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Cellular responses to naphthoquinones: juglone as a case study

M. Rudnicka · M. Polak · W. Karcz

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Abstract The effects of juglone (JG) on the endogenous growth, growth in the presence of either indoleacetic acid (IAA) or fusicoccin (FC) and on proton extrusion were studied in maize coleoptile segments. In addition, membrane potential changes were also determined at chosen JG concentrations. It was found that JG, when added to the incubation medium, inhibited endogenous growth as well as growth in the presence of either IAA or FC. Simultaneous measurements of growth and external pH indicated that inhibition of either IAA-induced growth or proton extrusion by JG was a linear function of JG concentration. Addition of JG to the control medium caused depolarization of the membrane potential (E_m), value of which was dependent on JG concentration and time after its administration. Hyperpolarization of E_m induced by IAA was suppressed in the presence of JG. It was also found that for coleoptile segments initially preincubated with JG, although subsequently removed, addition of IAA was not effective in the stimulation of growth and medium acidification. Taken together, these results suggest that the mechanism by which JG inhibits the IAA-induced growth of maize coleoptile segments involves inhibition of PM H^+ -ATPase activity.

Keywords Juglone · *Zea mays* · Coleoptile segments · Growth rate · Proton extrusion · Membrane potential

Introduction

Naturally occurring naphthoquinones, such as juglone (JG) (5-hydroxy-1,4-naphthoquinone), lawsone (2-hydroxy-1,4-naphthoquinone), plumbagin (2-methyl-5-hydroxy-1,4-naphthoquinone) and others, have been studied for a long time due to their importance in medicinal and biological research (O'Brien 1991; Jose 2002; Dayan and Duke 2009). JG is an amber-colored compound isolated from leaves, roots, husks and bark of plants of the Juglandaceae family, particularly black walnut (*Juglans nigra*). JG and related quinones are referred to as allelochemicals. In agreement with the definition recently proposed by Dayan and Duke (2009), the word allelochemical means a phytotoxin that may negatively influence vegetation in the vicinity of the producing plant. The allelopathic effect of JG on plants is generally toxic, although in some cases it may be also beneficial (Rizvi and Rizvi 1992; Chobot and Hadacek 2009). The toxic effect of JG has been intensively studied in maize (*Zea mays* L.) and soybean (*Glycine max* L. Merr). It has been shown in these studies that JG may inhibit the growth of both shoots and roots (Jose and Gillespie 1998; Hejl and Koster 2004; Böhm et al. 2006; Sytykiewicz 2011), photosynthesis (Hejl et al. 1993; Jose and Gillespie 1998), respiration (Jose and Gillespie 1998; Hejl and Koster 2004), transpiration (Jose and Gillespie 1998), and stomatal conductance (Jose and Gillespie 1998). In spite of the large number of papers published on the biological activity of JG (for review see Jose 2002; Dayan and Duke 2009), little is

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known about the mechanism of its toxic effect on plant cells growth.

The main objective of the present study was to determine the effect of JG on IAA-induced growth in maize coleoptile segments. In agreement with the so called “acid growth hypothesis”, auxin causes acidification of cell wall via stimulation of the plasma membrane H^+ -ATPase that pumps protons into the cell wall and lowers its pH (Rayle and Cleland 1970, 1992; Hager et al. 1971, 1991). In turn, a lower pH either directly lowers the yield threshold of the wall or optimizes the activity of cell wall-localized proteins that loosen the wall (for review see Hager 2003). Both processes provide favorable conditions for cell elongation. Activation of the proton pump by auxin also causes hyperpolarization of the membrane potential and activation of voltage-dependent, inwardly rectifying K^+ channels, activity of which contributes to water uptake necessary for cell expansion (Cleland et al. 1977; Keller and Van Volkenburgh 1996; Philippar et al. 1999; Becker and Hedrich 2002; Karcz and Burdach 2002, 2007).

It should be added that segments excised from coleoptiles of grasses represent a classical model system for studies on the elongation growth of plant cells. In this system the number of cells is constant and organ grows by elongation only. Moreover, most of crucial evidence on the mechanisms of auxin action in plant cell growth was obtained from maize coleoptile segments. To the best of our knowledge, no research has been reported on the effects of JG on IAA-induced growth in coleoptile cells.

Materials and methods

Plant material

Seeds of maize (*Z. mays* L. cv. KOKA) were soaked in tap water for 2 h, sown on wet lignin in plastic boxes, and placed in a growth chamber (Type MIR—533, Sanyo Electric Co., Japan) at 27 ± 1 °C. The experiments were performed with 10 mm-long coleoptile segments cut from 96 h old etiolated maize seedlings. Intact coleoptile segments, with the first leaves removed, were excised 3 mm below the tip and collected in an incubation medium of the following composition (control medium): 1 mM KCl, 0.1 mM NaCl, 0.1 mM $CaCl_2$, initial pH 5.7–6.0.

