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Delay of avocado (*Persea americana*) fruit ripening by 1-methylcyclopropene and wax treatments

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Abstract

1-Methylcyclopropene (1-MCP), an inhibitor of ethylene action, has been shown to extend the postharvest storage period of avocado fruit. Waxing is also known to extend the storage life of avocado by reducing water loss and modifying the fruit internal atmosphere. In this study, 1-MCP and waxing were used to investigate their combined effects on ripening characteristics of avocado fruit. Preclimacteric avocado (*Persea americana* Mill. cv. 'Tower II') fruit were treated with 1-MCP (0.9 $\mu l\,l^{-1}$) for 12 h at 20 °C. Half of the fruit were waxed (Sta-Fresh 819F®, FMC FoodTech) after 1-MCP treatment and subsequently stored at 20 °C in ethylene-free air at 85% relative humidity. In a separate experiment, 'Booth 7' avocados were treated as above and stored at 13 °C. As evaluated by fruit firmness, ethylene evolution, and respiration rate, 1-MCP and wax significantly delayed the ripening of 'Tower II' avocado stored at 20 °C. Fruit treated with both 1-MCP and wax had better retention of green peel color and fruit firmness, and delayed climacteric ethylene evolution and respiration rates compared with other treatments. Waxing alone reduced weight loss and delayed softening, but did not delay climacteric ethylene evolution and respiration rates. Whereas firmness of control fruit decreased from > 100 to 20 N over a 7-d period at 20 °C, fruit treated with both 1-MCP and wax required more than 11 d at 20 °C to soften to 20 N. The firmness of waxed 'Booth 7' avocados declined from > 170 to 15 N during 19 d storage at 13 °C whereas fruit treated with both 1-MCP and wax required nearly 5 weeks to reach firmness values of 25 N. 1-MCP treatment, which completely suppressed polygalacturonase activity in 'Tower II' and 'Booth 7' fruit through 9 d at 20 °C and 36 d at 13 °C, respectively, significantly affected the rate but had little influence on the extent of fruit softening.

Keywords: Avocado; 1-Methylcyclopropene; Polygalacturonase; Ripening; Softening; Waxing

1. Introduction

The avocado (*Persea americana* Mill.) is a climacteric fruit characterized by a surge in ethylene production at the onset of ripening. This

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climacteric increase in ethylene production is associated with hastened ripening. Avocado is one of the most rapidly ripening of fruits, often completing ripening within 5 d following harvest (Seymour and Tucker, 1993).

As ethylene plays an important role in regulating fruit ripening, inhibiting ethylene biosynthesis or action should slow the ripening process and extend the postharvest storage life. 1-Methylcyclopropene (1-MCP), a synthetic cyclopropene, blocks ethylene receptors and prevents ethylene effects in plant tissues for extended periods (Sisler et al., 1996). This material is nontoxic, odorless, and effective when plants are treated at concentrations as low as 0.5 nl l^{-1} (Sisler and Serek, 1997).

1-MCP has been shown to delay fruit ripening and improve storage quality of climacteric fruits including pear (Lelievre et al., 1997b), banana (Golding et al., 1998, 1999; Sisler and Serek, 1997), plum (Abdi et al., 1998), tomato (Nakatsuka et al., 1997; Sisler and Serek, 1997), apple (Fan and Mattheis, 1999; Watkins et al., 2002), and avocado (Feng et al., 2000; Jeong et al., 2002). 1-MCP, therefore, has proved a valuable tool to investigate ethylene action during ripening of climacteric fruit (Nakatsuka et al., 1997) and has the potential to extend the commercial storage life of horticultural products.

In a previous study (Jeong et al., 2002), we demonstrated that the storage life of avocado treated with 1-MCP could be extended by 4 d at 20 °C; however, fruit quality was somewhat compromised by excessive water loss. As with other commodities (Littmann, 1972), water loss is one of the factors limiting the postharvest storage life of avocado (Adato and Gazit, 1974). Joyce et al. (1995) reported that waxing extended the storage life of avocado both through a reduction in water loss and modification of the internal atmosphere. The objective of the present study was to examine the effects of 1-MCP in conjunction with waxing on the ripening properties of 'Tower II' and 'Booth 7' avocado fruit. An experiment employing waxing and 1-MCP treatment followed by low-temperature (13 °C) storage was conducted to determine the potential for long-term storage and quality maintenance of avocado fruit.

