Differential Sensitivity of 32 kDa-D1 Protein Degradation and Photosynthetic Electron Flow to Photosystem II Herbicides

Marcel A. K. Jansen1, Shmuel Malkin2, and Marvin Edelman3
Departments of Plant Genetics1 and Biochemistry2, Weizmann Institute of Science, Rehovot 76100, Israel

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Degradation of the 32 kDa-D1 protein, a photosystem II reaction centre component, was studied as a function of linear electron flow in visible light in the presence of various photosystem II herbicides. Under these conditions, herbicide specific effects on protein degradation were clearly evident. 32 kDa-D1 protein degradation and electron flow between Qa and Qb proved to be only partially correlated. We conclude that inhibition of protein degradation by PS II herbicides in visible light is not simply correlated to displacement of Qb.

Introduction

Photosystem II (PS II) of oxygenic phototrophs is a highly structured protein-pigment complex consisting of a water splitting system, a light-harvesting chlorophyll protein complex and a reaction centre [1, 2]. The core of the PS II reaction centre consists of the 32 kDa-D1, D2 and cytochrome b559 proteins [3, 4]. Based on the resolved crystal structure of the functionally-analogous reaction centre of photosynthetic bacteria [5], and molecular characterization of herbicide resistant mutants [2], a structure for the PS II reaction centre has been proposed [6, 7]. The 32 kDa-D1 and D2 proteins each span the membrane five times and are, respectively, the apoproteins of Qb and Qa [8]. Various classes of PS II herbicides interact with the 32 kDa-D1 protein at overlapping but different sites [7, 9–11]. These herbicides interrupt electron flow from PS II to the plastoquinone pool by seemingly-competitive displacement of Qb from the protein [12–16].

The 32 kDa-D1 protein is unstable in the light, turnover occurring at low light intensities with rates exceeding those for other proteins [17–19]. A cleavage site for light-dependent degradation of the protein has been proposed in the loop between helices 4 and 5, somewhere between Arg238 and Ile248 [20]. This site is in close proximity to the Qb/herbicide binding niche [6, 7]. Degradation

Chemical names of herbicides used: Diuron (DCMU), 3-(3,4-dichlorophenyl)-1,1-dimethyleurea; Dinosol, 2-(1-methylpropyl)-4,6-dinitrophenol; Bromoxynil, 4-hydroxy-3,5-dibromobenzonitrile.

Reprint requests to M. A. K. Jansen.

Materials and Methods

Spirodea oligorrhiza (Kurtz) Helgm was grown phototropically under cool white fluorescent lamps. Radiolabeling with [35S]methionine was carried out as previously described [22]. Plants were radiolabeled for 3 h under 25 μE·m−2·s−1 white light and chased in the presence of inhibitors for up to 20 h under 6 μE·m−2·s−1 white light. Membrane proteins were prepared by SDS-PAGE and visualized by fluorography [22]. The rate of 32 kDa-D1 protein degradation was quantified by microdensitometry [20]. Herbicides (chemical pu-
Oxygen evolution was measured in vivo by photoacoustic spectroscopy [23]. The measuring light (15 μE·m⁻²·s⁻¹) was modulated at a frequency of 15 Hz. Signals were processed by a lock-in amplifier (SR530, Stanford Research Systems, U.S.A.) using vectorial analysis [24]. Photochemical quenching of fluorescence (Q-quenching), representing the fraction of Qₐ oxidized, was calculated according to Schreiber [26]. Steady-state chlorophyll fluorescence was studied using modulated measuring light (660 nm) of low intensity (0.1 μE·m⁻²·s⁻¹) from a pulse fluorometer (PAM 101, Fa. Walz, Effeltrich, F.R.G.) operated at 1.6 kHz pulse frequency [25]. The measuring light and the actinic light (660 nm, 6 μE·m⁻²·s⁻¹) were combined on the leaf using fibre optics. Chlorophyll fluorescence-induction kinetics were studied using the same pulse fluorometer as above, coupled to a storage oscilloscope (7623 A, Tektronix, U.S.A.). The intensities of the modulated light (100 kHz, 660 nm) and the actinic light (660 nm) were 0.07 μE·m⁻²·s⁻¹ and 40 μE·m⁻²·s⁻¹, respectively. The degree of inhibition of electron transport between Qₐ and Qₖ was calculated from the decrease of the complementary area above the induction curves, which was normalized to maximal fluorescence [27].

Results and Discussion

The effects of bromoxynil, dinoseb and diuron on oxygen evolution, Q-quenching of fluorescence, fluorescence induction area and 32 kDa-D₁ protein degradation are shown in Fig. 1. The rates of electron flow and protein degradation remained constant during the experiment. Thus, under the conditions used, the herbicides did not noticeably damage the photosynthetic apparatus. Using these data, the inhibition of PS II electron flow (oxygen evolution or Q-quenching measurements) or the inhibition of electron flow between Qₐ and Qₖ (fluorescence-induction area measurements) was plotted vs. inhibition of 32 kDa-D₁ degradation. The derived plots are shown in Fig. 2.

In the presence of diuron, a linear correlation was found between inhibition (up to 90%) of photosynthetic electron flow and 32 kDa-D₁ protein degradation. However, the diuron regression lines are displaced from the origin. This shows that at concentrations where Q-quenching, oxygen evolution, and electron flow between Qₐ and Qₖ were
abolished, degradation of the 32 kDa-D1 protein still proceeded at appreciable rates. Only at higher herbicide concentrations was degradation fully blocked. Bromoxynil, on the other hand, inhibited 32 kDa-D1 protein degradation with a considerably lower efficiency than it did photosynthetic electron flow (measured by any of the three methods). Thus, at herbicide concentrations which reduced electron flow to less than 50% of non-inhibited control, protein degradation was not measurably impeded. Only at higher bromoxynil concentrations was 32 kDa-D1 degradation also affected. In contrast, dinoseb inhibited degradation more strongly than it did photosynthetic electron flow. A concentration reducing the rate of protein degradation by about 50%, hardly affected oxygen evolution, Q-quenching or electron flow between Qa and Qb. Only higher inhibitor concentrations affected photosynthetic electron flow and degradation proportionally.

Although effects of herbicide impurities at the highest concentrations used cannot be excluded, the derived plots in Fig. 2 suggest that under photosynthetically active radiation, correlations between 32 kDa-D1 protein degradation and electron flow do exist, but are complex. We conclude that inhibition of protein degradation by PS II herbicides in visible light is not simply correlated to displacement of plastoquinone, although the two processes are related.

The specific effects of individual herbicides on protein degradation may reflect their different binding sites within the Qb niche. In this regard, we note the binding of the diuron-type inhibitor, azidomonuron to protein residues Tyr237 and Tyr254 [11], and the bromoxynil type inhibitor, azidoioxynil to residue Val249 [10]. The relationship in vivo between linear electron flow and 32 kDa-D1 protein degradation seems inhibitor specific. Thus, co-analysis of electron flow and degradation, coupled with site directed mutagenesis, may help pinpoint binding sites of various herbicides in the Qb-region and the mechanism of 32 kDa-D1 protein degradation.

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