Postharvest Ripening and Quality of Guatemalan-West Indian Avocado Hybrids under Simulated Commercial Shipping Temperatures Following Treatment with Aqueous 1-Methylcyclopropene

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SUMMARY. Two Guatemalan-West Indian avocado (*Persea americana*) hybrids ('Monroe' and 'Booth 8') were treated with an aqueous formulation of 1-methylcyclopropene (1-MCP) to determine effects on ripening and quality during storage simulating commercial shipping temperatures. Fruit harvested at preclimacteric stage were immersed in aqueous 1-MCP at 75 $\mu\text{g}\cdot\text{L}^{-1}$ (1.39 $\text{mmol}\cdot\text{m}^{-3}$) or in deionized water for 1 minute, stored at 10 °C for 14 days, and then transferred to 20 °C until ripe. Respiration rate, ethylene production, softening, and change in epidermal hue* angle were delayed and/or suppressed in both cultivars exposed to 1-MCP, although effects were less pronounced with Booth 8. Hue* angles for 1-MCP-treated 'Monroe' fruit had the highest values (darkest green peel color) of all treatments at full-ripe stage (hue* angle = 117). For control and treated 'Monroe' fruit respiration peaked on days 15 and 21, while ethylene production from both treatments peaked on day 16. Respiration and ethylene production peaked on day 16 for both control and 1-MCP-treated 'Booth 8' fruit. Fruit treated with 1-MCP consistently showed diminished respiration and ethylene peaks. Days to full-ripe stage were unaffected by treatment. 'Booth 8' fruit from both treatments were considered ripe (15 N whole fruit firmness) after 17 days; however, only 8% of control fruit were marketable, whereas 58% of 1-MCP-treated fruit were marketable, based on subjective appearance ratings using the Jenkins-Wehner score. The development of peel blemishes during storage was the primary cause of unmarketable fruit. 'Monroe' control and 1-MCP-treated fruit were soft after about 22 days and were significantly more marketable (control 70% and 1-MCP 85%). Avocados treated with 1-MCP ripened over a longer period than control fruit but maintained a higher percentage of marketable fruit.

Hybrid avocado cultivars of Indian and West Indian-Guatemalan origin are the main types grown in tropical production areas around the world. More than 60 cultivars are grown in southern Florida, permitting an extended harvest season from May to early March (Crane et al., 2007). Since $\approx 80\%$ of the fruit is shipped outside the state, quality maintenance over extended periods is critical to growers and shippers (Bronson, 2009; Evans and Nalampang, 2006).

Avocados typically ripen within a few days of harvest (Seymour and Tucker, 1993); however, fruit can be

stored for 10 to 21 d at 4 to 13 °C, depending on cultivar (Woolf et al., 2004). West Indian and Guatemalan-West Indian avocado hybrids are more temperature sensitive than Guatemalan and Mexican types and are prone to develop chilling injury when stored below 13 °C, depending upon the cultivar (Campbell and Hatton,

1959). A limiting factor of storing avocados for extended periods is the expression of internal pulp discoloration, a chilling injury symptom that can develop during poor temperature management or ethylene exposure (Chaplin et al., 1983; Pesis et al., 2002). Other reports have noted that application of the inhibitor of ethylene perception, 1-MCP (Sisler, 2006; Sisler et al., 2003) reduced the expression of certain physiological disorders during storage such as flesh discoloration, stringy vascular tissue, and decays for numerous crops (Blankenship and Dole, 2003; Huber, 2008), including 'Hass' avocado, a Guatemalan type cultivar (Adkins et al., 2005; Woolf et al., 2005).

Gaseous 1-MCP is commercially applied to fruit held in sealed containers or rooms over periods up to 24 h; however, an aqueous formulation of 1-MCP available for preharvest application shows promise for postharvest application. Choi et al. (2008) demonstrated that a 1-min immersion in a solution of 1-MCP at 625 $\mu\text{g}\cdot\text{L}^{-1}$ suppressed 'Hass' avocado ripening comparable to a 9-h exposure to gaseous 1-MCP at 500 $\text{nL}\cdot\text{L}^{-1}$. Aqueous 1-MCP treatments at 1.39 and 2.77 $\mu\text{mol}\cdot\text{L}^{-1}$ delayed ripening of 'Simmonds' by 33% and 67%, 'Booth 7' by 40% and 80%, and 'Monroe' by 50% and 83% (Pereira et al., 2013b). Issues of concern regarding commercial postharvest use of aqueous 1-MCP include the necessity for uniform coverage of the targeted commodity, the compatibility of aqueous 1-MCP with other postharvest treatments and potential volatilization into the surrounding area causing loss of aqueous 1-MCP efficacy or unintended exposure of other crops (Choi et al., 2008). Published studies have focused on avocado ripening under ideal ripening conditions

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Units

To convert U.S. to SI, multiply by	U.S. unit	SI unit	To convert SI to U.S., multiply by
29.5735	fl oz	mL	0.0338
3.7854	gal	L	0.2642
25.4	inch(es)	mm	0.0394
0.0044	lbf	kN	224.8089
4.4482	lbf	N	0.2248
28.3495	oz	g	0.0353
1	ppb	$\mu\text{g}\cdot\text{kg}^{-1}$	1
1	ppb	$\mu\text{g}\cdot\text{L}^{-1}$	1
1	ppm	$\mu\text{L}\cdot\text{kg}^{-1}$	1
(°F – 32) ÷ 1.8	°F	°C	(°C × 1.8) + 32

(20 °C). However, typical transit shipping temperatures for Guatemalan-West Indian avocado hybrids range from 10 to 13 °C, depending on the cultivar and shipping distance; however, upon receiving at distribution centers, they are normally held at room temperature (20 to 22 °C).

The objective of this study was to examine the potential of using an aqueous formulation of 1-MCP to delay fruit ripening of two Guatemalan-West Indian avocado hybrids under a simulated commercial handling scenario.

Materials and methods

PLANT MATERIAL. Two late-season avocado cultivars, Monroe and Booth 8 were harvested at preclimacteric stage according to the 2009–10 shipping schedule regulated by the Florida Avocado Administrative Committee (FAAC). The FAAC annually establishes four harvest dates (labeled A, B, C, D) for each cultivar based on minimum fruit size and weight (FAAC, 2014). The largest fruit are harvested at Harvest Date A, and the minimum required fruit size/weight decreases with successive Harvest Dates B, C, and D. ‘Monroe’ fruit were harvested on 18 Nov. 2009 (Harvest Date A) and ‘Booth 8’ on 7 Jan. 2010 (Harvest Date D) from commercial groves in Miami-Dade County, FL. On the day of harvest, fruit were transported at 22 °C to the Postharvest Horticulture Laboratory, (Horticultural Sciences Department, University of Florida, Gainesville). Following overnight storage at 20 °C, sound fruit of uniform size (average weight of 853 g for ‘Monroe’ and 445 g for ‘Booth 8’) were selected for treatment.

AQUEOUS 1-MCP PREPARATION, TREATMENT, AND STORAGE. Fruit were placed in mesh bags (‘Booth 8’: $n = 24$; ‘Monroe’: $n = 20$ per treatment), then immersed in aqueous 1-MCP (prepared from AFXRD-038 powder, 3.8% a.i.; AgroFresh, Rohm and Haas, Philadelphia, PA) at $75 \mu\text{g}\cdot\text{L}^{-1}$ ($1.39 \text{ mmol}\cdot\text{m}^{-3}$) or in deionized water (control) at 20 °C for 1 min, according to (Choi et al., 2008). Following treatments, fruit were dried with paper towels and packed in single-layer, commercial shipping cartons. Fruit were stored at 10 °C (85% to 90% relative humidity) for 14 d to simulate commercial shipping

conditions, then transferred to 20 °C for ripening.

FRUIT QUALITY ASSESSMENTS. During storage, whole fruit firmness, subjective quality ratings, external color, ethylene production, respiration rate, and weight loss were measured at 2- to 3-d intervals. Nondestructive compression tests were performed on whole, unpeeled fruit (‘Booth 8’: $n = 24$; ‘Monroe’: $n = 20$ per treatment) using a Universal Testing Instrument (model 4411; Instron, Canton, MA) fitted with a flat-plate probe (5 cm diameter) and 0.5-kN load cell. The probe was driven with a crosshead speed of $20 \text{ mm}\cdot\text{min}^{-1}$ and the force was recorded at 2.5 mm deformation on opposite sides of the equatorial region of each fruit. Maximum force generated during probe travel was used for firmness values. Avocados were considered full-ripe when whole fruit firmness decreased to 15 N, the point at which the fruit was considered too soft for commercial handling (Jeong et al., 2002).

During storage, avocado marketability was evaluated based on peel blemishes. Surface area affected by blemishes was estimated using the Jenkins–Wehner score, where: 0 = 0%, 1 = 0% to 3%, 2 = 3% to 6%, 3 = 6% to 12%, 4 = 12% to 25%, 5 = 25% to 50%, 6 = 50% to 75%, 7 = 75% to 87%, and 8 = 87% to 100% (Jenkins and Wehner, 1983). A score of 3 was considered to be the limit of marketability based on the U.S. Department of Agriculture (USDA) avocado grade standards that limit appearance defects to 10% of the fruit surface (USDA, 1957). Percent marketable fruit were calculated from the number of fruit that softened to full-ripe stage ($\leq 15 \text{ N}$) with a Jenkins–Wehner score of ≤ 3 .

Peel color at the equatorial region was monitored during storage by reflectance colorimetry (hue* angle) with a chroma meter (model CR-400; Konica Minolta, Tokyo, Japan) operating with a C illuminant and 11-mm diameter aperture according to McGuire (1992). When possible, peel blemishes were avoided during color readings. A hue* angle of 180° represents green and 90° represents yellow.

Respiration rate and ethylene production were measured daily on fruit held at 10 °C for 14 d, then transferred to 20 °C until ripe. Avocado fruit were individually placed in 2-L plastic containers ($n = 4$ per treatment) fitted with

septa and sealed for 60 or 20 min while stored at 10 or 20 °C, respectively. A 5-mL headspace sample was withdrawn and analyzed as described in detail by Zhang et al. (2011). Individual fruit weights were tracked throughout storage and percent weight loss was calculated and reported on fresh weight basis.

Avocados remained in storage, regardless of peel appearance, and the above mentioned parameters were measured until fruit firmness reached 15 N or at the first signs of decay at which time they were removed from storage.

STATISTICAL ANALYSIS. The experiment was conducted in a completely randomized design. Data were analyzed using SAS (version 9.1.3, SAS Institute, Cary, NC). Significant differences between means were separated using Duncan’s multiple range test ($P \leq 0.05$).

Results and discussion

At harvest, initial firmness values were 250 and 192 N for ‘Monroe’ and ‘Booth 8’ fruit, respectively (Fig. 1). During storage at 10 °C, 4% of ‘Booth 8’ control fruit softened and reached full-ripe stage (the 15-N limit for whole fruit firmness) by day 12. However, after 14 d at 10 °C, there were no differences in firmness due to treatment: ‘Monroe’ fruit remained relatively firm (130 N), while ‘Booth 8’ fruit were significantly softer (37 N) (Fig. 1). Following transfer to 20 °C, there was no effect of 1-MCP on ‘Booth 8’, where the majority of fruit from both treatments ripened by day 17. ‘Monroe’ fruit for both treatments ripened after 20 d (control) and 23 d (1-MCP); however, these ripening periods were not significantly different due to fruit-to-fruit variability. Control ‘Monroe’ fruit ripened within a 3-d period (19 to 21 d), whereas 1-MCP-treated fruit ripened over an extended 8-d period (from 19 to 27 d).

In previous studies by Pereira et al. (2013b), ‘Monroe’ avocados were treated in the same manner with aqueous 1-MCP, but under continuous storage at 20 °C; these fruit ripened in 12 and 18 d for control- and 1-MCP-treated fruit, respectively. The authors also reported that avocado ripening rate was cultivar-dependent; the early season cultivar Simmonds (West Indian type) responded to 1-MCP, but softened at an accelerated rate compared with late-season cultivar Monroe (6 and 10 d for

control and treated fruit, respectively). Similar responses were reported for another early-to-midseason cultivar, Beta (Guatemalan-West Indian type), that softened in 8 (control) and 14 d (1-MCP-treated) at 20 °C (Pereira et al., 2013a). Ripening asynchrony in individual fruit was reported for 1-MCP-treated avocados (Pereira, 2010); however, in the present tests, fruit from both cultivars ripened uniformly, possibly due to application of lower 1-MCP concentrations than those used by Pereira (2010).

Based on the L^* data ($L^* 0$ = black and 100 = white), peel blemishes did not affect peel color determinations, combined mean L^* values (control and 1-MCP-treated fruit) during storage ranged from 38.96 to 46.75 for 'Monroe' and from 38.12 to 40.27 for 'Booth 8' (data not shown). Initial peel color was similar for both cultivars (hue* angle = 121° to 124°); during storage at 10 °C, Monroe fruit remained slightly darker green than Booth 8 fruit (Fig. 2). Following transfer to 20 °C, hue* angles for control 'Monroe' fruit were higher (darker green) than 'Booth 8' fruit on day 18; 1-MCP-treated 'Monroe' fruit had the highest values of all treatments when ripe (hue* angle = 117). This effect of 1-MCP in delaying the breakdown of chlorophyll was also observed with several Guatemalan-West Indian avocado cultivars that were treated with either gaseous (Jeong et al., 2002) or aqueous 1-MCP (Pereira et al., 2014).

During storage at 10 °C, the respiration rate and ethylene production remained at basal levels for 'Monroe' fruit. After transfer to 20 °C, respiration peaked on days 15 and 21 for control and 1-MCP-treated 'Monroe' fruit, respectively, although the latter peak was attenuated by 40% relative to the control (Fig. 3A). Ethylene production for 'Monroe' fruit from both treatments peaked 2 d after transfer to 20 °C (day 16) (Fig. 3B). By contrast, respiration and ethylene production for 'Booth 8' fruit began to increase during storage at 10 °C. By day 9, the respiration rate of control 'Booth 8' was about twice that of 1-MCP-treated fruit, and this trend continued following transfer to 20 °C and subsequent ripening (Fig. 3A). The onset of the ethylene climacteric in 'Booth 8' preceded that of respiration,

Fig. 1. Whole fruit firmness of 'Monroe' and 'Booth 8' avocado untreated or treated with $75 \mu\text{g}\cdot\text{L}^{-1}$ (ppb) aqueous 1-methylcyclopropene (1-MCP) during storage at 10 °C (50.0 °F) for 14 d and transfer to 20 °C (68.0 °F) until ripe. Vertical bars represent SD; 1 N = 0.2248 lbf.

Fig. 2. External hue* angle values for 'Monroe' and 'Booth 8' avocado untreated or treated with $75 \mu\text{g}\cdot\text{L}^{-1}$ (ppb) aqueous 1-methylcyclopropene (1-MCP) during storage at 10 °C (50.0 °F) for 14 d and transfer to 20 °C (68.0 °F) until ripe. Vertical bars represent SD (n = 4).

beginning by day 6 at 10 °C (Fig. 3B). Both respiration and ethylene production peaked on day 16; maxima for 1-MCP-treated fruit were attenuated.

Control and 1-MCP-treated 'Booth 8' fruit were ripe after 17 d; only 8% of control fruit were marketable, whereas 58% of 1-MCP-treated fruit were marketable, a 7-fold increase (Table 1). At full-ripe stage, there were significantly more

marketable 'Monroe' avocados (70% to 85%) than 'Booth 8' avocados (Table 1). Some fruit from both cultivars never softened to full-ripe stage: more 'Booth 8' fruit remained unripe (control = 33%, 1-MCP = 17%) compared with 'Monroe' fruit (control = 0% and MCP = 10%) (data not shown). Peel blemishes were the principal reason that fruit from both cultivars were rated unmarketable

(A)

(B)

Fig. 3. Avocado respiration [CO_2 (A)] and ethylene (B) rates for 'Monroe' and 'Booth 8' avocado untreated or treated with $75 \mu\text{g}\cdot\text{L}^{-1}$ (ppb) aqueous 1-methycyclopropene (1-MCP) during storage at 10°C (50.0°F) for 14 d and transferred to 20°C (68.0°F) until ripe. Vertical bars represent SD ($n = 4$); $1 \mu\text{g}\cdot\text{kg}^{-1} = 1$ ppb, $1 \mu\text{L}\cdot\text{kg}^{-1} = 1$ ppm.

Table 1. Effect of 1-methycyclopropene (1-MCP) on ripening, marketability, and weight loss of 'Monroe' and 'Booth 8' avocados during 27 d storage [14 d at 10°C (50.0°F) plus 13 d at 20°C (68.0°F)].

Cultivar	Ripening period (d) ^a		Marketable fruit (%) ^b		Wt loss (%)	
	Control	1-MCP	Control	1-MCP	Control	1-MCP
Monroe	20 ± 0.94	23 ± 2.57	70 ± 14.14	85 ± 8.40	6.83 ± 0.91	8.17 ± 1.35
Booth 8	17 ± 1.74	17 ± 1.45	8 ± 2.41	58 ± 11.80	5.92 ± 1.05	6.09 ± 1.14

^aFull-ripe stage was determined from the average days for the majority of fruit to soften to 15 N (3.4 lbf).

^bPercent marketable fruit were calculated from the number of ripe fruit with Jenkins–Wehner Score of ≤ 3 (Jenkins and Wehner, 1983). Unripe fruit after 27 d of storage were not included.

(Jenkins–Wehner score $>3\%$, or $>12\%$ surface affected) and developed primarily following transfer to 20°C .

There was no obvious decay on 'Monroe' fruit; however, 'Booth 8' fruit showed 4% and 8% decay on 1-MCP-

treated and control, respectively, putatively identified as anthracnose (data not shown).

In this study, both cultivars lost 6% to 8% weight during storage; Monroe fruit lost more weight than Booth 8, likely due to longer storage/ripening times (Table 1). These findings are similar to those reported by Jeong et al. (2002), where control and gaseous 1-MCP-treated avocado fruit displayed 6% to 7% weight loss during 12-d storage at 20°C . However, despite similar weight loss in this study, no stem-end shriveling was observed, consistent with a report by Pereira et al. (2013a).

Avocado is unique among climacteric fruits in that ripening initiates only following detachment from the tree. Gazit and Blumenfeld (1970) reported that 'Hass' avocado did not uniformly respond to ethylene exposure until 2 d postharvest. The minimal response of 'Booth 8' to 1-MCP in this study was most likely due to the extremely late harvest date (7 Jan. 2010). Harvest date D (the latest date for commercial harvest) began on 26 Oct. for 'