

# The Relationship between Photosynthesis and a Mastoparan-Induced Hypersensitive Response in Isolated Mesophyll Cells<sup>1</sup>

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The G-protein activator mastoparan (MP) was found to elicit the hypersensitive response (HR) in isolated *Asparagus sprengeri* mesophyll cells at micromolar concentrations. The HR was characterized by cell death, extracellular alkalinization, and an oxidative burst, indicated by the reduction of molecular O<sub>2</sub> to O<sub>2</sub><sup>•-</sup>. To our knowledge, this study was the first to monitor photosynthesis during the HR. MP had rapid and dramatic effects on photosynthetic electron transport and excitation energy transfer as determined by variable chlorophyll *a* fluorescence measurements. A large increase in non-photochemical quenching of chlorophyll *a* fluorescence accompanied the initial stages of the oxidative burst. The minimal level of fluorescence was also quenched, which suggests the origin of this nonphotochemical quenching to be a decrease in the antenna size of photosystem II. In contrast, photochemical quenching of fluorescence decreased dramatically during the latter stages of the oxidative burst, indicating a somewhat slower inhibition of photosystem II electron transport. The net consumption of O<sub>2</sub> and the initial rate of O<sub>2</sub> uptake, elicited by MP, were higher in the light than in the dark. These data indicate that light enhances the oxidative burst and suggest a complex relationship between photosynthesis and the HR.

Plants employ a wide array of defense mechanisms against pathogenic microbes. Although plants have protective structures that are always in place (including cuticle layers and thick cell walls) and constitutive biochemical defenses (such as fungitoxic exudates), many resistance strategies are induced after an encounter with a pathogen (Johal et al., 1995). The HR is an induced plant-resistance mechanism. The HR has been defined as localized cell death in an area of pathogen invasion, a phenomenon that may function to isolate and thus limit colonization by biotrophic pathogens (Mehdy, 1994). Certain characteristics have consistently been observed in conjunction with hypersensitive cell death. These include ion fluxes across the plasma membrane (namely Ca<sup>2+</sup> influx and K<sup>+</sup> and Cl<sup>-</sup> effluxes), external pH changes (usually alkalinization; Atkinson et al., 1985; Levine et al., 1994), plasma membrane depolarization (Keppler and Novacky, 1986), and the oxidative burst, which features the consumption of molecular O<sub>2</sub> and its reduction to O<sub>2</sub><sup>•-</sup> at the plasma membrane

(Bolwell et al., 1995). Cell death accompanied by these phenomena provides substantial evidence for the HR.

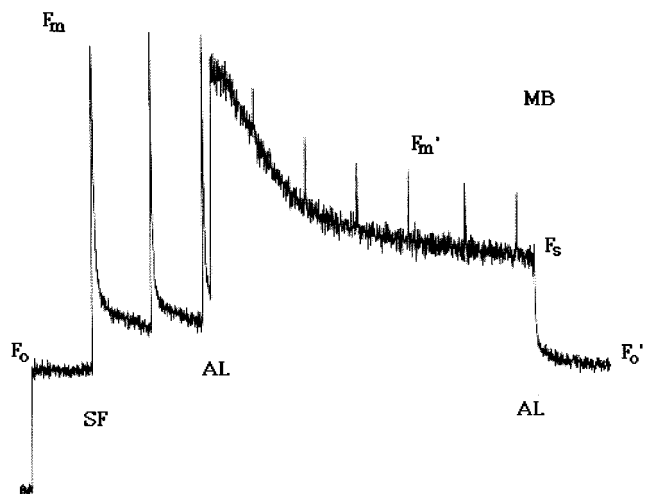
Micromolar concentrations of MP have been used to evoke cellular responses, similar to those evoked by fungal elicitors, in suspension cultures of parsley (Kauss and Jeblick, 1995) and soybean cells (Legendre et al., 1992, 1993; Chandra et al., 1996), as well as in etiolated cucumber hypocotyls (Kauss and Jeblick, 1996). First isolated from wasp venom, MP is an amphipathic tetradecapeptide. Although MP possesses numerous biological activities, at micromolar concentrations it is best known for its ability to activate G proteins (Higashijima et al., 1988, 1990). Although it exists as a random coil in aqueous solution, MP takes on an  $\alpha$ -helical secondary structure when associated with a lipid bilayer (Higashijima et al., 1983). In this form MP displays four positive charges similar to the cytosolic domain of an activated ligand-receptor complex in the plasma membrane. MP accelerates the exchange of GDP (bound by inactive G protein) for GTP (bound by active G protein) in the  $\alpha$ -subunit (Ross and Higashijima, 1994). Thus, MP activation of the HR provides evidence for G-protein signal transduction linking of elicitor recognition and the HR.

The centrality of photosynthesis to plant function argues for the use of photosynthetic tissue or cells in the investigation of plant responses to environmental stimuli. In particular, investigations of the HR using nonphotosynthetic plant cell cultures may misrepresent the in situ response of photosynthetic cells that may be affected directly or indirectly by light. There is some evidence for light stimulation of the HR. For example, severe necrosis was observed in 11-week-old tomato plants that had been unshaded, whereas heavily shaded plants of the same type and age were nonnecrotic. Thus, the "reduction of light prevented the development of typical symptoms of necrosis" (Langford, 1948). In another study necrosis in tomato leaf tissue induced by incompatible fungal elicitation was delayed in the dark (Peever and Higgins, 1989). In Arabidopsis mutants necrotic lesions were induced by red and white light in the absence of a pathogen (Genoud et al., 1998). Conversely, cell death in response to the HR will inevitably

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Abbreviations:  $F_m$ , maximal fluorescence;  $F_m'$ , maximal fluorescence in any light-adapted state;  $F_o$ , minimal (background) fluorescence;  $F_o'$ , minimal fluorescence in any light-adapted state;  $F_s$ , steady-state fluorescence; HR, hypersensitive response; MP, mastoparan; PAM, pulse-amplitude-modulated;  $Q_A$ , the primary quinone electron acceptor of PSII;  $q_N$ , nonphotochemical quenching;  $q_P$ , photochemical quenching.



