Studies on Acidification of Media by *Avena* Stem Segments in the Presence and Absence of Gibberellic Acid

Received for publication April 20, 1976 and in revised form July 12, 1976

FREDERICK V. HEBARD, STEVEN J. AMATANGELO, P. DAYANANDAN, AND PETER B. KAUFMAN

Department of Botany, Division of Biological Sciences, University of Michigan, Ann Arbor, Michigan 48109

**ABSTRACT**

The rate of acidification of media by *Avena* stem segments was studied with a titrimeter. GA$_3$, increased this rate by an average of 17% if supplied to the segments 90 min prior to measurement. GA$_3$ inhibited the rate by 15% if supplied 10 min prior to measurement. After 90 min incubation, stimulation of elongation had started; at 10 min, GA$_3$ had not yet started to stimulate elongation in the segments.

The acidification rates of the nodes (including the sheath-pulviscum), leaf sheath bases, and the internode bases of the stem segments were determined for plus and minus GA$_3$-treated segments. The internode fraction contributes most to modification of the acidification rate, the node-pulviscum fraction less so, and the nongrowing sheath not at all.

Acidification rates were measured for segments in different stages of elongation (lag, log, and plateau phases of growth). Segments in these growth stages were obtained from intact plants and from segments preincubated in sucrose and sucrose + GA$_3$. Segments from all sources which are in the log phase of growth have the highest rates, those in the plateau phase the lowest. For lag and log growth phases, segments preincubated in sucrose + GA$_3$ show the highest rates, those preincubated in sucrose the lowest rates. The opposite occurs for segments in the plateau phase of growth.

Segments stimulated to grow by GA$_3$ cause the pH of their incubation media to drop to pH 5.15 from an initial pH of 6.5. Nonstimulated segments cause a drop to pH 5.6. Long-term growth of the segments is maximal in media buffered to pH 5 in the presence and absence of GA$_3$.

Our results support the idea that GA$_3$ stimulates an active acidification process in *Avena* stem segments just after GA$_3$ starts to stimulate growth in the segments, and that such an acidification process could play an important role in wall-loosening during active growth of the internode.

Very little information is available on the effects of gibberellins (GAs) on hydrogen ion efflux, or any other acidification process during the relatively short times just before and after GA begins to stimulate growth in *Avena* stem segments. In this paper, we report on acidification induced in the medium by *Avena* stem segments in the presence and absence of gibberellic acid (GA$_3$).

**MATERIALS AND METHODS**

Preparation and Incubation of Stem Segments for Growth and Titrimeter Experiments. For the growth experiments 2-cm stem segments, containing next-to-last internodes (p-l) were excised from *Avena* shoots according to methods cited in Kaufman (10) and Montague et al. (14). These segments include the basal node, the intercalary meristem portion of p-l, and the surrounding sheath base. The segments were thoroughly washed with three to four changes of sterile distilled H$_2$O. They were grown horizontally in Petri dishes (100 × 15 mm) on filter paper saturated with 6 ml of incubation medium. Sucrose (0.1 M) served as the control medium; 0.1 M sucrose plus 30 μM GA$_3$ was used for the hormone treatment. All cultures were incubated in the dark at 30 C. Growth was measured to the nearest 0.5 mm. All experiments were repeated at least five times.

In the pH experiments, our standard buffers were 50 M citrate for pH 3 and 4 and 50 M citrate phosphate for pH 5 to 8. Potassium phosphate and acetate buffers were also tested to assess any nutrient effect from the citrate and citrate phosphate buffers. The pH of the medium in each experiment was checked at the end of the experiment with a pH meter and found not to change.

Except for experiments testing the effects of abrasion and cutting, we did not abrade or strip the epidermis. This is often done with *Avena* coleoptile and pea stem segments in order to obtain an acidification response, but is unnecessary with *Avena* stem segments, which have a cuticle $1/10$ as thick as that in coleoptiles and pea stems.

**Determination of Acidification Rates.** The rate of acidification of the incubation media was assayed with a Fisher automatic titrimeter model no. 36 equipped with a glass Ag-AgCl combination electrode. The titrimeter was modified to dispense base in amounts of 0.005 ml/increment. A 0.20-ml pipette, fitted with a three-way stopcock for refilling, was used to measure the volume of 20 mM NaOH added to the titrimeter reservoir (a 100-ml beaker). The temperature of the reservoir was maintained at 30 C by a water jacket. The medium (50 ml of 0.1 M sucrose or 0.1 M sucrose plus 30 μM GA$_3$) was mixed by a glass stirring rod spinning at approximately 250 rpm. After the pH of the medium was adjusted to 6.5, 50 *Avena* stem segments, or fractions thereof, were routinely transferred to the reservoir. The pH was then automatically maintained by the titrimeter. The amount of NaOH added to maintain constant pH was plotted every 15 sec over 20-min periods. The slope of the recorded curve is a

---

Evans (6), Cleland and Rayle (5), and Marrè et al. (12) have shown that IAA causes a significant increase in proton efflux from *Avena* coleoptile and *Pisum* epicotyl sections. Evans and Schmitt (7) have indicated that such hydrogen ion efflux can also be evoked in oat coleoptile sections by cutting them. These investigators have suggested that IAA-stimulated proton efflux could play a significant role in the initiation of hormone-promoted growth. In contrast to these systems, Fisher and Albersheim (8) report that in sycamore (*Acer pseudoplatanus*) cell suspension cultures, IAA does not stimulate hydrogen ion efflux from the cells.

1 This research was supported by National Science Foundation Grant BMS 75-16359.

2 Present address: Department of Plant Pathology and Physiology, Virginia Polytechnic Institute and State University, Blacksburg, Va. 24061.

3 To whom reprint requests should be addressed.
measure of the rate of acidification of the medium caused by the stem segments or their parts.

**pH Drop Experiments.** The same apparatus was employed for determining to what pH the segments caused the media to drop from an initial pH of 6.5. However, no base (NaOH) was added. pH was recorded on a 25-cm strip chart recorder adjusted to show full scale deflection for a change of 2 pH units. All pH and titrimeter experiments were repeated at least three times.

Gibberellic acid was a gift of Imperial Chemical Industries, Ltd., England. "Victory" oat seed was obtained from Svenska Utsades, A. B., Svalöf, Sweden.

**RESULTS**

**Long Term Growth Responses of Avena Stem Segments at Different pHs.** Since the cell wall of Avena stem segments is plasticized by gibberellin treatment (3), it was of interest to test the idea that gibberellin-promoted growth is favored by low pH, and the possibility that low pH will mimic the GA₃ growth response.

Figure 1, A and B illustrates typical growth responses of Avena stem segments at pH values ranging between 3 and 8 in the presence and absence of 30 μM GA₃ after incubation for 16 and 47 hr. These curves indicate that a pH effect can be seen at 16 hr, but the differences are very slight from pH 3 to 8. The beginning of a peak at pH 5 for the plus GA₃ treatment is evident, however. By 47 hr, a very pronounced pH profile is evident: the peak growth response is at pH 5 for both minus and plus GA₃ treatments. Both curves are very similar in shape, indicating that the pH response is not peculiar to exogenous GA₃ treatment. The final pH was checked for each treatment at the end of the experiment (66 hr), and it remained unchanged for each of the respective pH values. A 50 mM sodium acetate buffer was used at pH 5 to compare with 50 mM citrate phosphate buffer, pH 5, and a 50 mM K-phosphate, pH 7, to compare with 50 mM citrate phosphate buffer at pH 7, to determine if there was any nutrient effect being derived from the citrate phosphate buffer rather than a pH effect. In either case, the growth was the same, irrespective of the buffer employed.

The above experiment clearly shows that maximum growth is attained, over long periods of time, at pH 5 in the segments, both in the presence and absence of GA₃. However, a pH of 3 or 4 does not elicit as much growth in the segments as does GA₃ at any of the pH values tested. It appears that we obtain an acid pH effect on growth of Avena stem segments, but it does not occur at very low pH values from 3 to 4, as with Avena coleoptile sections, nor is the GA₃ effect mimicked by very low pH values.

**Development of a Standard Curve for Acidification of the Medium by Avena Stem Segments.** The number of segments in the titrimeter reservoir was varied from 12 to 75 and the rate of NaOH addition to maintain a pH of 6.5 was determined. Results are shown in Figure 2, in which it is seen that the rate of acidification varies linearly with the number of segments. For our basic experiments, we chose to use 50 segments.

Figure 3 illustrates a standard curve for acidification of the medium by 50 stem segments over a 20-min period. The segments were obtained from next-to-last internodes of Avena plants in the lag phase of growth (1-2 cm in length). The curve shows that the acidification of the medium begins within 30 sec after segments are placed in the titrimeter reservoir. It also indicates that the acidification rate is linear over a 14-min period. The acidification rate, expressed as ml 20 mM NaOH added/10 min, is usually taken at midpoint on the linear part of the curve; in this experiment, it has a rate of 0.181 ± 0.002 ml NaOH added/10 min. In essentially all of our other runs with the titrimeter (over 240), the curves are linear for 14-min experimental periods. Between 14 and 20 min, the rate drops and approaches a value of zero. The segments also stop growing after 14 min in the titrimeter reservoir parallel with the time when acidification ceases.

---

**Fig. 1.** Linear growth response of Avena stem segments at different pH values ranging from 3 to 8. Segments were incubated in the presence of 30 μM GA₃ (+GA₃) or absence of GA₃ (−GA₃) for 47 hr in the dark at 27°C. Buffers employed to obtain pH regimes are indicated in "Materials and Methods." Standard error of the means (±6/√n) at pH 5 were as follows: ±0.01 (−GA₃) and ±0.03 (+GA₃) at 16 hr; ±0.05 (−GA₃) and ±0.08 (+GA₃) at 48 hr. Standard errors at pH 8 were as follows: ±0.01 (−GA₃) and ±0.02 (+GA₃) at 16 hr; ±0.08 (−GA₃) and ±0.08 (+GA₃) at 48 hr.

**Fig. 2.** Acidification rates plotted against number of Avena stem segments contained in titrimeter reservoir.
Acidification Rates in Lag, Log, and Plateau Phases of Development. Segments were obtained from next-to-last internodes in lag (mean length = 2.0 ± 0.1 cm), log (mean length = 4.5 ± 0.2 cm), and plateau (mean length = 10.5 ± 0.3 cm) phases of development. Fifty segments from each stage were placed directly in the titrimer reservoir immediately after cutting. Typical acidification rates for each stage are shown in Table 1. Segments from lag and log phase internodes have essentially the same acidification rates, whereas those in the plateau phase manifest a significantly lower rate. Thus, relatively high acidification rates are associated with rapidly growing internodes and low rates with internodes which are decelerating in their growth rate.

A comparable experiment was performed with segments initially taken from next-to-last internodes in the lag phase of development (1–2 cm in length). These segments were preincubated in either 0.1 M sucrose or 0.1 M sucrose + 30 μM GA3 for 6, 24, and 72 hr, corresponding to lag, log, and plateau phases of growth in vitro, respectively (2). Data in Table 1 present typical acidification rates for these respective stages and treatments. The log phase segments show the highest acidification rates and plateau phase segments the lowest. Furthermore, GA3 stimulates the acidification rate only in the lag and log phases and causes a decrease in the rate during the plateau phase.

Contribution of Different Parts of the Avena Stem Segment to the Acidification Response. Segments (Fig. 4) were fractionated into three portions: node-pulvinus, internodes, and sheath bases, in order to determine to what extent each of these parts contributed to the acidification process. The sheath base is a nongrowing portion, the node-pulvinus the primary geotropically sensitive part of the segment, and the internode base the portion which shows marked sensitivity in its linear growth response to gibberellins.