Chemicals

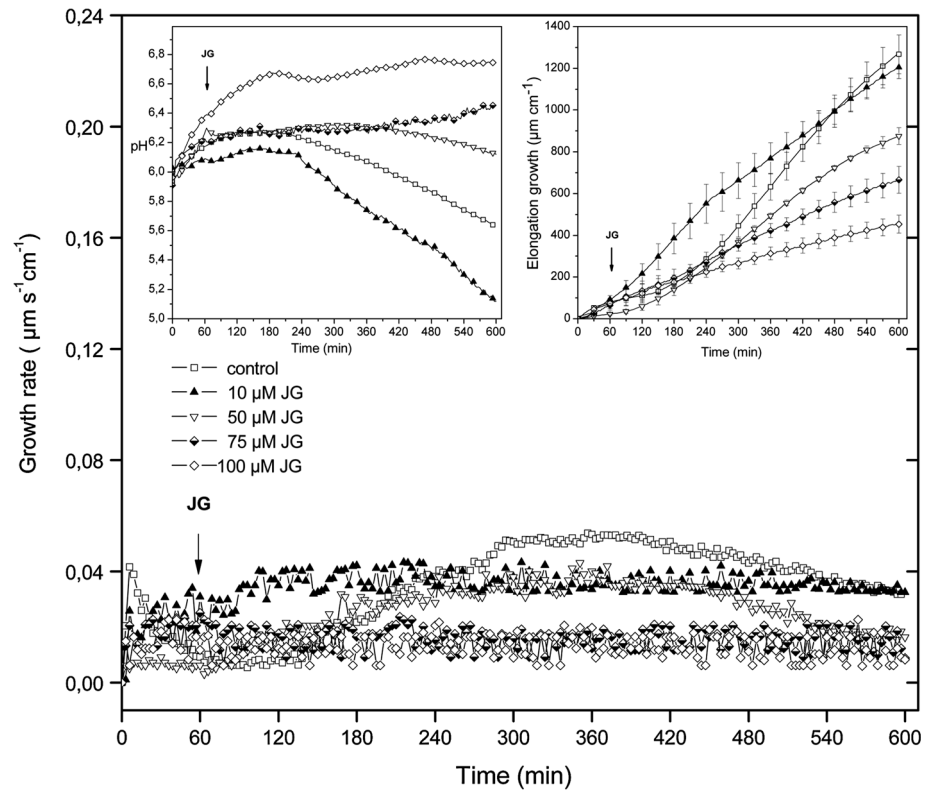
Juglone (5-hydroxy-1,4-naphthoquinone) was obtained from Sigma Aldrich Inc. (St. Louis, MO, USA). The tested concentrations of JG were prepared by dissolving the allelochemical in distilled water. A 10^{-3} M stock solution is at the limit of JG water solubility (Neave and Dawson 1989).

Indole-3-acetic acid (IAA) (Serva, Heidelberg, Germany) was used as a potassium salt, since it could be rapidly dissolved in water. IAA was used at 100 μ M. This concentration is optimal for parameters measured for over 10 h in our elongation and pH-measuring apparatus (Polak 2010). For comparison, IAA at 10 μ M is optimal for both parameters at the same experimental conditions (e.g. number of coleoptiles per medium volume and composition of the incubation medium), however in short-term recordings (Karcz et al. 1990). Fusicoccin (FC) (Sigma, USA) was dissolved in ethanol and added to the incubation medium at a final concentration of 1 μ M. The maximal ethanol concentration of 0.2 % did not affect the growth of coleoptile segments (data not shown).

Growth and pH measurements

Growth experiments with coleoptile segments were carried out in an apparatus that allowed simultaneous measurements of elongation growth and pH of the incubation medium from the same tissue sample (Polak et al. 2012). A somewhat similar procedure for measuring elongation growth of maize coleoptile segments and pH changes of their incubation medium was described previously (Karcz et al. 1990; Karcz and Burdach 2002). Briefly, 60 coleoptile segments were arranged vertically in the apparatus, in three narrow glass pipettes (20 segments in each), connected by means of a silicon hose (Polak et al. 2012, Fig. 1). High-resolution measurements of growth rate were performed with an angular position transducer (TWK Electronic, Düsseldorf, Germany), what resulted in a precise record of the growth kinetics. Coleoptile segments were incubated in an intensively aerated medium. Volume of the incubation medium in the elongation and pH-measuring apparatus amounted to 18 ml ($0.3 \text{ ml segment}^{-1}$). The incubation medium also flowed through the lumen of coleoptile cylinders. This feature permitted experimental solutions to be in direct contact with the interior of segments, what significantly enhanced both elongation growth of coleoptile segments and proton extrusion (Karcz et al. 1995). This experimental set-up enabled avoidance of coleoptile abrasion (Dreyer et al. 1981) that inhibits (c. 30 %) elongation growth (Lüthen et al. 1990; Karcz et al. 1995). Medium circulation was driven by a peristaltic pump (1B-05A; Zalimp, Poland). Extension growth of a stack of 20 segments and pH of the incubation medium were sampled every 3 min by a multi-functional computer meter (CX-771; Elmetron, Poland). pH measurements were performed with a pH electrode (OSH 10-10; Metron, Poland). Temperature of all solutions in the elongation and pH-measuring system was thermostatically controlled at a level of 25 ± 0.5 °C. All manipulations and growth measurements were carried out under dim green light.