2. Materials and methods

2.1. Plant material

'Tower II' and 'Booth 7', mid-season avocado varieties, were selected for these experiments. Both are crosses of West Indian and Guatemalan strains (Hatton and Campbell, 1960; Hatton et al., 1964). Mature avocado fruit were obtained from a commercial grove in Homestead, Florida (harvest date for 'Tower II'—August 1999; harvest date for 'Booth 7'—October 1999), packed in fiberboard cartons, and transported to the Postharvest Horticulture Laboratory in Gainesville, Florida, within 24 h after harvest. Fruit were selected for uniformity of size ('Tower II' 575 ± 48 g; 'Booth 7' 526 ± 40 g) and shape (diameter at equatorial region, 'Tower II' 9.0 ± 0.3 cm; 'Booth 7' 9.5 ± 0.2 cm), and then were surface sterilized in a 15% (90 mM NaOCl) commercial bleach solution, rinsed, and dried.

2.2. 1-MCP and wax treatment

Twelve fruit were placed in 18-l containers and exposed to 1-MCP by releasing the gas from a commercial powdered formulation (Ethylblock®, FloraLife, Burr Ridge, IL). The concentration selected, 0.9 μl l^{-1}, was achieved through addition of 10 mg of the powder to 100 ml of FloraLife buffer following manufacturer's instructions (FloraLife, Ethylblock product specification sheet). Following addition of the buffer to the powder, the beakers were immediately transferred to the 18-l containers, which were immediately sealed. 1-MCP treatment was performed for 12 h at 20 °C and 85% relative humidity (RH).

In the experiment with 'Tower II', the fruit immediately following 1-MCP treatment were removed from the treatment chambers and then half of the fruit were coated with a water-based, food-grade wax (Sta-Fresh 819F®, FMC FoodTech). Fruit were dipped in the wax concentrate for 1 min, allowed to drain, and air-dried with a fan. The fruit were subsequently stored at 20 °C in ethylene-free air at 85% RH. Control fruit (not exposed to 1-MCP and not waxed) were maintained under identical storage conditions.

In the experiment with 'Booth 7', fruit were treated with 1-MCP as described above, and all fruit were waxed after 1-MCP treatment. To determine the long-term storage potential afforded by the wax and 1-MCP treatments, the fruit were subsequently stored at 13 °C. Control fruit (waxed but not exposed to 1-MCP) were maintained under identical storage conditions.

In both experiments, samples of fruit from each treatment were evaluated for quality every other day until they reached the full-ripe stage (10–20 N). Fruit behavior during storage was assessed on the basis of firmness, weight loss, CO_2 and C_2H_4 production, as well as peel color. Mesocarp tissue (400 g) derived from the equatorial region of selected fruit was stored at −30 °C and later used for analysis of polygalacturonase (PG, E.C. 3.2.1.15) activity.

2.3. Fruit firmness

Firmness was determined on whole, unpeeled fruit using an Instron Universal Testing Instrument (Model 4411, Canton, MA) fitted with a flat-plate probe (5 cm in diameter) and 50-kg load cell. After establishing zero force contact between the probe and the equatorial region of the fruit, the probe was driven with a crosshead speed of 10 mm min^{-1}. The force was recorded at 2.5 mm deformation and was determined at two equidistant points on the equatorial region of each fruit. The same four fruit of each treatment were measured every other day during storage.

2.4. Respiration and ethylene evolution

Respiration and ethylene production were measured every other day using another sub-sample of four fruit from each treatment. Fruit were individually sealed for 30 min in 2-l plastic containers prior to sampling. A 0.5 ml headspace sample was withdrawn by syringe through a rubber septum, and carbon dioxide determined using a Gow-Mac gas chromatograph (Series 580, Bridgewater, NJ) equipped with a thermal conductivity detector. The carrier gas (Helium) flow rate was 30 ml min^{-1}. The oven was set at 40 °C, and detector and injector were operated under ambient temperature (26–27 °C). Ethylene was measured by injecting a 1.0 ml headspace sample into a HP 5890 gas chromatograph (Hewlett Packard, Avondale, PA) equipped with a flame ionization detector. The carrier gas (Nitrogen) was 30 ml min^{-1}. Oven, injector, and detector were 70, 200, and 250 °C, respectively.

2.5. Peel color

Individual fruit were marked at the equatorial region (2 opposite regions per fruit), and color at the same location was recorded every other day as L^*, hue angle, and chroma value with a Minolta Chroma Meter CR-2000 (Minolta Camera Co Ltd, Japan). The chroma meter was calibrated with a white standard tile. The color was reported as hue angle (H°), with a value of 90° representing a totally yellow color and 180° a totally green color. The results are presented as lightness (L^*, where 0 = black, 100 = white), chroma (C^*, color saturation), and hue angle (H°).

