Numerical Expression for Estimating the Minimum Ethylene Exposure Time Necessary to Induce Ripening in Banana Fruit

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Abstract. A numerical expression for the minimum treatment time (MTT) for ethylene necessary to induce ripening in banana [Musa (AAA group, Cavendish subgroup) 'Giant Cavendish'] fruit was determined using the concentration of applied ethylene, fruit temperature, and a number of fruit variables. The content of sugars, organic acids and ACC, and the activity of the ethylene-forming enzyme (EFE) in the fruit just prior to ethylene treatment were measured as fruit variables. In a linear regression analysis between MTT determined at 30°C with 1000 μl-liter⁻¹ ethylene and each fruit variable, significant correlations were found with ACC (r = -0.84) and individual sugar content. MTT (y hours) in banana fruit treated with a selected ethylene concentration (x μl-liter⁻¹) at a given temperature (°C) could be estimated from their initial ACC content (k nmol-g⁻¹) by the following equation: y = (0.202 - 0.238k)t² - (11.92 - 13.1k)t + 185.8 - 190.7k - (0.02t² - 1.3t + 22)log₁₀x. When the calculated values for MTT were compared with the observed values, this equation adequately represented the MTT for Japanese commercial bananas. Chemical name used: 1-aminocyclopropane-1-carboxylic acid (ACC).

The banana shows a typical ethylene-dependent ripening. Although the threshold concentration of ethylene to initiate banana ripening is widely suggested to be 0.1-1.0 μl-liter⁻¹ (2, 3, 6, 7, 13), the minimum effective exposure period for ripening is not known. We have suggested in a previous report (10) that the minimum treatment time for ethylene to induce banana ripening can be expressed as a function of ethylene concentration and fruit temperature: y = (0.04 + 0.02k)t² - (3 + 1.1k)t + 16k - (22 - 1.3t + 0.02²)log₁₀x, where y = MTT (hr), x = applied ethylene concentration (μl-liter⁻¹), t = fruit temperature (°C), and k = a real number that varied from hand to hand but was constant for fingers within each hand. These data indicated that the individual finger on the same hand had an equal response to applied ethylene, but the responsiveness varied with different hands.

In the previous work (10), we also found that the applied ethylene enhanced the induction of both ACC synthase and EFE in banana fruit, with a more rapid induction of the latter. Similar responses have been reported with apples (4, 5), tomatoes (8, 11, 14), muskmelons (8, 14), and avocados (18). Furthermore, autocatalytic ethylene synthesis is a common feature of ripening in climacteric fruits (1, 7, 16). These facts have led us to suggest that the real number, k, in the above equation could be generalized by using the activity of already existing EFE or ACC synthase in the fruit prior to ethylene treatment. In this study, we investigated whether or not this was true, and also whether k could be replaced by a measure of these or some other fruit components closely related to ripening.

Materials and Methods

Preliminary bananas imported from the Philippines were supplied by a local market in Okayama, Japan. On arrival at the laboratory, each banana hand was separated into individual fingers and the fingers then were incubated overnight at selected temperatures prior to ethylene exposure. In all experiments, fingers from the same hand were used as a sample group. The response of fingers to applied ethylene varied considerably among different hands, whereas fingers on the same hand responded almost similarly to applied ethylene. Fingers located at either end of the hand, however, were excluded because they ripened more slowly than the other fingers on the same hand.

A total of 27 hands of widely ranging maturities were chosen visually in terms of the angularity of fingers (17) and the color intensity of surface green. The correlations of MTT with each fruit variable were determined for these specific selected hands.

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Table 1. Relationship between minimum treatment time (MTT) in hours and several banana fruit characteristics just prior to ethylene treatment.

<table>
<thead>
<tr>
<th>MTT (hr)</th>
<th>No. hands</th>
<th>Sugars (%)</th>
<th>Organic acids (%)</th>
<th>ACC (nmol g⁻¹)</th>
<th>EFE activity (µmol C₂H₄ per hr)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Saccharose</td>
<td>Glucose</td>
<td>Fructose</td>
<td>Citric</td>
</tr>
<tr>
<td>1</td>
<td>3</td>
<td>1.19 ± 0.39*</td>
<td>0.22 ± 0.13</td>
<td>0.23 ± 0.13</td>
<td>0.12 ± 0.06</td>
</tr>
<tr>
<td>2</td>
<td>2</td>
<td>0.90 ± 0.11</td>
<td>0.23 ± 0.01</td>
<td>0.19 ± 0.01</td>
<td>0.22 ± 0.01</td>
</tr>
<tr>
<td>3</td>
<td>3</td>
<td>1.11 ± 0.51</td>
<td>0.26 ± 0.11</td>
<td>0.24 ± 0.10</td>
<td>0.18 ± 0.04</td>
</tr>
<tr>
<td>4</td>
<td>2</td>
<td>0.88 ± 0.07</td>
<td>0.20 ± 0.03</td>
<td>0.18 ± 0.03</td>
<td>0.10 ± 0.01</td>
</tr>
<tr>
<td>5</td>
<td>5</td>
<td>0.68 ± 0.20</td>
<td>0.14 ± 0.08</td>
<td>0.15 ± 0.07</td>
<td>0.17 ± 0.04</td>
</tr>
<tr>
<td>6</td>
<td>5</td>
<td>0.91 ± 0.35</td>
<td>0.14 ± 0.08</td>
<td>0.15 ± 0.09</td>
<td>0.13 ± 0.05</td>
</tr>
<tr>
<td>7</td>
<td>4</td>
<td>0.66 ± 0.31</td>
<td>0.09 ± 0.04</td>
<td>0.11 ± 0.05</td>
<td>0.13 ± 0.03</td>
</tr>
<tr>
<td>8</td>
<td>3</td>
<td>0.68 ± 0.21</td>
<td>0.11 ± 0.03</td>
<td>0.13 ± 0.02</td>
<td>0.13 ± 0.02</td>
</tr>
<tr>
<td>Regression</td>
<td></td>
<td>y = 7.49 - 3.09x</td>
<td>y = 7.22 - 14.56x</td>
<td>y = 7.31 - 15.07x</td>
<td>NS</td>
</tr>
</tbody>
</table>