Fig. 1 Effect of juglone (JG) on the endogenous growth (growth in a medium without growth substances) of maize coleoptile segments. The growth of a stack of 20 segments was measured as described in section “Materials and methods”. Coleoptile segments were first preincubated (over 1 h) in a control medium, whereupon juglone was added. *Inset on the right side* shows the total elongation growth, calculated as the sum of extensions measured at 3-min intervals over 10 h, while *inset on the left* shows the effect of juglone on the pH of medium (with maize coleoptile segments), measured simultaneously with growth. The data presented are means of at least seven independent experiments. Bars indicate means \pm SEs



Electrophysiology

Electrophysiological experiments were performed on coleoptile segments prepared in the same manner as for growth experiments. A standard electrophysiological technique was used for membrane potential measurements, as previously described (Karcz and Burdach 2002; Kurtyka et al. 2011). Briefly, membrane potential (E_m) was measured by recording the voltage between a 3 M KCl-filled glass micropipette inserted into the parenchymal cells and a reference electrode in the bathing medium of the same composition as used in growth experiments. For electrophysiological experiments, the segments were preincubated for 1 h in an intensively aerated bathing medium, whereupon the segments were transferred into a perfusion Plexiglass chamber mounted on a vertically placed microscope stage. Changes of medium were provided by a peristaltic pump (Type Peri-Star PRO; World Precision Instruments, USA) that allowed for changing the bathing medium in the chamber (usually four times within less than 2 min). Microelectrodes were inserted into the cells under a microscope by means of a micromanipulator (Hugo Sach Elektronik; March-Hugsteten, Germany). Micropipettes were prepared as previously described by Karcz and Burdach (2002) and Kurtyka et al. (2011).

Statistical analysis

Data were analyzed with the Statistica computer software for Windows (StatSoft 2008, STATISTICA data

analysis software system, version 8.0 <http://www.statsoft.com>, USA).

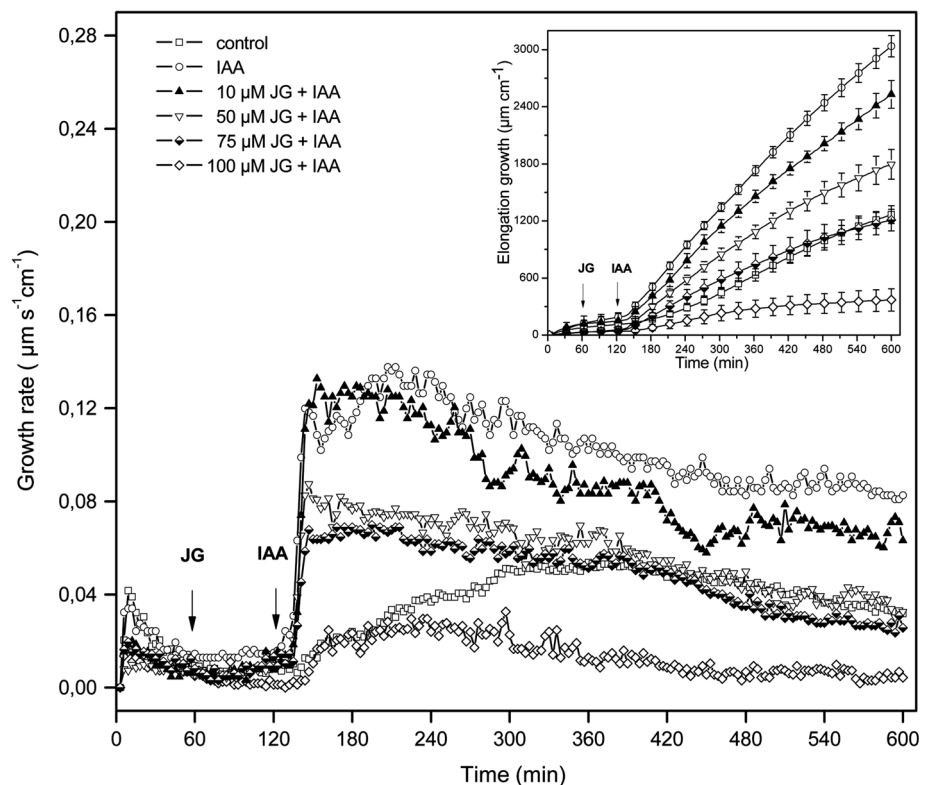
Results

Effect of juglone (JG) on the endogenous growth, growth in the presence of IAA, and medium pH measured simultaneously with growth

Addition of JG to the incubation medium inhibited, in a concentration-dependent manner, the endogenous growth (growth in a medium without growth substances) of maize coleoptile segments (Fig. 1). In the presence of 10 μ M JG, stimulation of endogenous growth was observed within the first 5 h. Measurements of the medium pH, taken simultaneously with the growth of maize coleoptile segments (Fig. 1, inset on the left), indicated that at concentrations of 75 and 100 μ M JG caused alkalization of the incubation medium, whereas at 10 μ M stimulated medium acidification, as compared to the control. At 50 μ M, after an initial transient alkalization of the incubation medium, JG induced a slow decrease of medium pH.