Table II shows that 37% of the total acidification is from the node-pulvinus and 23% from the sheath base. Forty per cent of the total acidification comes from the internode base. The sum of the acidification rates for the three fractions is greater than that for the intact segment. This is probably due to a wound respiration effect on acidification rate. These results demonstrate that the node-pulvinus and internode fractions account for most of the acidification response in the segment. Interestingly, the node-pulvinus acidification rate is essentially the same as that of the internode. The node-pulvinus is necessary for a maximum growth response in the internode to GA3 (14).

Acidification Rates Before and After GA3-Stimulated Growth. Stem segments were obtained from internodes in the lag phase of growth (1–2 cm in length) and incubated in either 0.1 M sucrose or 0.1 M sucrose + 30 μM GA3. The preincubation period was either 10 min (before GA3 stimulates the growth rate) or 90 min (just after GA3 begins to stimulate the growth rate) (2). For 10-min preincubation segments, or fractions thereof, were used immediately after preincubation. Fractions not used immediately were discarded. For 90-min preincubation, all segments were placed in a refrigerator held at 4 C. One set of 50 segments was fractionated after 5 min in the refrigerator into node-pulvinus, internode, and sheath portions (Fig. 4). The other set of 50 segments was not fractionated and served as intact controls. All material was kept at 4 C until ready for placing in the titrimer reservoir. Different refrigeration times (0–60 min) had no significant effect on acidification rates.

![Diagram of Avena stem segment](https://www.plantphysiol.org/)

**Fig. 4.** Diagramatic representation of an *Avena* stem segment illustrating the primary parts (node-pulvinus, sheath base, and internode base) used in titrimer experiments and general gross structural features of the segment that are referred to in the text.

---

Table 1. Acidification Rates Before and After GA3-Stimulated Growth in Intact Shoots and Preincubated Segments

<table>
<thead>
<tr>
<th>Growth Phase</th>
<th>Mean Length (cm)</th>
<th>Acidification Rate (μM HCl/hr · cm)</th>
<th>Mean Length (cm)</th>
<th>Acidification Rate (μM HCl/hr · cm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lag</td>
<td>2.0 ± 0.10</td>
<td>0.02 ± 0.01</td>
<td>0.1 M Sucrose</td>
<td>0.17 ± 0.02</td>
</tr>
<tr>
<td>Log</td>
<td>4.5 ± 0.17</td>
<td>0.4 ± 0.02</td>
<td>0.1 M Sucrose + 30 μM GA3</td>
<td>2.5 ± 0.10</td>
</tr>
<tr>
<td>Plateau</td>
<td>10.5 ± 0.31</td>
<td>0.13 ± 0.03</td>
<td>0.1 M Sucrose + 30 μM GA3</td>
<td>4.0 ± 0.22</td>
</tr>
</tbody>
</table>

1Expressed as ml of 20 M NaOH added per 10 min. Fifty stem segments were used for each titrimer run.

2Mean length of next-to-last internodes (Fig. 4) at respective growth phases. Fifty 1-cm stem segments were excised from the bases of these internodes for the titrimer runs.

3Net internodal extension after 6 hr (lag), 24 hr (log), and 72 hr (plateau) of growth of the segments in vitro (incubated in dark at 30 C).
TABLE III contains the results of these experiments. For intact segments, 10-min preincubation in sucrose + GA3 caused a 15% decrease in acidification rate compared with sucrose control segments. In fractionated segments, the internodes contributed 59%, the node-pulvinus 31%, and the sheaths 10%, to a total drop for all fractions of 11%. In contrast, 90-min preincubation in sucrose + GA3 caused a 17% increase in the acidification rate compared with sucrose controls. In fractionated segments, the internode contributed 72%, the node-pulvinus 33%, and the sheaths -5%, to a total increase for all fractions of 12%. These results suggest that some time between 10 and 90 min is a crossover point between inhibition and promotion of the acidification rate.