*MTT was determined using 1000 µl·liter⁻¹ ethylene at 30°C.
*Numbers represent the numbers of hands that initiated ripening after ethylene treatment with the given MTT.
*Mean ± SE of analyses for a single finger from each hand.
NS, **Nonsignificant or significant at the 5% or 1% levels, respectively.

Fig. 1. Relationship between minimum treatment time (MTT) in hours using 1000 µl·liter⁻¹ C₂H₄ at 30°C and ACC content in the fruits just prior to ethylene treatment.

Sugars and organic acid in alcoholic extracts of the flesh were fractionated by ion exchange resins, and then determined by a high performance liquid chromatography, as outlined previously (9). ACC content was determined according to the method described by Lizada and Yang (15), with a slight modification (10). EFE activity was assayed by measuring the conversion of administered ACC to ethylene in vivo (10).

Results

The contents of individual sugars, organic acids and ACC, and EFE activity measured for one finger from each hand are summarized in Table 1 in relation to MTT obtained from treatment at 30°C with 1000 µl·liter⁻¹ ethylene. The observed MTT covered a wide range from 1 to 8 hr, as was expected from their appearance. The most significant correlation was observed between MTT and ACC content (P < 0.01, Fig. 1). Fruit high in ACC were induced to ripen by the short ethylene applications. Based on 27 sample groups of banana hands, a linear regression equation relating MTT (as output y) and ACC content (as input x) was obtained as y = 8.11 - 11.92x, with a correlation coefficient of 0.84. Significant correlation also was found between MTT and each sugar content, but the correlation coefficients were lower than for ACC. There was no correlation between MTT and the other fruit variables, including EFE activity.

In the previous experiment (10), MTT determined at the condition of 1000 µl·liter⁻¹ at 30°C was used as a real number, k. This k could be directly replaced by the regression equation between MTT and ACC content, which showed the highest correlation coefficient in the present study, because the fruits were treated under the same conditions as those of the previous experiment. The following generalized new formula for estimating MTT of banana fruit was derived: y = (0.202 - 0.238k)x² - (11.92 - 13.1k)x + 185.8 - 190.7k - (0.02x² - 1.3x + 22)log₁₀x; where, y = MTT (hr), x = ethylene concentration (µl·liter⁻¹), t = fruit temperature (°C), and k = ACC content (nmol g⁻¹) just prior to ethylene treatment.

The validity of the new equation is shown in Table 2. The estimated MTT values obtained from the initial ACC content at a selected ethylene treatment condition agreed approximately with the observation values at a given condition. The differences between the estimated value and the one observed were <2 hr for the hands responding to ethylene under all treatment conditions, though six out of a total of 45 hands failed to ripen within the period tested. Therefore, when allowance for the difference between the two values was set to 2 hr, the equation adequately predicted the MTT of more than 86% of the hands over a wide range of ethylene concentrations and temperatures.

Discussion

It is characteristic of banana fruit that starch accumulated during development is converted rapidly to sugars, with an increase in organic acid content once ripening is initiated. In our previous report, sugar and acid content increased during shipment from the Philippines to Japan, and the higher content was associated with shorter preclimacteric periods (9). These phenomena also were observed in the present study; the fruit high in sugar content were initiated to ripen by a short period of ethylene application. However, the correlation coefficient for sugar content with MTT was lower than for ACC, so that the sugar contents were excluded from the equation for estimating MTT of banana fruit.

EFE and ACC synthase are widely known as the two key
regulatory enzymes of ethylene biosynthesis (19). EFE activity in preclimacteric banana fruit was previously found to vary markedly in different hands (10), though EFE activity was stimulated prior to activation in ACC synthase by applied ethylene (10). Liu et al. (14) reported that ethylene treatment of preclimacteric muskmelon or tomato fruits for a short period promoted conversion of ACC in the tissue to ethylene without promoting ACC synthesis. Similar results have been obtained in preclimacteric avocado (18) and apple (5) fruits. Unexpectedly, there was no correlation between MTT and EFE activity in this study, suggesting that EFE activity is not a factor limiting the initiation of ripening in banana fruit, although EFE may have a common feature of being rapidly activated by exogenous ethylene.