As can be seen in Fig. 2, auxin added to the control medium (after 2 h of preincubation) with maize coleoptile segments induced their strong growth rate, kinetics of which could be divided into two phases (biphasic reaction). The first phase, very rapid, was followed by a long-lasting

Fig. 2 Effect of juglone (JG) on the growth rate ($\mu\text{m s}^{-1}\text{cm}^{-1}$) of maize coleoptile segments incubated in the presence of IAA ($100\ \mu\text{M}$). The growth rate of a stack of 20 segments was measured as described in section “Materials and methods”. Coleoptile segments were first preincubated (over 1 h) in a control medium, whereupon juglone was added. IAA was added to the incubation medium at 2 h. *Inset on the right side* shows the total elongation growth, calculated as the sum of extensions measured at 3-min intervals over 10 h. All curves are means of at least 9 independent experiments. *Bars* indicate means \pm SEs



one which began about 30 min after auxin addition. Administration of JG (after 1 h incubation of coleoptile segments in a control medium) inhibited the growth of coleoptile segments. JG at $10\ \mu\text{M}$ diminished the second (long-lasting) phase of IAA-induced growth, while at concentrations of 50 and $75\ \mu\text{M}$ proportionally reduced both phases (Fig. 2). In turn, JG at the highest concentration ($100\ \mu\text{M}$) abolished the first and second phase of IAA-induced growth. On the basis of growth rate responses shown in Fig. 2, the total elongation growth over 10 h, calculated as the sum of extensions from 3-min interval measurements (see section “Materials and methods”), was obtained (Fig. 2, inset). Taking these data into account, it should be stated that JG, in a concentration-dependent manner, inhibited IAA-induced elongation growth of maize coleoptile segments.

Simultaneous measurements of growth and external medium pH (Fig. 3, inset on the left) indicated that coleoptile segments incubated in the control medium characteristically changed the pH of the external medium. Generally, within the first 2 h a pH increase to 6.0–6.5 was observed, followed by a slow decrease to pH of approximately 5.6–5.7 after 10 h. When IAA was added to the control medium (after 2 h of preincubation), an additional decrease in pH to 4.8 was recorded. However, when JG ($100\ \mu\text{M}$) and IAA were added at 1 and 2 h, respectively, pH displayed an initial transient decrease followed by a slow increase (to ca. 6.2). At $10\ \mu\text{M}$, JG only slightly

inhibited IAA-induced medium acidification (Fig. 3, inset on the left side). In order to present pH changes in the medium much more suggestively, they have been shown as changes of H^+ concentration per coleoptile segment ($[\text{H}^+] \text{cm}^{-1}$) (Fig. 3). As indicated in Fig. 3, JG diminished, in a concentration-dependent manner, IAA-induced proton extrusion, similarly as in case of growth (see also the inset on the right in Fig. 3).

Figure 4 shows interdependences between the effects of JG on the IAA-induced growth and medium pH measured simultaneously with growth. These data indicate that inhibition of either IAA-induced growth or proton extrusion by JG is a linear function of JG concentration. The linear regression fit of both magnitudes delivers a similar (negative) slope. Taking the above into account, it may be deduced that proton extrusion and elongation growth are strongly correlated with JG concentration.

For comparison, the effect of JG at $100\ \mu\text{M}$ on FC-induced growth and medium pH has also been shown. This fungal toxin is known to enhance H^+ -ATPase activity, through phosphorylation of the penultimate Thr, as well as to induce elongation growth (Marrè 1979; Kinoshita and Shimazaki 2001). FC added to incubation medium in the same way as IAA, at a final concentration of $1\ \mu\text{M}$, enhanced endogenous growth of maize coleoptile segments to the level comparable with the growth seen in the presence of IAA (Fig. 5). As indicated in Fig. 5, FC added at 2 h was much more effective in acidifying of the medium, as compared to IAA. For FC, 8 h

Fig. 3 Effect of juglone (JG) on the pH of medium with maize coleoptile segments incubated in the presence of IAA (*inset on the left side*). To avoid illegibility, only chosen curves have been shown in the *inset*. Medium pH changes observed in the presence of all studied juglone concentrations were expressed as changes of H⁺ concentration per coleoptile segment ([H⁺] cm⁻¹) and showed below the figure. The *inset on the right side* shows H⁺ concentration per coleoptile segment at 600 min. Auxin and JG were added to the incubation medium at the same time protocol as described for growth experiments showed in Fig. 1. pH values are means of seven independent experiments, performed simultaneously for growth on the same tissue sample (as described in section “Materials and methods”). Bars indicate means ± SEs