2.6. Polygalacturonase extraction and assay

Cell-free extracts containing PG activity were prepared as described in Jeong et al. (2002). PG activity was assayed reductometrically by incubating a 100-μl aliquot of the cell-free protein extract with 500 μl (2 mg) of polygalacturonic acid (orange peel, Sigma Chemical Co, St. Louis, MO) dissolved in 30 mM KOAc, pH 5.5, containing 100 mM KCl. After 30 min at 34 °C, uronic acid reducing groups were measured using the method of Milner and Avigad (1967). PG activity was expressed as kat per kg protein. Protein content was measured using the bicinchoninic acid method (Smith et al., 1985) with bovine serum albumin as a standard.

2.7. Statistical analysis

The experiments were conducted in a completely randomized design. Statistical procedures were performed using the PC-SAS software package (SAS-Institute, 1985). Data were subjected to ANOVA using the General Linear Model (Mini-

tab, State College, PA). Means were separated by Duncan's multiple range test.

3. Results

3.1. 'Tower II' experiment

3.1.1. Fruit firmness and weight loss

Control fruit (no 1-MCP and no wax) softened rapidly and completed ripening (10–20 N) within 7 d of storage at 20 °C (Fig. 1A). In contrast, fruit treated with either wax, 0.9 μl l^{-1} 1-MCP, or both exhibited firmness values of 31.2, 36.6, and 51.5 N, respectively, after 7 d at 20 °C. Softening of fruit treated with 1-MCP and/or wax was significantly delayed and varied by treatment. Waxed fruit without 1-MCP reached the full-ripe stage (10–20 N) after about 9 d, whereas fruit treated with 1-MCP alone or both 1-MCP and wax reached the full-ripe stage after about 11 d at 20 °C.

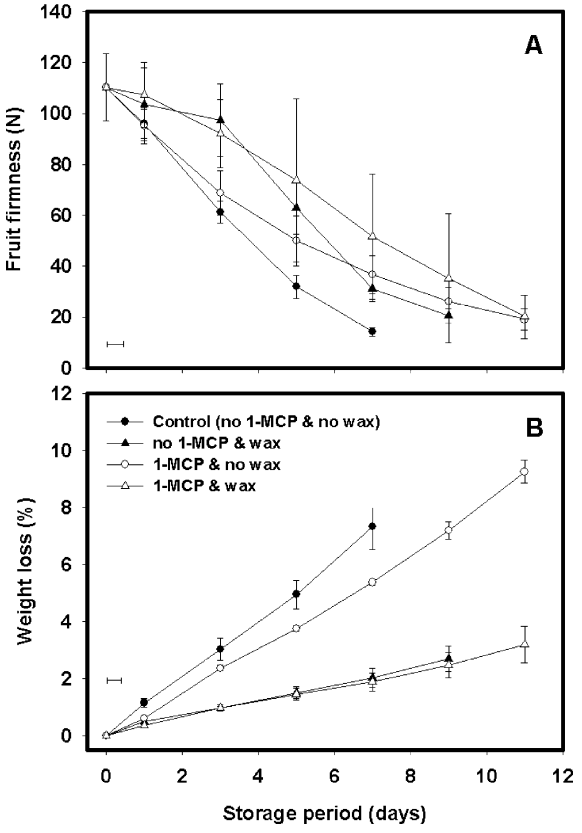

Fig. 1. Fruit firmness (N) and weight loss (%) of 'Tower II' avocados stored at 20 °C with 1-MCP (0.9 μl l^{-1} for 12 h at 20 °C) and/or wax treatments. Control fruit (no 1-MCP, no wax) were stored at 20 °C. Vertical bars represent standard deviation of 4 independent samples. Horizontal bar represents the time interval of 1-MCP treatment (0.9 μl l^{-1} for 12 h at 20 °C).

After 7 d of storage at 20 °C, weight loss for the control fruit was 7.3% whereas fruit treated with either 1-MCP, wax, or both showed weight loss values of 5.4, 2.0, and 1.9%, respectively (Fig. 1B). At the full-ripe stage, weight loss of non-waxed fruit treated with 1-MCP (9.3%) was significantly higher than that of control fruit (7.3%) and that of waxed fruit with (2.7%) or without (3.2%) 1-MCP treatment. Waxed fruit treated with or without 1-MCP showed no significant differences in the magnitude and rate of weight loss. It is clear that waxing was quite effective at attenuating weight loss in stored avocado, with weight loss values ranging from a high of 9.3% in non-waxed, 1-MCP-treated fruit over 11 d to values as low as 2.7% in waxed fruit over 9–11 d at 20 °C (Fig. 1B).