ACC content in the fruit just prior to ethylene treatment showed the highest significant correlation to MTT in the present study. The shorter MTT values were observed in the fruit containing the higher level of predetermined ACC. Sitrit et al. (18) recently demonstrated in avocado fruit that ACC synthase is first synthesized during ripening. This ACC synthase leads to the production of ethylene, which, in turn, induces an additional increase in ACC synthase activity. Enhancement of ACC synthase activity by exogenous ethylene also has been demonstrated in apples (4) and bananas (10). Similarly, in greenhouse-grown 'Dwarf Cavendish' bananas, Liu (12) reported that fruits with a short minimum time required for a ripening response to 10 μl-liter⁻¹ ethylene had a short storage life at 21°C. These facts, together with our results, indicate that applied ethylene induces banana ripening through the activation of ACC synthase. In this process, it seems that ACC synthase activity may reach a threshold level within a shortened period of ethylene application if ACC synthase activity is already high and higher concentrations of applied ethylene and higher temperatures are used. In our present results, there was a clear numerical relationship between MTT and ACC content, applied ethylene concentration, or fruit temperature.

Banana fruit have been ripened commercially by 24-hr exposure to 1000 μl-liter⁻¹ ethylene or higher at a temperature of 20°C or lower in Japan. The highest and lowest content in ACC in the fruit used in the present study were 0.71 and 0.08 nmol-g⁻¹, respectively, with an average of 0.25 nmol-g⁻¹ in a total of 72 hands. MTT for these bananas under Japanese ordinary ripening conditions (1000 μl-liter⁻¹, 20°C) can be calculated ranging from 0 to 14.3 hr, with an average value of 10.2 hr. Alternatively, 10 μl-liter⁻¹ ethylene would be sufficient to induce ripening when bananas were treated at 20°C for 24 hr, even if the ACC content was as low as 0 nmol-g⁻¹. These calculated values for MTT indicate that the commercial bananas in Japan may have been treated with ethylene in excess. The effects of this overexposure to ethylene on fruit quality should be investigated further.

**Literature Cited**


Harvest Indices, Dessert Quality, and Storability of 'Jonagold' Apples in Air and Controlled Atmosphere Storage

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Additional index words. Malus domestica, fruit maturity, ethylene, starch, water core, flesh breakdown, postharvest physiology

Abstract. Starch index (SI) was correlated negatively with starch content and positively with internal ethylene concentration (IEC) and logarithm to the base 10 of IEC (logIEC) in 'Jonagold' (Malus domestica Borkh.) apples. The initial rapid increase in SI, logIEC, and yellow ground color coincided with one another and occurred +20 days before the increase in IEC and incidence of watercore (WC). In 1984, 1985, and 1986, the first acceptable picking date for British Columbia-grown 'Jonagold' was about 10 Oct., when the fruit had attained an acceptable amount of color (50% to 85% area greater than No. 2 red color and 4.0-4.5 yellow color units on a 0-10 scale) and a good level of firmness (73-76 N), soluble solids (13.5% to 14.5%), starch (SI of 6.5-7.0 on a 0-9 scale), and acids (661-782 mg malate/100 ml of juice), but without much WC (2% to 13%) or ethylene (0.3-1.5 µl-liter⁻¹ IEC; 5% to 40% of fruit with IEC > 1 µl-liter⁻¹). Fruit picked on 20 Oct. were softer, lower in acids and storage potential, and more susceptible to WC, coreflush (CF), and breakdown (BD) than those picked 10 Oct. Fruit harvested from mature trees stored well at 0°C in air until February and in controlled atmosphere (CA, 1.5% O₂ + 1.5% CO₂) until June. Fruit from young trees were large and developed BD in air storage as early as November; fruit afflicted with BD were lower in Ca and higher in K : Ca ratio than those free of the disorder. Dessert and sensory ratings were higher in 'Jonagold' than in 'Mcintosh', 'Golden Delicious', 'Spartan', and 'Delicious' and were also higher in fruit from CA than from air storage.

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Materials and Methods

Maturity and storage studies. Fruit of 'Jonagold' trees on MM.111 rootstock planted in 1974 were harvested on 10 Oct. 1984 or at 7- and 10-day intervals between 28 Aug. and 25 Oct. in 1985 and between 15 Sept. and 27 Oct. in 1986. The experimental design of each trial (numbers of fruit harvests, fruit and tree replicates, and storage treatments) is specified in each table. Starch index (SI, described below) and internal ethylene concentration (IEC, by gas chromatography) of each individual fruit, and flesh firmness (FF, by Magness-Taylor penetrometer with a 11.1-mm-diameter tip), soluble solids (SS, by refractometry), titratable acidity (TA, by titration to pH 8.1 with NaOH), yellow ground color and red color (by "Golden Delicious Color Meter" and "Red Color Meter", respectively, Techwest Enterprises Ltd., Vancouver, B.C.; higher values on a 0-10 scale indicate more yellow and red color, respectively), and water core (WC,