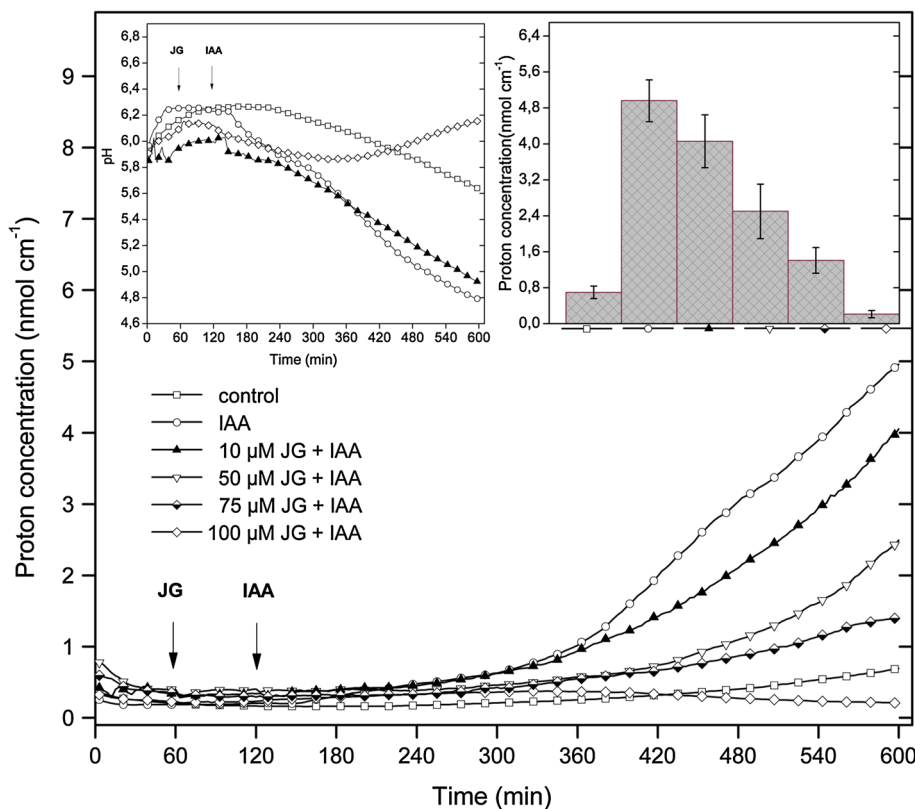
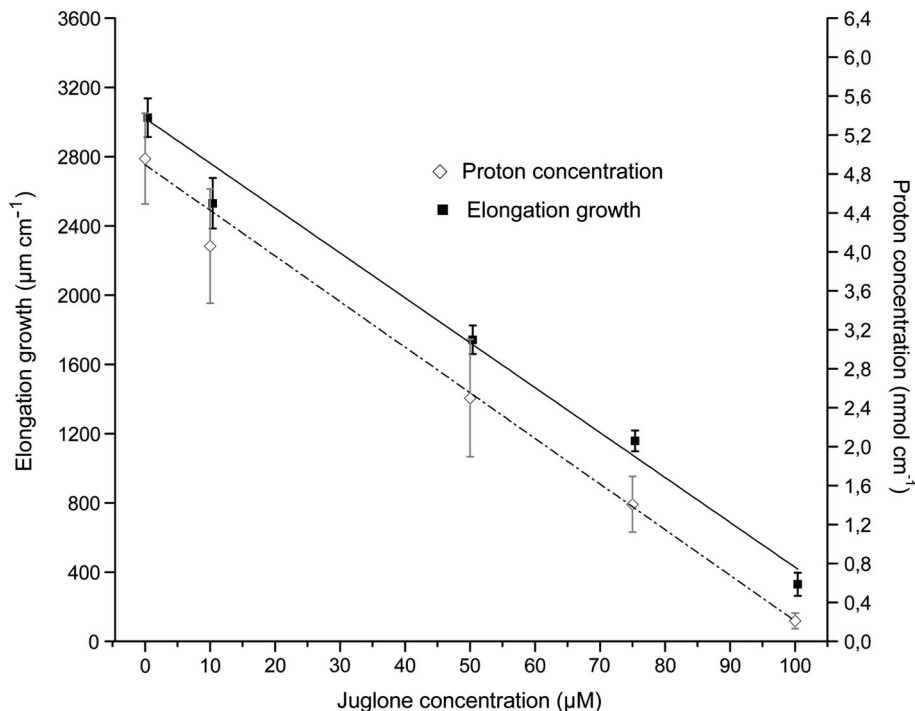


Fig. 4 Interdependences between the effects of juglone on IAA-induced growth and medium pH measured simultaneously with growth. Data presented in this figure are the same as showed in Figs. 1, and 2 at 600 min. Bars indicate means ± SEs



after its addition, pH of the incubation medium dropped to approximately 3.6, whereas for IAA pH attained only 4.8. It has also been found that FC is much more effective than IAA in stimulating the elongation growth of maize coleoptile

segments which were previously incubated in the presence of JG. For example, JG applied to the medium (after 1 h of preincubation) at a concentration of 100 μM decreased the growth of coleoptile segments incubated in the presence of

Fig. 5 Effect of juglone (JG) on the growth rate ($\mu\text{m s}^{-1}\text{cm}^{-1}$) of maize coleoptile segments incubated in the presence of FC ($1\ \mu\text{M}$). The growth rate of a stack of 20 segments was measured as described in section “Materials and methods”. Coleoptile segments were first preincubated (over 1 h) in a control medium, whereupon juglone ($100\ \mu\text{M}$) was added. FC was added to the incubation medium at 2 h. *Inset on the right side* shows the total elongation growth, calculated as the sum of extensions measured at 3-min intervals over 10 h, while *inset on the left* shows the effect of juglone ($100\ \mu\text{M}$) on the pH of medium (with maize coleoptile segments), measured simultaneously with growth. The data presented are means of at least eight independent experiments. Bars indicate means \pm SEs