3.1.2. Respiration and ethylene evolution

Fruit from all treatments showed characteristic respiratory climacteric patterns during storage at 20 °C (Table 1). Respiration in control fruit (no 1-MCP and no wax) and waxed fruit without 1-MCP began to increase after 1 d storage at 20 °C (data not shown). In control and waxed fruit, CO_2 production reached maximum values of 145 and 157 mg kg^{-1} h^{-1} after 6 and 5 d storage at 20 °C, respectively (Table 1). CO_2 production of fruit treated with 1-MCP alone or both 1-MCP and wax increased initially after 3 d storage at 20 °C (data not shown) and reached maxima of 145.5 and 150.9 mg kg^{-1} h^{-1} after 8 and 9 d storage at 20 °C, respectively (Table 1). Thus, 1-MCP treatment significantly delayed the respiratory climacteric pattern of waxed and non-waxed fruit by 2 and 4 d, respectively. Waxing did not significantly influence the respiratory climacteric pattern or the magnitude of the respiratory peak (Table 1).

Fruit from all treatments also showed characteristic ethylene climacteric patterns during storage at 20 °C (Table 1). Ethylene production in control

Table 1
Days to peak and maximum CO_2 and C_2H_4 production in 'Tower II' avocados stored at 20 °C with 1-MCP (0.9 μl l^{-1} for 12 h at 20 °C) and/or wax treatments

Treatments	CO_2		C_2H_4	
	Days to peak	Maximum (mg kg^{-1} h^{-1})	Days to peak	Maximum (μg kg^{-1} h^{-1})
No 1-MCP, no wax	6 b	144.9 ± 15.1	4 c	143.4 ± 12.6
No 1-MCP, wax	5 b	156.8 ± 22.7	5 bc	111.8 ± 17.4
1-MCP, no wax	8 a	145.5 ± 31.8	8 a	412.5 ± 83.1
1-MCP, wax	9 a	150.9 ± 7.6	7 ab	163.1 ± 44.1

Control fruit (no 1-MCP, no wax) were stored at 20 °C. Initial rates of CO_2 and C_2H_4 production were 38.3 mg kg^{-1} h^{-1} and 1.5 μg kg^{-1} h^{-1}, respectively. Values followed by the same letter in a column do not differ significantly according to Duncan's Multiple Range Test ($P < 0.05$). Data are means ± standard deviation of 4 independent samples.

fruit and waxed fruit without 1-MCP treatment began to increase after 1 d in storage (data not shown) and reached maximum values of 143.4 and 111.8 μg kg^{-1} h^{-1} after 4 and 5 d storage at 20 °C, respectively (Table 1). Ethylene production of fruit treated with 1-MCP alone or both 1-MCP and wax began to rise after 3 d storage at 20 °C, reaching a maximum of 412.5 and 163.1 μg kg^{-1} h^{-1} after 8 and 7 d storage at 20 °C, respectively. 1-MCP treatment delayed the ethylene climacteric of waxed and non-waxed fruit by 2 and 4 d, respectively. The application of 1-MCP also increased the maximum ethylene production of waxed and non-waxed fruit about 1.5- and 2.9-fold over respective treatments without 1-MCP treatment. There were no significant differences in days-to-peak ethylene production between waxed and non-waxed fruit with 1-MCP or between waxed and non-waxed fruit without 1-MCP, whereas there were significant ($P < 0.05$) differences in peak ethylene production (Table 1). Maximum ethylene production of waxed fruit with or without 1-MCP was reduced about 60 and 22%, respectively, compared with non-waxed fruit with or without 1-MCP.

3.1.3. Peel color

The peel of fruit after harvest had a moderate green color (hue angle = 125.3, where pure yellow = 90 and pure green = 180). At the full-ripe stage (10–20 N), there were significant ($P < 0.05$) differences in the L value (L^*), chroma value (C), and hue angle (H°) of the peel color among fruit from all treatments (Table 2). Changes in hue angle constituted the major alteration of fruit color coordinates. The decline in hue angle represented the change from green to yellow, and the increase in chroma value reflected increasing intensity of yellow color. At the full-ripe stage, fruit treated with wax and/or 1-MCP had more green color than non-waxed fruit without 1-MCP treatment (Table 2). Waxed fruit with or without 1-MCP treatment also had significantly lower L^* value and chroma value than non-waxed fruit.