As in Table II, the data in Table III show that fractionation causes an increase in acidification rate when one compares the sums of the acidification rates of the three fractions with the rate for intact segments. Furthermore, the node-pulvinus in these 10- and 90-min preincubated segments contribute 33 to 34% to the acidification rate, the internodes 38 to 45%, and the sheaths the least, 21 to 28%. These relative percentages are the same as those obtained from intact shoots where no preincubation treatments were employed (Tables II and III).

Measurement of the pH Drop in the Medium in the Presence and Absence of GA3. Since Avena stem segments cause a significant acidification of the medium after pretreatment in sucrose or sucrose + GA3, we wanted to monitor the pH over the time of this drop. Using 50 stem segments for each treatment, we preincubated the segments in either 0.1 M sucrose or 0.1 M sucrose + 30 μM GA3 in the dark at 30 °C for 90 min, then immediately placed the segments in the titrimer reservoir with base being added to maintain a pH of 6.5. When a steady rate of addition of NaOH was attained, the supply of base was shut off and a trace was run on the pH drop in the medium (Fig. 5). The pH of the medium for the sucrose treatment dropped from 6.5 to 5.6 within 5 min and remained at this pH. For segments preincubated in sucrose + GA3, the pH dropped from 6.5 to 3.3 in 5 min and stabilized at 3.15 within 10 min. Thus, the acidification response is greater with GA3 treatment than with sucrose alone.

### Table II

<table>
<thead>
<tr>
<th>Type of Fraction</th>
<th>Acidification Rate</th>
<th>Total Acidification Rate</th>
</tr>
</thead>
<tbody>
<tr>
<td>Node-Pulvinus</td>
<td>0.125 ± .004</td>
<td>37</td>
</tr>
<tr>
<td>Internodes</td>
<td>0.135 ± .004</td>
<td>40</td>
</tr>
<tr>
<td>Sheaths</td>
<td>0.082 ± .003</td>
<td>23</td>
</tr>
<tr>
<td>Total for Fractions</td>
<td>0.342 ± .011</td>
<td>100</td>
</tr>
</tbody>
</table>

1. All segments were obtained from Avena next-to-last internodes in lag phase of growth (1-2 cm in length). All segments or parts thereof were placed directly into the titrimer reservoir after cutting. There was no preincubation.
2. Expressed as ml of 20% NaOH added per 10 min. Fifty segments or parts were used for each run.

### Table III

<table>
<thead>
<tr>
<th>Type of Fraction</th>
<th>Acidification Ratea</th>
<th>Total Acidification Rate</th>
<th>Acidification Rateb</th>
<th>Total Acidification Rateb</th>
<th>Percent Promotion</th>
<th>Weighted % Promotion</th>
<th>% Contribution</th>
</tr>
</thead>
<tbody>
<tr>
<td>Node-Pulvinus</td>
<td>0.123 ± .004</td>
<td>33</td>
<td>0.112 ± .003</td>
<td>34</td>
<td>-10</td>
<td>-3.5</td>
<td>31</td>
</tr>
<tr>
<td>Internodes</td>
<td>0.153 ± .008</td>
<td>41</td>
<td>0.127 ± .006</td>
<td>38</td>
<td>-17</td>
<td>-6.7</td>
<td>59</td>
</tr>
<tr>
<td>Sheaths</td>
<td>0.096 ± .003</td>
<td>26</td>
<td>0.092 ± .001</td>
<td>28</td>
<td>-4</td>
<td>-1.1</td>
<td>10</td>
</tr>
<tr>
<td>Total for Fractions</td>
<td>0.375 ± .015</td>
<td>90</td>
<td>0.331 ± .010</td>
<td>90</td>
<td>-11</td>
<td>-11.3</td>
<td></td>
</tr>
<tr>
<td>Intact Segments</td>
<td>0.230 ± .011</td>
<td>29</td>
<td>0.195 ± .008</td>
<td>31</td>
<td>-15</td>
<td>-5.1</td>
<td>46</td>
</tr>
</tbody>
</table>

1. All segments were obtained from Avena second-to-last internodes in lag phase of growth (1-2 cm in length). Fractions were preincubated prior to treatment and used immediately (10 min pretreatment) or refrigerated (90 min pretreatment).
2. Expressed as ml of 20% NaOH added per 10 min. 50 segments or parts thereof were used for each titrimer run.
3. (Promotion x average of % of total acidification rate)/100 x (weighted % promotion).