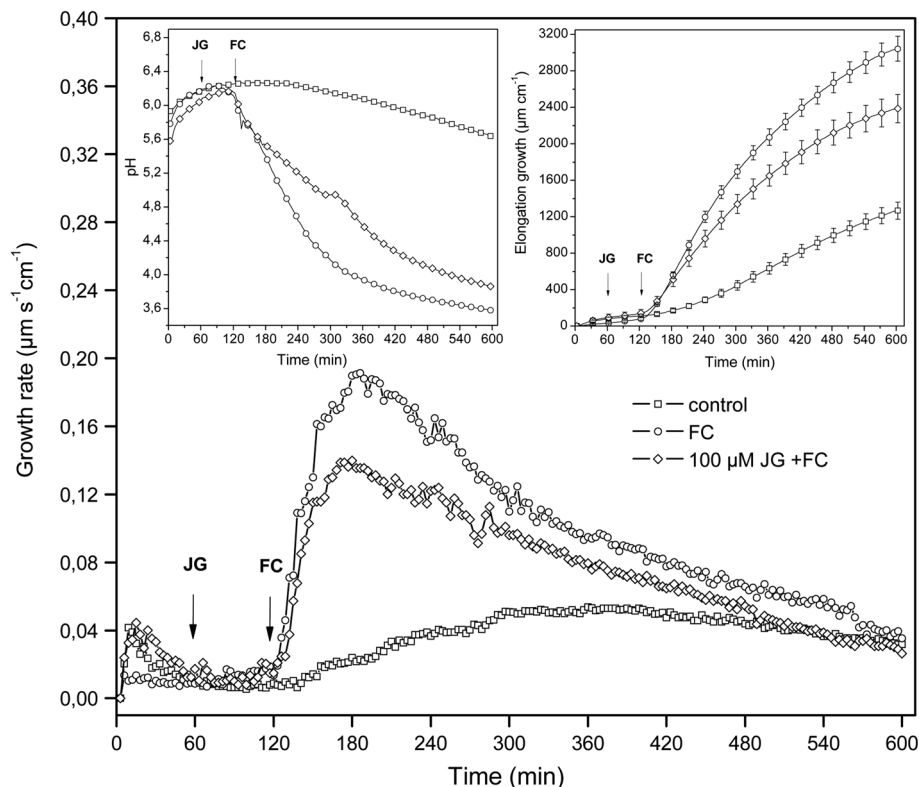
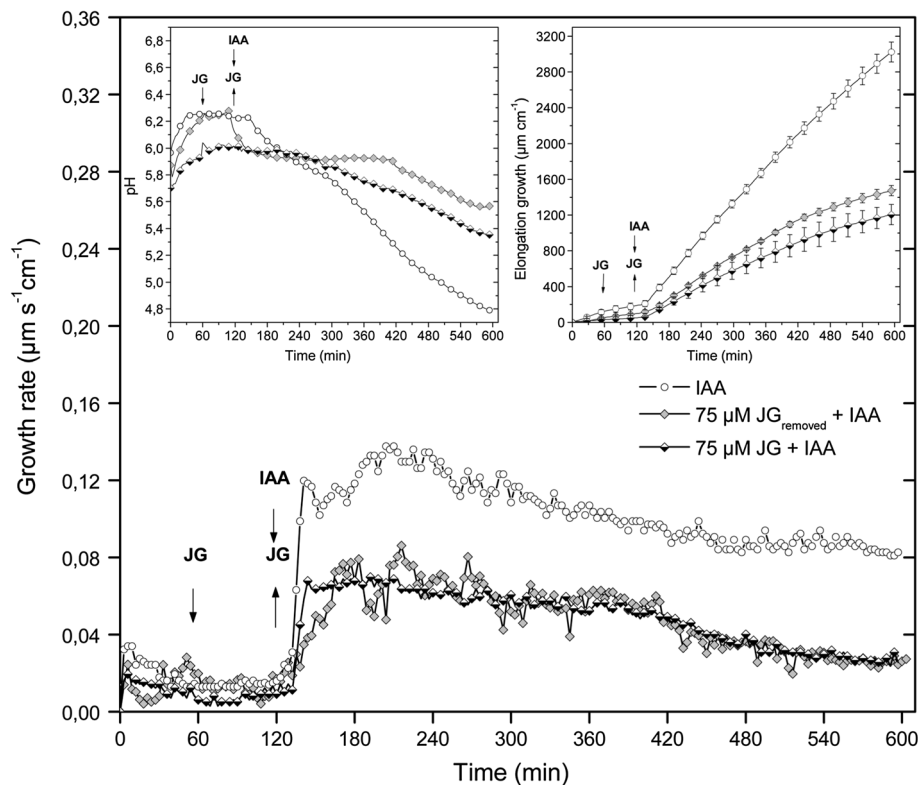


Fig. 6 Simultaneous measurements of the growth rate and the medium pH (*inset on the left*) of maize coleoptile segments. Segments were first treated with JG for over 1 h, whereupon the medium was changed into the control one, additionally containing IAA. *Inset on the left side* shows IAA-induced elongation growth, calculated as the sum of extensions measured at 3-min intervals over 10 h. *Downward arrows* indicate addition of substances and *upward arrows* their removal. All curves are means of at least six independent experiments. Bars indicate means \pm SEs



IAA by 90 %, while in the presence of FC only by 20 %. pH of the incubation medium recorded after 10 h in the presence of JG ($100\ \mu\text{M}$) and FC was approximately by 0.3 pH unit

higher than for FC alone (Fig. 5). However, in the case of IAA, JG at $100\ \mu\text{M}$ abolished IAA-induced proton extrusion, causing alkalization of the incubation medium.

Table 1 E_m changes in parenchymal coleoptile cells with addition of juglone (JG), indole-3-acetic acid (IAA) and JG together with IAA. At time 0, the control medium was changed for a new one, of the same salt composition, containing JG, IAA or JG with IAA

Treatments	E_m (mV)			
	E_m after stabilization in control medium (time 0)	E_m after 20 min	E_m after 40 min	E_m after 60 min
50 μ M JG	-107.9 ± 4.3	-109.4 ± 5.1	-102.1 ± 4.6	-106.2 ± 6.1
75 μ M JG	-108.6 ± 5.7	-110.2 ± 6.1	-97.9 ± 4.1	-98.2 ± 5.7
100 μ M JG	-110.6 ± 4.8	-67.3 ± 3.5	-57.4 ± 5.1	-55.6 ± 4.8
100 μ M IAA	-111.7 ± 5.3	-117.5 ± 6.7	-124.8 ± 4.8	-126.2 ± 5.2
75 μ M JG +IAA	-99.7 ± 4.1	-98.6 ± 3.8	-95.5 ± 5.1	-92.1 ± 4.3

In the case of adding JG together with IAA, coleoptile segments were first preincubated for over 1 h in the presence of juglone, whereupon E_m was measured. Data are means of at least eight independent experiments. Error indicates \pm SE

The inhibitory effect of juglone is irreversible

If coleoptile segments were first incubated for 1 h (between 1 and 2 h) with JG and subsequently JG was removed, addition of IAA at 2 h was not effective in the stimulation of growth and medium acidification (Fig. 6).

Effect of juglone on the membrane potential (E_m)

Addition of JG to the control medium caused depolarization of the E_m , value of which was dependent on JG concentration and time after its administration (Table 1). For example, treatment of parenchymal cells from maize coleoptile segments with 75 or 100 μ M JG caused depolarization of the E_m by 10 and 55 mV, respectively. In turn, addition of IAA to the control medium caused, after over 1 h, hyperpolarization of the E_m by 14.5 mV (from -111.7 ± 5.3 to -126.2 ± 5.2 mV). For coleoptile segments initially preincubated with JG at 75 μ M ($E_m = -99.7 \pm 4.1$ mV), for 1 h, and subsequently kept in a bathing medium changed for JG with IAA, a suppression of IAA-induced hyperpolarization of E_m was observed. Interestingly, JG at 75 μ M not only suppressed IAA-induced hyperpolarization of the E_m but also caused an additional membrane depolarization (Table 1).

Discussion

Despite the availability of extensive research on JG toxicity, our knowledge on the effect of this allelochemical on plant growth is still limited. The main goal of this work was to determine the mechanisms by which JG inhibits IAA-induced growth of maize coleoptile segments. In the study, we selected three response parameters concerning auxin action: elongation growth, proton extrusion and membrane potential. Interdependences between these parameters provided basis for the “acid growth hypothesis” of auxin action.

Data presented in this paper, showing that IAA causes (1) acceleration of elongation growth, as compared to growth in control (Fig. 2), (2) enhancement of proton extrusion, as compared to IAA-free medium (Fig. 3), and (3) hyperpolarization of the membrane potential (Table 1), are in good agreement with results obtained by other investigators (Cleland et al. 1977; Kutschera and Schopfer 1985; Felle et al. 1991; Lüthen et al. 1990; Rucke et al. 1993; Keller and Van Volkenburgh 1996; Karcz and Burdach 2002, 2007; Kurtyka et al. 2011). There is no doubt that plasma membrane hyperpolarization observed in the presence of IAA is a consequence of stimulated proton extrusion through H^+ -ATPase (Cleland et al. 1977; Lohse and Hedrich 1992; Rucke et al. 1993; Hedrich et al. 1995).

Simultaneous measurements of elongation growth and medium pH showed that in maize coleoptile segments JG inhibited both IAA-induced growth (Fig. 2) and proton extrusion (Fig. 3) in a concentration-dependent manner. The linear regression fit of both magnitudes delivered a similar (negative) slope, suggesting that growth and proton concentration are strongly correlated with JG concentration (Fig. 4). This finding is in good agreement with the “acid growth hypothesis” of auxin action (for review see Hager 2003) and clearly indicates that changes in IAA-induced growth of maize coleoptile cells observed in the presence of JG are mediated via PM H^+ -ATPase activity. This suggestion is also supported by two facts: first, that the FC-induced growth and proton extrusion (Fig. 5), attributed to PM H^+ -ATPase activity (Marrè 1979), were also diminished in the presence of JG, and second that JG depolarized and abolished the IAA-induced hyperpolarization of the E_m (Table 1). In contrast to IAA, FC was much more effective in stimulating both the growth and medium acidification of maize coleoptile segments treated with JG. This observation probably results from the fact that IAA and FC differ in their signal transduction pathway (Hager 2003). At least in maize coleoptile cells, auxin-induced medium acidification is

mediated by an increased activity and/or amount of PM H⁺-ATPase, while FC stimulates only proton extrusion by the increased PM H⁺-ATPase activity (Hager et al. 1991; Frias et al. 1996; Philippar et al. 1999). Interestingly, it has been only recently shown (Takahashi et al. 2012) that application of IAA to endogenous auxin-depleted hypocotyl sections of *Arabidopsis* seedlings induced phosphorylation of the penultimate threonine of H⁺-ATPase and increased H⁺-ATPase activity without altering the amount of enzyme. In addition, these authors also showed that an auxin antagonist specific for the nuclear receptor TIR1/AFBs had no effect on the IAA-induced H⁺-ATPase phosphorylation.