3.1.4. Polygalacturonase activity

PG activity in control fruit (no 1-MCP and no wax) was very low in freshly harvested fruit, increased during the climacteric period, and continued to increase during the post-climacteric phase (Fig. 2). This pattern of PG accumulation in 'Tower II' avocado fruit is consistent with that shown for 'Fuerte' avocado Awad and Young, 1979; Zauberman and Schiffmann-Nadel, 1972 PG activity in waxed and non-waxed fruit without 1-MCP treatment increased significantly and reached levels 8.3- and 7.8-fold higher after 9 and 7 d at 20 °C, respectively, than initial activity values (Fig. 2). PG activity levels were significantly suppressed in both waxed and non-waxed 1-MCP-treated fruit. PG activity levels of waxed fruit treated with 1-MCP increased and reached levels 5.0-fold higher than initial levels after 11 d at 20 °C. PG levels of non-waxed fruit treated with 1-MCP were completely suppressed through 9 d and then increased, reaching values 4.6-fold higher than initial levels after 11 d at 20 °C (Fig. 2).

Table 2
Peel color of 'Tower II' avocados stored at 20 °C with 1-MCP (0.9 μl l^{-1} for 12 h at 20 °C) and/or wax treatments

Treatments	Days to fully ripe at 20 °C	L^*	Chroma	Hue angle
No 1-MCP, no wax	7	49.5 a	39.3 a	117.6 b
No 1-MCP, wax	9	42.8 b	27.8 b	121.9 a
1-MCP, no wax	11	46.2 a	36.6 a	120.7 ab
1-MCP, wax	11	40.7 b	26.0 b	124.1 a

Control fruit (no 1-MCP, no wax) were stored at 20 °C. Peel color was measured at the full-ripe stage. Values followed by the same letter in a column do not differ significantly according to Duncan's Multiple Range Test ($P < 0.05$). Initial L^*, chroma, and hue angle were 43.5, 30.1, and 125.3, respectively.

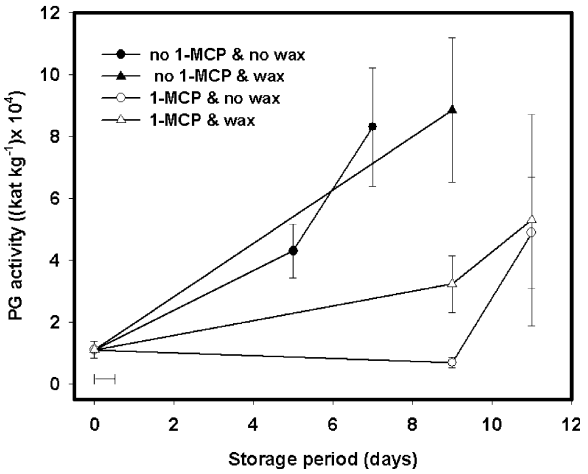

Fig. 2. Effect of 1-MCP on PG activity of 'Tower II' avocados stored at 20 °C with 1-MCP (0.9 μl l^{-1} for 12 h at 20 °C) and/or wax treatments. Control fruit (no 1-MCP, no wax) were stored at 20 °C. Vertical bars represent standard deviation of 3 independent samples. Horizontal bar represents the time interval of 1-MCP treatment (0.9 μl l^{-1} for 12 h at 20 °C).

3.2. 'Booth 7' experiments

The shelf-life extension (an additional 4 d at 20 °C) afforded by 1-MCP treatment of 'Simmonds' avocado fruit was similar to that reported for 'Tower II' avocado maintained under similar storage conditions (Jeong et al., 2002). In the present study, the adjunct use of wax was shown to dramatically reduce fruit weight loss during the prolonged storage periods. In order to estimate the long-term storage potential of West Indian/Guatemalan avocado strains in response to 1-MCP treatment, fruit (±1-MCP, all waxed) were stored at 13 °C, the lowest safe storage temperature for West Indian and Guatemalan avocado cultivars (Seymour and Tucker, 1993).

3.2.1. Fruit firmness and weight loss

Control fruit (waxed but not exposed to 1-MCP) softened and completed ripening (10–20 N) within 19 d of storage at 13 °C. In contrast, after 19 d of storage at 13 °C, fruit treated with both 1-MCP and wax exhibited a firmness value of 76.8 N. Softening of waxed fruit treated with 1-MCP was significantly delayed and firmness reached values (26.5 N) comparable to control fruit only after 37 d at 13 °C (Fig. 3A). Fruit after storage at 13 °C for 37 days showed no evidence of chilling injury (pitting, internal browning) and, based on informal assessment, retained acceptable organoleptic (taste and odor) quality. During storage beyond 37 d, fruit quality declined due to pathogen proliferation.

Weight loss of control fruit was 4.5% after 19 d of storage at 13 °C (Fig. 3B), whereas waxed fruit treated with 1-MCP showed weight loss values of 3.8%. After about 37 d, waxed fruit with 1-MCP (7.5%) lost more weight than waxed fruit without 1-MCP treatment (4.5%) at the full-ripe stage (day 19).

3.2.2. Respiration and ethylene evolution

Control fruit (waxed but not exposed to 1-MCP) showed characteristic respiratory climacteric patterns during storage at 13 °C (Table 3). Respiration in control fruit began to increase after 7 d storage at 13 °C (data not shown), with CO_2 production reaching a maximum of 66 mg kg^{-1} h^{-1} after 17 d storage at 13 °C. Respiration of waxed fruit treated with 1-MCP increased

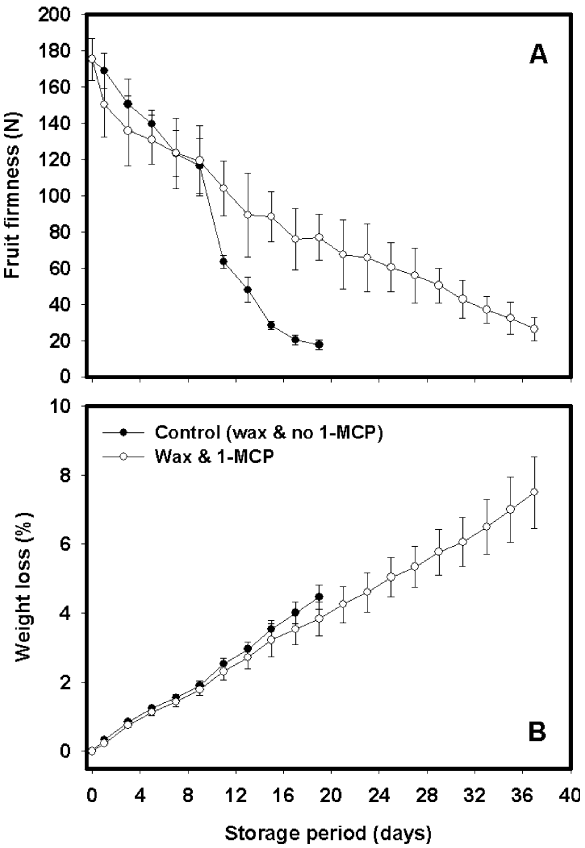

Fig. 3. Fruit firmness (N) and weight loss (%) of 'Booth 7' avocados stored at 13 °C after wax treatment with or without 1-MCP (0.9 μl l^{-1} for 12 h at 20 °C). Control fruit (no 1-MCP) were stored at 13 °C after wax treatment. Vertical bars represent standard deviation of 6 independent samples.

initially after 22 d storage at 13 °C (data not shown). A distinct respiratory peak in waxed fruit treated with 1-MCP was not observed during storage at 13 °C, but the maximum CO_2 production rate (61 mg kg^{-1} h^{-1}) observed at day 33 (the final respiratory determination) was similar to that of control fruit at their climacteric peak (day 17, Table 3). 1-MCP treatment delayed the respiratory climacteric pattern of waxed 'Booth 7' fruit by more than 16 d (Table 3).

Waxed fruit with or without 1-MCP showed characteristic ethylene climacteric patterns during storage at 13 °C (Table 3). Ethylene production in control fruit began to increase after 7 d storage at 13 °C (data not shown) and reached maximum production values 40.6 μg kg^{-1} h^{-1} after 16 d at 13 °C. Ethylene production of waxed fruit treated with 1-MCP began to rise after 20 d at 13 °C, reaching a maximum of 50.8 μg kg^{-1} h^{-1} after 25 d at 13 °C (Table 3). 1-MCP delayed the ethylene climacteric pattern of waxed fruit by about 9 d.

3.2.3. *Polygalacturonase activity*

PG activity in control 'Booth 7' avocado fruit (waxed but not exposed to 1-MCP) was very low in freshly harvested fruit, increased during the climacteric period, and continued to increase during the post-climacteric phase (Fig. 4). This pattern of PG activity in 'Booth 7' avocado fruit is consistent with that shown for 'Tower II' avocado. PG levels of control fruit increased significantly during the climacteric period, continued to in-

Table 3
Days to peak and maximum CO_2 and C_2H_4 production for 'Booth 7' avocados stored at 13 °C after wax treatment with or without 1-MCP (0.9 μl l^{-1} for 12 h at 20 °C)

Treatments	CO_2		C_2H_4	
	Days to peak	Maximum (mg kg^{-1} h^{-1})	Days to peak	Maximum (μg kg^{-1} h^{-1})
No 1-MCP, wax	17 b	65.7 ± 0.7	16 b	40.6 ± 13.6
1-MCP, wax	33 a[a]	60.7 ± 6.9[a]	25 a	50.8 ± 19.6

Control fruit (no 1-MCP) were stored at 13 °C after wax treatment. Initial rates of CO_2 and C_2H_4 production were 70.1 mg kg^{-1} h^{-1} and 2.0 μg kg^{-1} h^{-1}, respectively. Values followed by the same letter in a column do not differ significantly according to Duncan's Multiple Range Test ($P < 0.05$). Data are means ± standard deviation of 4 independent samples.

[a] Respiratory climacteric peak did not occur during storage at 13 °C, and data were measured before experiments were terminated due to decay incidence.

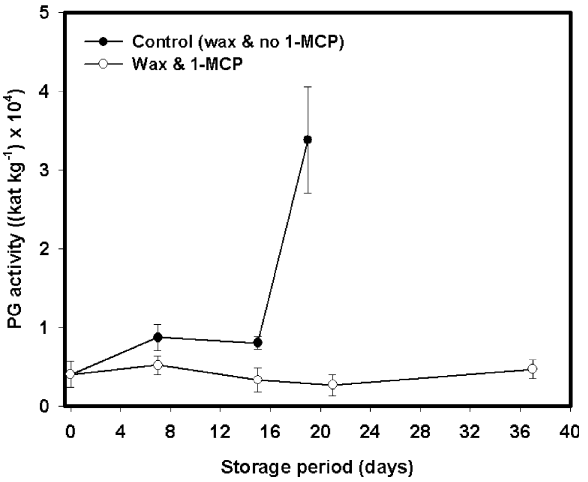

Fig. 4. Effect of 1-MCP on PG activity of 'Booth 7' avocados stored at 13 °C. Fruit were treated with wax and 1-MCP (0.9 μl l^{-1} for 12 h at 20 °C) and stored at 13 °C. Control fruit (no 1-MCP) were stored at 13 °C after wax treatment. Vertical bars represent standard deviation of 3 independent samples.

crease during the postclimacteric phase, and reached levels 8.5-fold higher than initial values (Fig. 4). PG activity levels of waxed fruit treated with 1-MCP showed little recovery during 37 d storage at 13 °C, remaining at levels comparable to or slightly lower than those detected at harvest.

4. Discussion

In the present study, 1-MCP and wax treatment significantly delayed the ripening and softening of 'Tower II' avocado fruit stored at 20 °C and 'Booth 7' avocado stored at 13 °C, as evaluated by firmness, weight loss, respiration and C_2H_4 production, peel color, and PG activity. 'Tower II' avocado fruit treated with 1-MCP required 2 to 4 more days at 20 °C to reach the full-ripe stage (10–20 N) than fruit without 1-MCP (Fig. 1A). In 'Booth 7' avocado, wax and 1-MCP significantly delayed fruit softening, and firmness decreased from >170 N to about 25 N over a 5-week period at 13 °C (Fig. 3A). Firmness of both cultivars was significantly retained in response to 1-MCP treatment, consistent with the fact that softening is one of the most sensitive ripening processes to ethylene (Lelievre et al., 1997a) Significantly delayed softening by 1-MCP in the present study substantiates that ethylene is involved in augmenting the activity of softening-related metabolism Lelievre et al., 1997a; Saltveit, 1999). Similar effects of 1-MCP at delaying fruit softening have been observed for 'Hass' (Feng et al. 2000) and 'Simmonds' (Jeong et al., 2002) avocado, apricot (Fan et al., 2000), and apple (Rupasinghe et al. 2000; Watkins et al., 2002) fruits.

Waxed 'Tower II' avocado fruit treated without or with 1-MCP required 2 or 4 more days, respectively, at 20 °C to reach the full-ripe stage than control fruit (Fig. 1A). This observation indicates that wax treatment alone also helped retain firmness and extended the storage life of avocado by reducing weight loss and ethylene production, as has been shown previously for 'Hass' avocado (Adato and Gazit, 1974; Joyce et al., 1995). Reduced water loss has been associated with shelf-life extension in ripening pear and banana (Littmann, 1972).

The results (Fig. 1) demonstrate that although there was a positive relationship between firmness and weight loss, they were not correlated with each other. Non-waxed 'Tower II' fruit treated with 1-MCP had significantly more weight loss (7.2%) than waxed fruit without 1-MCP treatment (2.7%) at day 9. At the same time, however, the firmness of non-waxed fruit treated with 1-MCP (26.1 N) was higher compared with waxed fruit without 1-MCP (20.4 N) (Fig. 1). A similar divergence in weight loss and firmness trends was evident for 'Booth' avocado fruit (Fig. 3).

1-MCP treatment significantly delayed the onset of climacteric ethylene and respiratory patterns in both 'Tower II' and 'Booth 7' avocado fruit (Tables 1 and 3). Similar effects of 1-MCP on climacteric behavior have been reported for other climacteric fruits (Fan and Mattheis, 1999; Fan et al., 2000; Golding et al., 1998, 1999; Feng et al. 2000; Jeong et al., 2002). The application of 1-MCP increased the magnitude of the ethylene peak in both 'Tower II' and 'Booth 7' cultivars (Tables 1 and 3), as was also reported for 1-MCP-treated banana fruit (Golding et al., 1998). Both 'Tower II' and 'Booth 7' treated with 1-MCP showed suppressed ethylene production and respiration for a significantly longer time than those treated

without 1-MCP (Tables 1 and 3). As evident from Table 2, green skin color was significantly retained in 1-MCP-treated fruit, consistent with a promotive effect of ethylene in chlorophyll catabolism (Knee, 1991; Jacob-Wilk et al., 1999).

The application of wax did not significantly influence the timing of the climacteric ethylene and respiratory patterns, but reduced the maximum ethylene production rate. In 'Tower II' avocado, wax significantly suppressed the magnitude of the ethylene peak but not the respiratory peak. In 'Booth 7,' fruit treated with wax and 1-MCP did not recover normal respiratory trends or rates during storage at 13 °C. The maximum CO_2 production rate, measured immediately prior to terminating the experiment, was significantly lower than that of waxed fruit without 1-MCP. Durand et al. (1984) reported that waxing caused an increase in internal CO_2 and a reduction in internal O_2 levels of 'Fuerte' avocado fruit. Although the present study showed that waxed fruit exhibited normal ethylene and respiratory patterns, suggesting that gas diffusion coefficients were not significantly altered, the possibility remains that modified internal atmosphere (higher CO_2/lower O_2) may have contributed to the delay in ripening. Controlled- and modified-atmosphere storage have been shown to be very effective in delaying the ripening and maintaining the keeping quality of 'Hass' avocado (Meir et al., 1994, 1997). The retention of green skin color in fruit treated with wax alone (no 1-MCP) is consistent with a role for modified-atmosphere conditions in the waxed fruit.

In an earlier study with 'Simmonds' avocado, several cell wall enzymes were monitored in 1-MCP-treated fruit. Of the enzymes examined, the activity trends of pectinmethylesterase, α-and β-galactosidases, and C_x-cellulase were delayed in 1-MCP-treated fruit but essentially followed patterns of accumulation or decline that paralleled the trends in control fruit (Jeong et al., 2002). In contrast, PG activity was strongly suppressed in 1-MCP-treated fruit, showing little or no recovery in activity during 12 d storage at 20 °C (Jeong et al., 2002). The present study showed that 1-MCP treatment of 'Tower II' and 'Booth 7' avocado fruit significantly suppressed PG activity. These data confirm the strong effect of 1-MCP on PG activity and recovery (Jeong et al., 2002), and are consistent with the report that PG mRNA accumulation is ethylene regulated (Sitrit and Bennett, 1998). Although softening was delayed in 1-MCP-treated fruit, it is clear that the main phase of softening does not require increased PG activity. The firmness of 1-MCP-treated 'Tower II' avocado fruit stored at 20 °C declined from values near 110 N to about 37 N prior to increases in PG activity. Similarly, 'Booth 7' avocado fruit stored at 13 °C softened from values near 180 N to near 40 N prior to detectable increases in PG (Fig. 3). We have observed that avocado fruit do not soften to values below 35 N in the absence of increased PG activity (Figs. 1 and 3; Jeong et al., 2002). As is the case for tomato fruit (Carrington et al., 1993; Kramer et al., 1992), PG activity is more closely associated with softening occurring during the late stages of avocado softening.

5. Conclusions

In an earlier study with 'Simmonds' avocado, 1-MCP delayed ripening of avocado fruit and extended the storage period at 20 °C. In the present study using 'Tower II' avocado, the adjunct use of wax along with 1-MCP did not extend shelf-life at 20 °C beyond that achieved with 1-MCP alone but significantly reduced weight loss and maintained more green color. Although wax alone was not as effective as 1-MCP, wax delayed firmness decline, reduced weight loss, and maintained green color. Experiments using 'Booth 7' avocado showed that low-temperature storage (13 °C) of fruit treated with wax and 1-MCP resulted in an additional extension in shelf-life and quality maintenance compared with 20 °C storage. Many fruit have been reported to respond favorably to 1-MCP treatment; however, it is evident that the avocado, in terms of postharvest storage extension and quality persistence, is a prime candidate for commercial application of ethylene action inhibitors.

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