**Figure 1.** Sample of PAM chlorophyll *a* fluorescence yield from a suspension of isolated asparagus mesophyll cells. AL, Actinic light; MB, measuring beam; SF, saturating flash.

inhibit photosynthesis. Chlorophyll fluorescence is inversely related to photosynthetic activity. Thus, fluorescence signals may offer a mechanism to investigate events associated with the HR-induced cell death, but the relationship between photosynthesis and the HR remains unclear.

Investigations using mesophyll cells isolated from *Asparagus sprengeri* Regel may elucidate these relationships. Mechanical isolation yields a suspension of photosynthetically competent cells that is separated from in planta conditions by only 1 or 2 h (Colman et al., 1979). The photosynthetic capacity of these cells makes PAM fluorometry measurements of chlorophyll *a* fluorescence possible. We used in vivo chlorophyll fluorescence measurements to monitor the status of photosynthesis in hypersensitively responding cells. To our knowledge, this is the first study that analyzes the HR with PAM fluorometry.

The questions posed in this study are: Does MP induce the HR, or is it merely cytotoxic? Does light stimulate the MP-induced oxidative burst? Does MP inhibit photosynthesis?

## MATERIALS AND METHODS

### Cell Isolation and Incubation

Photosynthetically competent mesophyll cells from greenhouse-grown *Asparagus sprengeri* Regel were isolated mechanically each day (Colman et al., 1979). For 5 min prior to initiation of measurements, cells were preincubated in a 5 mM Mes buffer (pH 6.0) that contained 1 mM  $\text{CaSO}_4$ . For alkalization experiments cells were resuspended in 1 mM  $\text{CaSO}_4$  without buffer. Depending on the experiment, cell-suspension volumes varied from 1 to 5 mL and cell concentrations ranged from  $1.5 \times 10^6$  to  $6 \times 10^6$  cells  $\text{mL}^{-1}$ . Cell suspensions were gently stirred. All chemicals added to cell suspensions were in aqueous solution, and the concentrations indicated were final. MP from *Vespula lewisii* and Mas17, an inactive MP analog, were

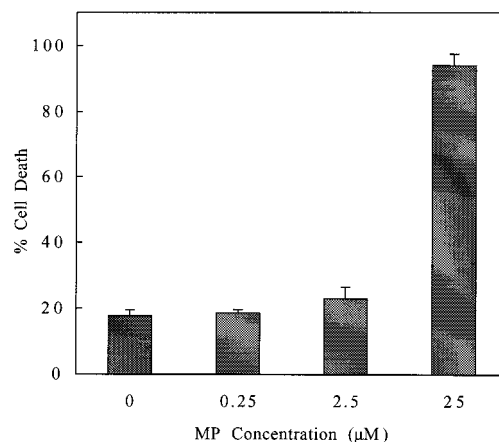
obtained from Peninsula Laboratories (Belmont, CA) and Bachem BioSciences (Philadelphia, PA). Mas7, a potent and inexpensive analog of MP obtained from Calbiochem, achieved results indistinguishable from those induced by MP and thus was used in later experiments. Since MP partitions into membranes (Cho et al., 1995), the effective concentration depends on cell density. Thus, although nominal MP concentrations are reported in micromolar units, when expressed in terms of cell number, they ranged from 4.2 to 8.8 nmol  $10^6$  cells $^{-1}$ .