What would be the mechanism by which JG inhibits IAA-induced growth of maize coleoptile cells? Evidently, inhibition of PM H⁺-ATPase activity by JG plays a key role in this phenomenon. In addition, our data, showing that JG depolarized the E_m and abolished the IAA-induced plasma membrane hyperpolarization, might suggest that voltage-dependent, inwardly rectifying K⁺ channels play a role in growth regulation of maize coleoptile cells incubated with JG. Interestingly, in patch-clamp experiments, Varga et al. (1996) observed that voltage-gated K⁺ channels in human lymphocytes were sensitive to externally applied JG with a half blocking concentration of approximately 57 μM. Blocking of K⁺ channels by JG was in concert with its depolarizing effect on human lymphocytes. Taking into account the above remarks, Varga et al. (1996) suggested that the reduced K⁺ channel activity reported in the presence of JG may also be responsible for its cell growth inhibiting effect. It should be also added that voltage-gated K⁺ channels involved in IAA-induced growth of maize coleoptile cells and K⁺ channels identified in human lymphocytes belong to the same family of voltage-gated (Shaker-like) K⁺ channels (reviewed in Dreyer and Uozumi 2011).

Considering the mechanisms by which naphthoquinones may inhibit the PM H⁺-ATPase activity, two major types of reaction should be taken into account (Rossi et al. 1986; Brunmark and Cadenas 1989; Öllinger and Brunmark 1991). The first is a direct interaction between the enzyme and quinone which leads to covalent modification of protein thiols and generation of thioethers (arylation process). The next mechanism is the capacity of quinone to produce reactive oxygen species (ROS), via redox cycling, and interaction with nucleophilic biomolecules, such as protein thiols or glutathione. It should be added that ROS were identified as an activator of Ca²⁺ influx channels which could be responsible for membrane potential depolarization (Schroeder et al. 2001). Interestingly, both mechanisms are associated with inhibition of jack bean urease activity by JG (Kot et al. 2010). Another possibility is that JG, being a strong electron acceptor, may inhibit plasma membrane

redox systems, which, in plant cells, are involved in elongation growth, proton release and plasma membrane depolarization (for review see Lühje et al. 1997). Moreover, it was also shown that auxin and FC modify plasma membrane redox activity (Lüthen and Böttger 1993; Le-kacz and Karcz 2006).

The inhibitory effect of JG on the growth of maize coleoptile segments incubated in the presence of IAA may also result from the reduced rate of degradation of AUX/IAA proteins (family of transcriptional regulators) due to their inhibited interaction with the SCF-TIR1 complex. Isomerization of prolines in domain II AUX/IAA, essential for the proper recognition of AUX/IAA by the SCF-TIR1 complex, is carried out by an enzyme of the PPIs family, parvulin. JG is known as a specific inhibitor of parvulin, interacting only with the PPIs subfamily (Hennig et al. 1998; Dharmasiri et al. 2003; Tian et al. 2003; Kepinski and Leyser 2004). Another possible explanation for the inhibitory effect of JG on the growth of maize coleoptile segments is its interaction at the level of gene transcription. JG may have the ability to inhibit RNA polymerase II, I and III within an interaction with thiol groups of cysteines of the conserved regions in all three polymerases (Chao et al. 2001).

Taking the above into account, it may be suggested that the inhibitory effect of JG results from two independent pathways; the first one associated with inhibition of PM H⁺-ATPase and second linked to system operating via the E3 ubiquitin-ligase complex SCF^{TIR1/AFB}, which includes TIR1/AFBs. These two pathways may reflect the effect of JG on the “fast” and “slow” phase of IAA-induced growth rate in maize coleoptile segments, respectively.

The herein presented results are generally in agreement with data obtained by Hejl and Koster (2004), who showed that JG inhibited H⁺-ATPase activity in corn and soybean root microsomal fractions. They also found that corn and soybean seedlings grown in a nutrient solution amended with 10, 50 or 100 μM JG (the same concentrations were also used in our experiments) showed a significant decrease in root and shoot dry weights and lengths. Interestingly, Hejl and Koster (2004) also observed that JG diminished the ability of roots to extrude protons and uptake water.

In conclusion, results presented in this article demonstrate that the mechanism by which JG inhibits the IAA-induced growth of maize coleoptile segments involves inhibition of PM H⁺-ATPase activity. This suggestion is supported by three lines of evidence: (1) inhibition of either IAA-induced growth or proton extrusion by JG is a linear function of JG concentration (Fig. 4); (2) JG added together with IAA suppresses the IAA-induced hyperpolarization of the E_m (Table 1); (3) FC-induced growth and proton extrusion are diminished in the presence of JG (Fig. 5).

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