (Fig. 3) that also have a critical role in the proper folding and stability of LHCII (Bassi et al., 1999; Croce et al., 1999). Furthermore, unlike most other LHC proteins, PsbS is stable in the absence of chlorophyll in vivo (Funk et al., 1995a).

Efforts to isolate PsbS with bound pigments have met with mixed success. Funk et al. (Funk et al., 1994, 1995b) were the first to publish evidence supporting pigment binding by isolated PsbS, and they called the protein CP22 (for chlorophyll-binding protein of 22 kDa). More
recently, Dominici et al. (2002) were unable to demonstrate a stable association of pigments with isolated PsbS, and their attempts to reconstitute recombinant PsbS with pigments in vitro were unsuccessful. Aspinall-O’Dea et al. (2002) also found no pigment binding that could withstand purification of PsbS, but they were able to provide evidence for an interaction between PsbS and zeaxanthin in vitro. This interaction resulted in a change in the absorption spectrum of zeaxanthin that reconstituted the \( \Delta A_{535} \) that is associated with qE in leaves and thylakoids (Aspinall-O’Dea et al., 2002). Overexpression of PsbS in tobacco was shown to increase the extent of violaxanthin de-epoxidation under relatively low light conditions in vivo, and it was suggested that this result could be explained by zeaxanthin binding to PsbS, which would sequester zeaxanthin and prevent feedback inhibition of de-epoxidation by VDE (Hieber et al., 2004). Ultrafast transient absorption studies of qE in isolated thylakoids revealed the PsbS-dependent presence of singlet excited zeaxanthin following the excitation of chlorophyll (Ma et al., 2003). Assuming that the excited zeaxanthin is bound to PsbS, this result implies that there must be chlorophyll in very close proximity to the zeaxanthin, either bound to PsbS itself or on the periphery of a closely associated protein.

The bottom line from the work to date seems to be that, if PsbS does indeed bind pigments in vivo, then the nature of this binding interaction must differ substantially from that in other LHC proteins. There is now some evidence for zeaxanthin binding by PsbS (Aspinall-O’Dea et al., 2002), which is consistent with the hypothesis that PsbS is the site of qE, but it is also consistent with other, more complicated hypotheses in which zeaxanthin has an indirect, allosteric role in qE (Horton et al., 2000; Aspinall-O’Dea et al., 2002). Unfortunately, the results showing a lack of chlorophyll binding, because they are negative results, neither support nor rule out the hypothesis.

**PsbS as a sensor of lumen pH**

It was suggested early on that one or more carboxylate side chains in PSII proteins might bind protons at low lumen pH and thereby trigger qE (Horton and Ruban, 1992). This idea was supported by the inhibition of qE by \( \text{N},\text{N}'\text{-dicyclohexylcarbodiimide} \) (DCCD) (Ruban et al., 1992), which binds to proton-active residues in hydrophobic environments. DCCD was shown to bind to LHC proteins, such as CP29 and CP26 (Walters et al., 1996; Pesaresi et al., 1997), which had been suspected to be involved in qE (Horton and Ruban, 1992; Bassi et al., 1993; Jahns and Schweig, 1995), but antisense experiments showed that CP29 and CP26 are unlikely to be sites of qE (Andersson et al., 2001).

After the involvement of PsbS in qE was discovered, it was shown that DCCD binds to PsbS as well (Dominici et al., 2002), and sequence analysis showed that PsbS has eight conserved acidic amino acid residues (glutamate and aspartate) located at or near the lumen side of the protein.
PsbS and qE capacity

If PsbS is the site of qE, then the level of qE should be related to the amount of PsbS per PSII. If there are more quenching sites, then there should be more quenching (up to a limit, of course). Molecular and genetic analysis of the npq4-1 mutant showed that there is indeed a PsbS gene dosage effect on qE. Heterozygous npq4-1/npq4 plants have half the number of psbS genes as the wild type, and they have a correspondingly lower level of PsbS mRNA, PsbS protein, and qE (Li et al., 2002a). Increasing PsbS expression in transgenic plants confers a higher qE capacity (Li et al., 2002b; Hieber et al., 2004), with saturation occurring in Arabidopsis at ~5 times the wild-type level of PsbS on a per PSII basis (Fig. 4). This saturation indicates that there is a maximum number of functional binding sites for PsbS per PSII. Thus, the PsbS protein level can be a determinant of qE capacity, and PsbS expression seems to limit qE in wild-type Arabidopsis and tobacco (Li et al., 2002b; Hieber et al., 2004). Alterations in PsbS level have been reported as explanations for lower qE in LHCII-deficient plants (Andersson et al., 2003) and higher qE in PsbD-deficient plants (Haldrup et al., 2003).

Does the stoichiometry of PsbS vary naturally in plants? The stoichiometry of PsbS has been reported to be two copies of PsbS per PSII in wild-type spinach thylakoids (Funk et al., 1995b), but the Arabidopsis mutants and transgenics show that the stoichiometry can vary widely, from zero (in the npq4-1 mutant) to many times the wild-type value (Fig. 4). The stoichiometry in low-light-grown, wild-type Arabidopsis plants has not yet been determined. It seems plausible that variations in PsbS expression might explain at least some cases of environmental (i.e. sun versus shade) and species-dependent variation in qE capacity (Johnson et al., 1993; Demmig-Adams and Adams, 1994; Demmig-Adams, 1998).