### Cell Viability Determination

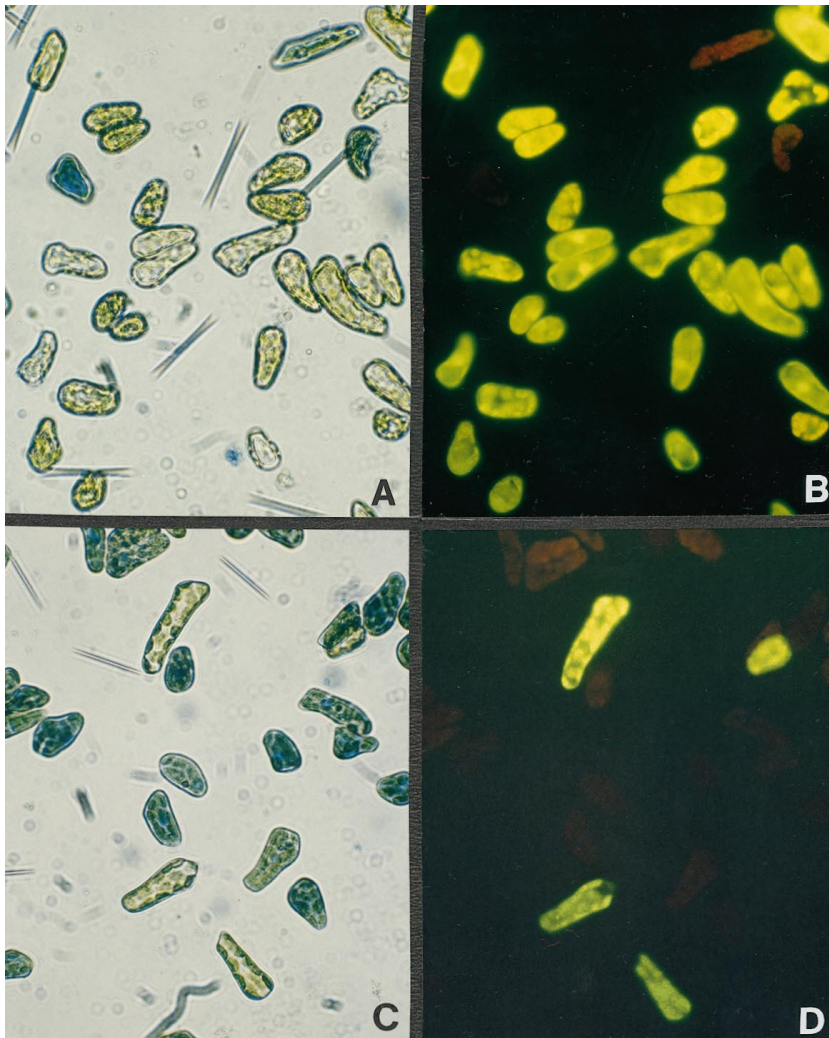
Uptake of Evan's blue dye was used to visualize dead mesophyll cells (Colman et al., 1979). Cells were counted with a hemocytometer and percentages of dead cells were tabulated. Mechanically isolated cell suspensions normally had 16% to 17% dead cells. Only cell suspensions with more than 75% viable cells were used in our experiments. Cells were also incubated simultaneously with Evan's blue dye and fluorescein diacetate to assess cell viability (Withers, 1985). Cells that accumulated free fluorescein and fluoresced yellow-green upon UV irradiation were deemed viable. Using a fluorescent microscope (Wild Leitz, Heerbrugg, Switzerland) equipped with a camera, photographs of cells were taken from the same field of view under both bright and dark fields to evaluate viability with Evan's blue dye and fluorescein diacetate, respectively. To determine the complementarity of the two viability tests, cell death was quantified from the photographs.

### Measurement of Extracellular Alkalinization

MP-induced alkalinization of the *A. sprengeri* mesophyll cell-suspension medium was monitored with a recording pH apparatus (PHM 64 research pH meter and REC 61 Servograph, Radiometer, Copenhagen, Denmark) (Mc-



**Figure 2.** Cell viability as a function of MP concentration. Two-milliliter cell suspensions containing  $12 \times 10^6$  cells were incubated with either 0, 0.25, 2.5, or 25  $\mu\text{M}$  MP. After 16 min of incubation with MP, the cells were incubated with Evan's blue dye for assessment of viability. Percentage cell death represents the mean of three experiments. SE bars are shown.



**Figure 3.** Individual cell viability assayed with Evan's blue dye and fluorescein diacetate. Two 2.5-mL cell suspensions, each containing  $10 \times 10^6$  cells, were incubated for 16 min with and without  $25 \mu\text{M}$  MP, respectively. Cells were then incubated with fluorescein diacetate in conjunction with Evan's blue dye. Photographs were taken of the same fields of view under both bright and dark fields. These photographs represent control cells under bright (A) and dark (B) fields, and MP-treated cells under bright (C) and dark (D) fields.

Cutcheon and Bown, 1987). Three milliliters of suspension (containing  $4.5 \times 10^6$  cells in 1 mM  $\text{CaSO}_4$ ) was transferred to a water-jacketed vessel at  $25^\circ\text{C}$ . The initial pH was adjusted to 5 with dilute  $\text{H}_2\text{SO}_4$ . After 5 min of dark adaptation,  $13.2 \mu\text{M}$  MP was added, keeping the suspension in the dark. After alkalization was completed, back-titration with standard  $0.10 \text{ N}$  HCl allowed us to quantify the nanomoles of  $\text{H}^+$  per  $10^6$  cells involved in the alkalization response.

### Chlorophyll *a* Fluorescence Measurements

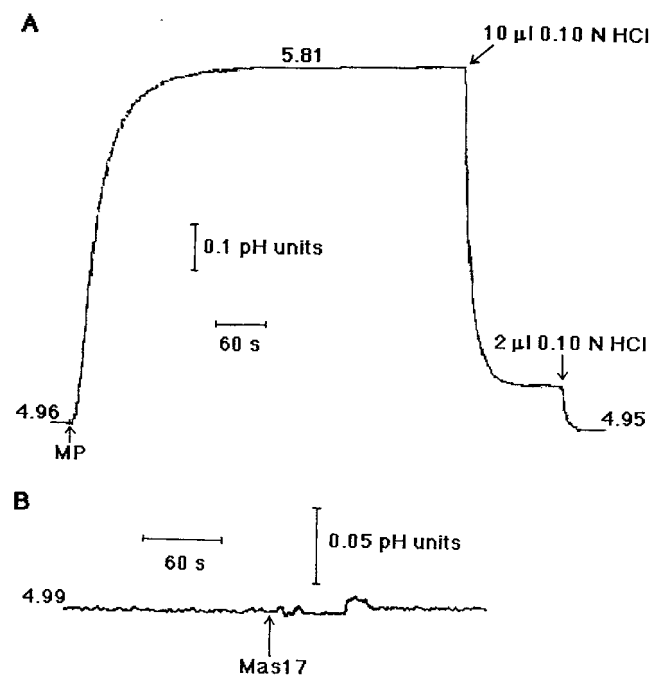
Modulated chlorophyll *a* fluorescence emission was measured *in vivo* using a PAM fluorometer (PAM 101, Heinz Walz, Effeltrich, Germany) (Genty et al., 1989). The intensity of the measuring beam was approximately  $0.02 \mu\text{mol m}^{-2} \text{s}^{-1}$  at a frequency of 1.6 kHz. This intensity was insufficient to drive appreciable photosynthetic  $\text{O}_2$  evolution. Measuring beam frequency was switched to 100 kHz during periods in which actinic light was employed to drive photosynthesis, to enhance the resolution of the signal. Three million cells in 2 mL of 5 mM Mes and 1 mM  $\text{CaSO}_4$ , pH 6.0, were dark-adapted for 5 min at  $25^\circ\text{C}$  with