**DISCUSSION**

As with IAA in other systems (9, 12, 17) GA3 causes a decrease in the pH of the medium in which Avena stem segments are incubated in comparison with control segments. The fact that the acidification stimulation by GA3 occurs primarily in the node-pulvinus as well as in the internode portions of the segments (Fig. 4 and Table II) may be of significance. The node-pulvinus play a major role in determining the amount of GA3-stimulated growth in the internode (14); deletion of the node-pulvinus greatly reduces linear growth in the internode either in plus or minus GA3-treated segments. The node-pulvinus is the second richest source of native gibberellin in the Avena shoot (11), so that the native gibberellins in this locus could play an active role in stimulating acidification in situ. Since the distance between the node-pulvinus and the intercalary meristem at the base of the internode is only of the order of 0.5 mm (Fig. 4), the stimulation of acidification in the node-pulvinus by GA3 could contribute significantly to any acid-promoted wall-loosening in the internode base. This internode base, the locus of the intercalar intercalary meristem, is that part of the internode where GA3 has its primary accelerating influence on linear growth (1, 2), where GA3 causes a marked increase in cell wall plasticity (3), and where it causes a significant increase in cell wall synthesis (13).

The acidification rate increase elicited by GA3 in Avena stem segments causes a drop in pH of the medium to 5.2 from an initial pH of 6.5; segments in control media cause the pH to drop to 5.6 from 6.5. Such an effect of GA3 on acidification of the
medium is nicely correlated with GA₃-stimulated growth at different pH values. Maximum growth occurs at pH 5. The same is true of non-GA₃-treated segments (Fig. 1). In addition, GA₃-promoted growth over a wide pH range of 3 to 8 is greater than growth at pH 3 in the absence of GA₃. pH 3 has been shown to stimulate growth in *Avena* coleoptiles and in pea epicotyl segments, usually showing similar kinetics as for IAA-stimulated growth (4, 17); this pH of 3 causes the pH in the vicinity of the cell wall to drop to pH 5 (5). In contrast, in *Avena* stem segments, pH 3 strongly suppresses growth both in the presence and absence of GA₃ (Fig. 1). The maximal growth response at pH 5 in these segments is one which appeals to us in that many cell wall hydrolases show maximal enzyme activity at around pH 5 (15, 16, 18, 19). Thus, increase in acidification rates elicited by GA₃, resulting in attainment of pH values approximating 5 (compared with pH 5.6 in control segments) could be of major significance in GA₃-stimulated growth, especially since GA₃ starts to increase cell wall plasticity in the internode base within 60 min (3). These results, furthermore, are consistent with several models for wall-loosening (*e.g.* stimulated cell wall endohydrolase activity, increased rate of xyloglucan creep, increased rate of turnover of cell wall polymers).

The drop in rate of acidification caused by GA₃ after a 10-min pretreatment in GA₃, before growth is stimulated by the hormone (at least 30 min is required for GA₃ to cause an acceleration in growth rate-2), is the earliest of any response we have obtained with GA₃ in the *Avena* internode system. This response may be caused by hormone-stimulated diversion of substrate from respiratory processes to cell wall synthesis machinery. Whatever the cause, the rate decrease points to an initial trigger of GA₃ action in stimulating growth of *Avena* internodes that is not due to acidification-mediated wall-loosening. Perhaps this rate decrease accounts for the 40- to 50-min lag before GA₃ begins to stimulate growth in *Avena* stem segments.

**Acknowledgment** — We wish to thank the University of Michigan Matthaei Botanical Gardens for providing *Avena* plants for this study.

**LITERATURE CITED**