To investigate this hypothesis, the genetic basis for natural variation in qE capacity in Arabidopsis accessions (often referred to as ‘ecotypes’) has started to be examined. A survey of the qE capacity was conducted in more than 50 accessions, and it was found that there is substantial intraspecies variation for qE in Arabidopsis (Fig. 5). However, selected high and low qE accessions appeared to have the...
same level of PsbS expression (H-S Jung and KK Niyogi, unpublished results). Analysis of F$_2$ plants resulting from
a cross between a high qE accession (Si-2) and a low qE accession (Col-0) showed continuous variation of the qE
phenotype, indicating that qE capacity in these accessions is a quantitative genetic trait that is controlled by multiple
genes. Mapping of quantitative trait loci (QTLs) uncovered two major QTLs that are responsible for much of the
variation in qE, but neither of these QTLs mapped to the position of the psbS gene, indicating that the naturally
occurring variation in qE between these two accessions is not attributable to PsbS (H-S Jung and KK Niyogi, un-
published results). The extent to which this conclusion can be generalized to other Arabidopsis accessions and to other
species remains to be determined.

PsbS in algae

Is PsbS a key player in qE in other photosynthetic organ-
isms? Besides angiosperms like Arabidopsis and tobacco,
genesis encoding PsbS have been identified in a moss (Phys-
comitrella patens) and in two green algae (C. reinhardtii and
V. carteri) (Anwaruzzaman et al., 2004), but the function of
these genes in qE has not yet been tested. C. reinhardtii is
an interesting case, because qE-deficient mutants have been
isolated (Niyogi et al., 1997), but so far no mutants have
been shown to affect PsbS. In fact, the most extensively
studied C. reinhardtii mutant, npq5, turned out to be
defective in an LHCII gene called Lhcbl (Elrad et al.,
2002). This finding raises intriguing questions about the
possible relationship between LHCII and PsbS in this alga,
and this can be resolved by studying PsbS-deficient mutants
generated through reverse genetics.

Although nearly all photosynthetic eukaryotes have qE, it
is becoming clear from genome sequencing projects that not
all have PsbS. For example, diatoms exhibit robust qE that
depends on a low thylakoid lumen pH and the presence of
a de-epoxidized xanthophyll (diatoxanthin instead of zeax-
anthin and anthexanthin), but the first completely se-
quenced genome of a diatom (Thalassiosira pseudonana
(http://genome.jgi-psf.org/thaps1/thaps1.home.html), lacks
a psbS gene. There are, however, many genes encoding other
members of the LHC protein superfamily, so it is possible
that another member of the family performs the function of
PsbS in diatoms. As genome sequence information becomes
available for other diverse photosynthetic eukaryotes, a chal-
lenge will be to identify the proteins that play the role that
PsbS has in plants. It is likely that investigation of qE in
algae will provide interesting insights into the evolution of
function in the LHC protein superfamily.

Conclusion

The discovery that PsbS is necessary for qE in Arabidopsis
was an important breakthrough in the study of qE (Li et al.,
2000), but it certainly did not mean that the problem of
understanding qE was solved. On the contrary, the mech-
anism of qE still remains one of the last major unresolved
mysteries in photosynthesis.

A simple hypothesis has been proposed that PsbS is the
site of qE in plants (Li et al., 2000). Several experimental
tests of the hypothesis have now been conducted, and at
present the hypothesis remains viable, although more com-
plicated scenarios are also consistent with the available
data. Previously hypothesized sites of qE, such as LHCII,
CP29, and CP26, look less promising in the light of recent
antisense experiments (Andersson et al., 2001, 2003). On
the other hand, the amount of the PsbS protein in thylakoids
has been shown to be a determinant of qE capacity (Fig. 4)
(Li et al., 2002b; Hieber et al., 2004), and two lumen-facing
glutamate residues in PsbS (Fig. 3) have been identified as
proton-binding sites that are probably involved in sensing
lumen pH and turning qE on and off (Li et al., 2002c, 2004).
Evidence for zeaxanthin binding by PsbS in vitro
has been reported (Aspinall-O’Dea et al., 2002), and a
follow-up of these results is eagerly anticipated. Ultrafast
PsbS-dependent excitation of zeaxanthin following laser
excitation of chlorophyll has been demonstrated (Ma et al.,
2003). This places strict constraints on the distance between
the nearest chlorophyll and the excited zeaxanthin, which
is assumed to reside in PsbS, but chlorophyll binding to PsbS
remains to be unequivocally demonstrated. It is possible
that the coupled chlorophyll might be located on the periph-
ery of PsbS, perhaps at the interface between PsbS and
PSII, which might explain the difficulty in isolating PsbS
with bound chlorophyll.

The next major breakthrough in understanding the role of
PsbS in qE will probably depend on biochemical reconsti-
tution of qE in a much simpler system than isolated thy-
lakoid membranes, the simplest system to date. Indeed,
a holy grail of qE research is the isolation of a complex
containing PsbS, zeaxanthin, and chlorophyll that exhibits
pH- and zeaxanthin-dependent de-excitation of singlet
excited chlorophyll (qE). In conjunction with methodolog-
ical advances in spectroscopy and structural biology, it will
then be possible to obtain a full picture of the mechanism
of qE.

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