$500 \mu\text{M}$   $\text{KHCO}_3$ . An initial exposure to the measuring beam, in addition to far-red light, was done to establish the  $F_o$  (Fig. 1). At  $F_o$  all PSII reaction centers have an oxidized  $\text{Q}_A$ . Subsequently, 500-ms saturating flashes were delivered at 20- or 40-s intervals to transiently reduce  $\text{Q}_A$ , producing  $F_m$ . After several saturating flashes (approximately  $6000 \mu\text{mol m}^{-2} \text{s}^{-1}$  each), continuous white actinic light ( $60 \mu\text{mol m}^{-2} \text{s}^{-1}$ ) from a halogen lamp was added. This intensity maximized photosynthetic  $\text{O}_2$  evolution while minimizing photoinhibition. The actinic light generated  $F_s$  after 1 to 2 min. Saturating flashes applied in the presence of actinic light produce  $F_m'$  levels, which are lower than  $F_m$  due to the presence of  $q_N$  of fluorescence.  $F_o'$  was determined by extinguishing the white actinic light, by illuminating the cells with far-red light, and, in experiments where  $\text{O}_2$  had been consumed by the MP-induced oxidative burst, by the reintroduction of  $\text{O}_2$ .  $F_m'$ ,  $F_m'$ ,  $F_o'$ ,  $F_o'$ , and  $F_s$  levels were used to calculate  $q_p$  and  $q_N$  as described by van Kooten and Snel (1990):

$$q_p = F_m' - F_s / F_m' - F_o'$$

$$q_N = 1 - (F_m' - F_o' / F_m - F_o)$$





**Figure 4.** The effect of MP and Mas17 on the pH of the incubating medium. The pH of suspensions containing  $4.5 \times 10^6$  cells in 3 mL of 1 mM  $\text{CaSO}_4$  was adjusted to approximately 5.0. A, The addition of  $13.2 \mu\text{M}$  MP and two aliquots of 0.10 N HCl (for back-titration) are indicated by arrows. B, The addition of  $13.2 \mu\text{M}$  Mas17 is indicated by an arrow. This figure is a representative of five runs.

#### Measurement of $[\text{O}_2]$

The photosynthetic  $\text{O}_2$  evolution of  $3 \times 10^6$  cells in 2 mL of 5 mM Mes and 1 mM  $\text{CaSO}_4$ , pH 6.0, at  $25^\circ\text{C}$  was measured using a Clark-type electrode (DW1, Hansatech, King's Lynn, Norfolk, UK), which was calibrated using sodium dithionite. Light sources used in chlorophyll fluorescence measurements were set up around the  $\text{O}_2$  electrode so that fluorescence and  $\text{O}_2$  could be measured simultaneously. Before the dark adaptation prior to each experiment,  $500 \mu\text{M}$   $\text{KHCO}_3$  was added to ensure that the cells did not exhaust dissolved inorganic C. The actinic light (as described above) was used to induce photosynthetic  $\text{O}_2$  evolution. Initial rates of  $\text{O}_2$  consumption in response to MP or Mas 7 are expressed in micromoles of  $\text{O}_2$  per milligram of chlorophyll per hour, and net  $\text{O}_2$  consumption is expressed in micromoles of  $\text{O}_2$  per milligram of chlorophyll.

#### Measurement of $\text{O}_2^{\cdot-}$

To measure  $\text{O}_2^{\cdot-}$ ,  $3 \times 10^6$  cells were incubated for 5 min in  $330 \mu\text{L}$  of 1 mM  $\text{CaSO}_4$ , pH 5.5. After the addition of  $5 \mu\text{M}$  Mas7, a  $200\text{-}\mu\text{L}$  aliquot of cell suspension was transferred to a cuvette containing  $700 \mu\text{L}$  of  $100 \mu\text{M}$  Gly-NaOH buffer, 1 mM EDTA, and  $110 \mu\text{M}$  lucigenin, pH 9.0 (Jabs et al., 1997). Chemiluminescence was measured within approximately 5 s of the transfer, and the time course of  $\text{O}_2^{\cdot-}$  production was monitored using a recorder connected

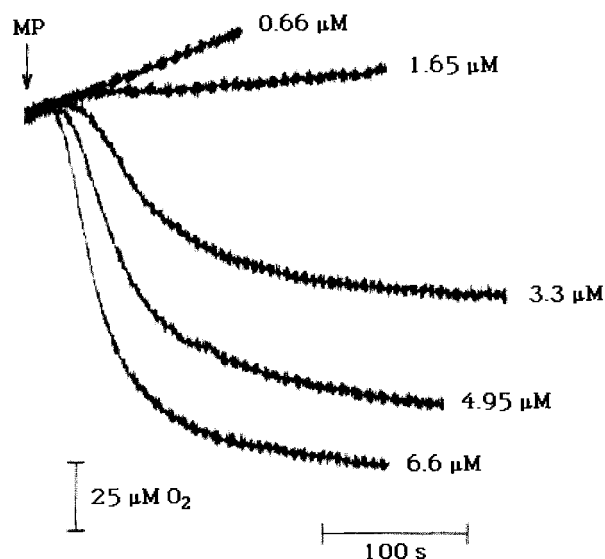
to a luminometer (model 1250, LKB Wallac Oy, Turku, Finland).

## RESULTS

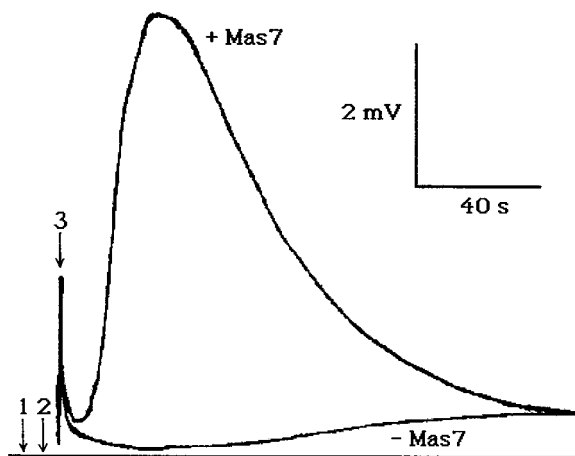
Cell viability was assessed with Evan's blue dye after incubating cell suspensions with either 0, 0.25, 2.5, or  $25 \mu\text{M}$  MP (Fig. 2). Although cell viability after incubation with 0.25 and  $2.5 \mu\text{M}$  MP did not differ notably from the control levels ( $0 \mu\text{M}$  MP), incubation with  $25 \mu\text{M}$  MP resulted in a significantly higher percentage of dead cells (94.0%) as compared with the control (17.7%). Thus, the threshold concentration of MP required to induce cell death is between 2.5 and  $25 \mu\text{M}$ .

To confirm viability determinations with Evan's blue dye, the viability of cells incubated  $\pm 25 \mu\text{M}$  MP was assessed with Evan's blue dye in conjunction with fluorescein diacetate. Photographs confirmed the complementarity of the two tests; Evan's blue dye and fluorescein diacetate viability tests identified the same cells to be dead (Fig. 3). In the absence of MP, the two tests indicated 15% cell death ( $n = 250$  cells), and in the presence of MP, both tests indicated 80% dead cells ( $n = 100$  cells).

Cell death is indicative of the HR, as are rapid changes in the pH of the cell-suspension medium. MP initiated alkalization within 2 s. The pH rose 0.85 pH units, which was equivalent to  $270 \text{ nmol H}^+ 10^6 \text{ cells}^{-1}$  (Fig. 4A). The addition of Mas17, an inactive analog of MP, did not result in alkalization (Fig. 4B). The cell-dependent alkalization was not reversed after 20 min and was pH dependent. When the initial pH was 6.0, only a slight alkalization was observed, and when the initial pH was 7.0, no alkalization occurred in response to MP (data not shown). Repeat additions of MP after approximately 4 to 5 min did not



**Figure 5.** The effect of MP concentration on  $\text{O}_2$  consumption in the light. This figure shows  $\text{O}_2$  consumption measurements compiled from five separate PAM experiments. In each experiment 2 mL of 5 mM Mes and 1 mM  $\text{CaSO}_4$ , pH 6.0, contained  $3 \times 10^6$  cells. Aliquots of MP were added to give the concentrations indicated.



**Figure 6.** The effect of Mas7 on  $O_2^{\cdot-}$  production. Three million cells were incubated in 330 mL of 1 mM  $CaSO_4$ , pH 5.5, for 5 min. Arrow 1 indicates the addition of 5  $\mu M$  Mas7 to the cell suspension. Arrow 2 indicates transfer of 200  $\mu L$  of the cell suspension to the luminometer cuvette. Arrow 3 indicates an artifact due to stray light detected by the photomultiplier as the cuvette is inserted into the luminometer. This figure is a representative of six runs.

result in further alkalization of the medium (data not shown).

Another characteristic of the HR is the consumption of molecular  $O_2$ . The concentration dependence of MP-induced  $O_2$  consumption was investigated (Fig. 5). Of the five MP concentrations involved, only 3.3, 4.95, and 6.6  $\mu M$  caused net  $O_2$  consumption. Thus, the threshold MP concentration for the stimulation of rapid and transient  $O_2$  consumption is between 1.65 and 3.3  $\mu M$ . The threshold MP concentration for decreasing viability of cells is between 2.5 and 25  $\mu M$  (Fig. 2). These threshold concentration ranges

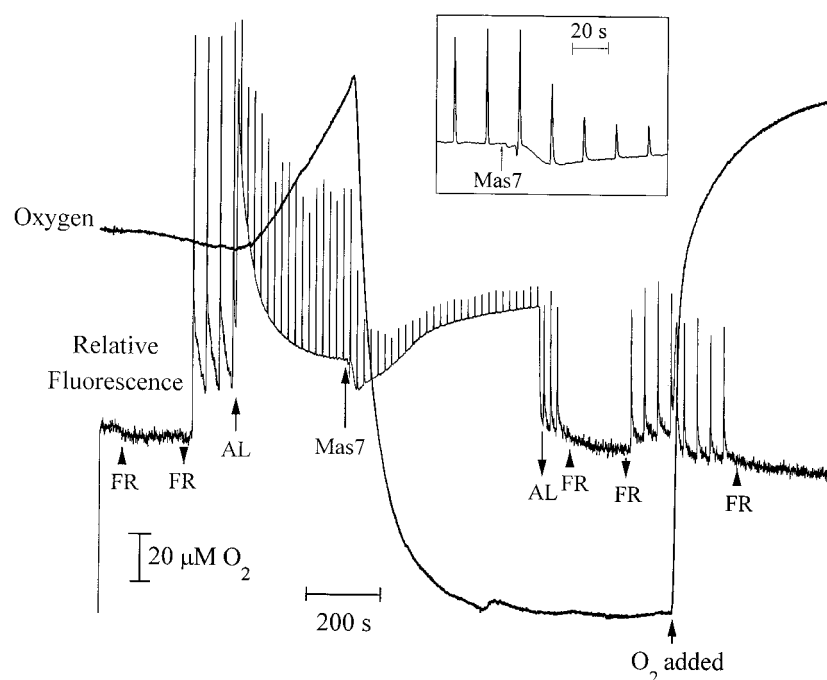
overlap, suggesting a single mechanism that results in an oxidative burst and in increased cell death.

The consumption of  $O_2$  has been attributed to its reduction to  $O_2^{\cdot-}$ . The chemiluminescent lucigenin assay for  $O_2^{\cdot-}$  demonstrated that Mas7, a highly potent MP analog, stimulated  $O_2^{\cdot-}$  production (Fig. 6). A burst of  $O_2^{\cdot-}$  was initiated 20 s after Mas7 addition and lasted approximately 80 s. The disappearance of  $O_2$  and the appearance of  $O_2^{\cdot-}$  were highly synchronous events (Figs. 7 and 6, respectively).

A PAM fluorometer in conjunction with an  $O_2$  electrode was used to obtain simultaneous measures of  $O_2$  consumption and relative fluorescence in illuminated cells.  $O_2$  consumption was initiated 12 ( $\pm 1$  SE) s after Mas7 addition. Net consumption of 387 ( $\pm 22$  SE) nmol of  $O_2$  occurred within 100 to 200 s (Fig. 7).

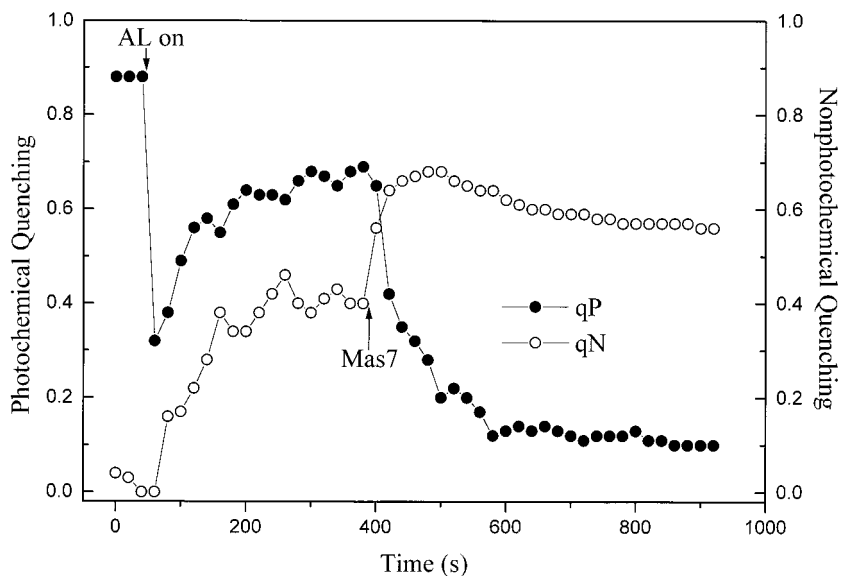
After this consumption of  $O_2$  no further photosynthetic  $O_2$  evolution was measured. During the rapid initial consumption of  $O_2$  the PAM fluorescence trace was dominated by a dramatic decrease of  $F_s$  and  $F_m'$  (Fig. 7). The decrease in  $F_m'$  indicated an increase in  $q_N$ , whereas the decrease in  $F_s$  reflected a maintenance of  $q_P$  (Fig. 8). These results demonstrate a continued oxidation of  $Q_A$  during the period in which the cells were rapidly consuming  $O_2$ . In some experiments a small increase in  $q_P$  immediately followed the addition of Mas7 (data not shown).

As the oxidative burst continued and the  $[O_2]$  approached its minimum value,  $F_s$  and  $F_m'$  increased (Fig. 7). These changes were indicative of a large decrease in  $q_P$  and a relatively smaller decrease in  $q_N$  (Fig. 8). In spite of this small decrease,  $q_N$  remained higher than at any time before the addition of Mas7. After the actinic light was extinguished,  $F_s$  dropped dramatically but  $F_m'$  was unchanged (Fig. 7). This indicates that  $q_P$  quickly increased in the dark, whereas  $q_N$  was unaffected by the actinic illumina-



**Figure 7.** The effect of Mas7 on chlorophyll a fluorescence yield and  $O_2$  level in the light. Two milliliters of 5 mM Mes and 1 mM  $CaSO_4$ , pH 6.0, contained  $3 \times 10^6$  cells. Far-red light (FR), actinic light (AL), 22  $\mu M$  MP, and  $O_2$  were added ( $\uparrow$ ) or removed ( $\downarrow$ ) as indicated. The inset represents relative fluorescence immediately before and after Mas7 addition. This figure is a representative of 20 runs.

**Figure 8.** The effect of Mas7 on  $q_P$  and  $q_N$ , respectively over time. Values of  $q_P$  and  $q_N$  shown were calculated from one representative trial. Actinic light (AL) and  $22 \mu\text{M}$  Mas7 were administered as indicated by the arrows.



tion (not shown). Finally, the subsequent addition of  $\text{O}_2$  decreased  $F_s$  and  $F_m'$  (Fig. 7). This is indicative of a small  $\text{O}_2$ -induced increase in  $q_N$  and a very small increase in  $q_P$  (not shown). These effects of  $\text{O}_2$  on  $q_N$  and  $q_P$  are consistent with the dual role of  $\text{O}_2$  as a quencher of excitation energy in the antenna and as an acceptor of electrons from the electron transport chain in the Mehler reaction (Vidaver et al., 1981).

In other experiments (data not shown), it was demonstrated that the high  $q_N$  always observed after the addition of Mas7 could not be relieved by the addition of the uncoupler nigericin. Nigericin was, however, competent to relieve any light-induced  $q_N$  observed in the absence of Mas7 (data not shown). In other control experiments neither the addition of Mas7 to cells killed by freezing in liquid nitrogen nor the addition of Mas17 to living cells resulted in  $\text{O}_2$  consumption or in changes in chlorophyll fluorescence.

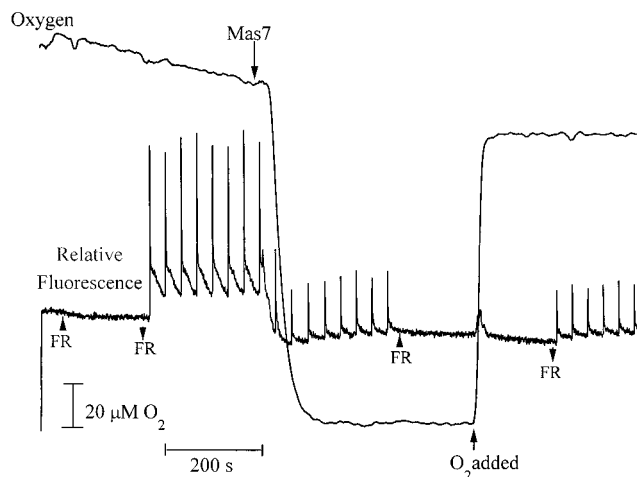
When Mas7 was added to nonilluminated cells, net  $\text{O}_2$  consumption and a dramatic decrease in  $F_m'$  were observed as in the light (Fig. 9). The oxidative burst and the increase in  $q_N$  were therefore not light dependent. In the absence of light, however, the rate and extent of Mas7-induced  $\text{O}_2$  consumption were significantly lower (Table I). The  $F_o$  level upon addition of Mas7 was lower than the initial  $F_o$  level achieved with far-red illumination, suggesting a change in organization of the antenna in response to Mas7. In contrast to experiments in the light,  $F_s$  did not increase after the oxidative burst, which suggests the origin of the decreased  $q_P$  observed in the light to be a limitation on the electron acceptor side of PSII. As observed in the light, the reintroduction of  $\text{O}_2$  in the dark was accompanied by a small increase in  $q_N$ .

## DISCUSSION

Characteristics of the HR include alkalization of the extracellular medium,  $\text{O}_2$  consumption, production of

$\text{O}_2^{\cdot-}$ , and cell death (Boller, 1989; Ebel and Cosio, 1994; Hammond-Kosack and Jones, 1996). In asparagus mesophyll cells, MP or its active analog Mas7 induces cell death (Fig. 2), alkalization of the medium (Fig. 4A),  $\text{O}_2$  consumption (Figs. 5, 7, and 9), and concurrent  $\text{O}_2^{\cdot-}$  generation (Fig. 6). Thus, the evidence indicates that MP induces the HR in asparagus cells and is not merely cytotoxic. Previous work demonstrated a MP-stimulated oxidative burst in suspension-cultured soybean (Legendre et al., 1992, 1993) and parsley cells (Kauss and Jeblick, 1995). Furthermore,  $10 \mu\text{M}$  MP (as well as guanine nucleotides) was shown to stimulate plasma membrane NADH oxidase activity in etiolated soybean hypocotyls (Morré et al., 1993). Because the oxidative burst is a critical component of the HR (Doke, 1983), the stimulation of the oxidative burst by MP (Fig. 5) or Mas7 (Figs. 7 and 8) is consistent with elicitation of the HR by these agents.

MP is a tetradecapeptide found in wasp venom and is known to activate G proteins in animal cells (Higashijima et al., 1988, 1990). In plant cells evidence for G-protein activation by MP is indirect. Various measures of phosphoinositide-based signal transduction in plants have been obtained in response to MP. Transient MP-stimulated increases in inositol triphosphate levels have been observed in *Samanea saman* pulvini protoplasts (Kim et al., 1996), cultured carrot cells (Drøbak and Watkins, 1994; Cho et al., 1995), and *A. sprengeri* mesophyll cells (data not shown). Enhanced phospholipase C activity has also been measured in wheat root microsomes in response to  $25 \mu\text{M}$  MP (Jones and Kochian, 1995). In addition, microinjection of Mas7 into staminal hairs of *Setcreasea purpurea* induced an increase in intracellular  $\text{Ca}^{2+}$ , an effect that was mimicked by inositol triphosphate microinjection (Tucker and Boss, 1996). MP elicited a greater oxidative burst in etiolated cucumber hypocotyls in comparison with fungal elicitor and other fungally derived compounds, indicating that the rate of the MP-stimulated oxidative burst was not limited by elicitor-receptor binding in contrast with the



**Figure 9.** The effect of Mas7 on chlorophyll *a* fluorescence yield and  $O_2$  level in the dark. Two milliliters of 5 mM Mes and 1 mM  $CaSO_4$ , pH 6.0, contained  $3 \times 10^6$  cells. Cell suspensions were not illuminated with actinic light. Far-red light (FR), 22  $\mu$ M MP, and  $O_2$  were added ( $\uparrow$ ) or removed ( $\downarrow$ ) as indicated. This figure is a representative of 10 runs.

other “elicitors” (Kauss and Jeblick, 1996). The data are consistent with G-protein activation of the oxidative burst by MP.

The death of asparagus cells was assessed with Evan’s blue dye (Fig. 2) and was confirmed with fluorescein diacetate (Fig. 3). The use of a fluorescent inclusion dye in conjunction with a nonfluorescent exclusion dye to test plant cell viability has been demonstrated previously (Huang et al., 1986) and allows for simultaneous, independent tests for living cells. Because complementary data were generated with these two tests (Fig. 3), it can be concluded that the Evan’s blue test alone provides a good measure of cell death.

The alkalinization observed in response to MP (Fig. 4) was not reversed after 20 min and was pH dependent. Only slight alkalinization was observed when the starting pH was 6.0 and none occurred with a starting pH of 7.0. Furthermore, after MP addition to the cells, titration of the suspension medium indicated an 18% increase in buffering capacity (data not shown). Alternatively, alkalinization due to the elicitation of cultured tomato cells by ergosterol was transient, lasting from 10 to 15 min (Granado et al., 1995). The present findings are more consistent with electrolyte leakage from hypersensitively responding cells than with altered  $H^+$  translocation mechanisms.

The oxidative burst stimulated by MP was confirmed by two separate measurements, the consumption of  $O_2$  (Fig. 5) and the production of  $O_2^{\cdot-}$  (Fig. 6). Superoxide production was calibrated using  $O_2^{\cdot-}$  generated by xanthine/xanthine oxidase (Murphy and Auh, 1996). Over 95% of the  $O_2$  consumed could be accounted for by  $O_2^{\cdot-}$  production.

Many investigations of the HR have been performed using suspension-cultured plant cells. Such cells are nonphotosynthetic. In this study the PAM fluorometer was used to measure chlorophyll *a* fluorescence and  $O_2$  levels as photosynthetic asparagus cells underwent a MP-stimulated oxidative burst.

Significant changes in photosynthesis occur during the MP-stimulated oxidative burst. The cessation of net photosynthetic  $O_2$  evolution (Fig. 7) indicates an inhibition of linear electron transport. During the oxidative burst a large degree of  $q_P$  of fluorescence was maintained as indicated by the low level of  $F_s$  compared with  $F_m'$ . This indicates that the  $Q_A$  of PSII was still being oxidized in the light during the oxidative burst. Upon completion of the oxidative burst the  $F_s$  increased and approached the  $F_m'$  level, indicating almost complete inhibition of  $q_P$  and therefore of photosynthetic electron transport. These phenomena were also observed when the cells were placed in a high osmoticum buffer, containing 330 m[scap]m sorbitol and 5 mM MgCl, ruling out the possibility that the changes were due to bursting of the chloroplasts and/or to destacking of the thylakoid membranes.

Another dramatic change in PSII was the large increase in  $q_N$  characterized by the large decrease in  $F_m'$ , which accompanied the oxidative burst in the light (Fig. 7) and in the dark (Fig. 9). Most  $q_N$  is caused by “energization” of thylakoid membranes, which results from the formation of a pH gradient. It is therefore termed “energy-dependent” quenching (Neubauer and Schreiber, 1988; Schreiber et al., 1991). Some stromal alkalinization and lumen acidification normally occur due to the proton pumping associated with photosynthetic electron transport. Thus, in the light, a degree of  $q_N$  is observed.  $q_N$  due to  $\Delta$ pH formation may be relieved by the protonophore nigericin. MP-induced  $q_N$  was not relieved by the addition of nigericin (data not shown), indicating that it is not a result of a pH gradient across thylakoid membranes. Photoinhibition is not a likely explanation of the increase in  $q_N$  because the effect occurred in the dark as well. An inhibition of the electron donor side of PSII and/or a decrease in its antenna size would also result in an increase in  $q_N$  (Bruce et al., 1997). Support for this decrease in antenna size is provided by the decrease in  $F_o$  level observed in response to Mas7. Further experiments are required to investigate these possibilities.

The data indicate that light stimulates the rate and extent of  $O_2$  consumption in the oxidative burst (Table I). They complement previous reports indicating that light may stimulate the HR (Langford, 1948; Peever and Higgins, 1989; Genoud et al., 1998). Application of the HR elicitor

**Table I.** The effect of MP on  $O_2$  consumption in the light and in dark

Two milliliters of 5 mM Mes and 1 mM  $CaSO_4$ , pH 6.0, contained  $3 \times 10^6$  cells. MP (13.2  $\mu$ M) was added to cell suspensions that were irradiated with actinic light and to suspensions kept in the dark. Mean initial rates of  $O_2$  consumption after MP addition and mean net  $O_2$  consumption values are shown. SE values are included ( $n = 3$ ). Wilcoxon rank sign analysis indicates that the probability that both of these parameters are not significantly different from the light to the dark is 0.05.

Condition	Initial Rate of $O_2$ Consumption	Net $O_2$ Consumption
	$\mu$ mol $O_2$ $mg^{-1}$ chlorophyll $hr^{-1}$	$\mu$ mol $mg^{-1}$ chlorophyll
Light	$260 \pm 4$	$3.8 \pm 0.03$
Dark	$210 \pm 4$	$2.4 \pm 0.16$



cryptogin to tobacco cells results in an oxidation of NADPH, which triggers activation of the pentose phosphate pathway, providing NADPH for a plasma membrane NADPH oxidase. These events are essential for the HR; inhibition of the pentose phosphate pathway in turn inhibits the oxidative burst, external alkalization, and cytoplasmic acidification (Pugin et al., 1997). The depletion of reducing power may in fact lead to the death of the cells.

In response to the questions posed in this study, we have drawn the following conclusions: (a) MP induces the HR, (b) light stimulates the MP-induced oxidative burst, and (c) MP ultimately inhibits photosynthesis.

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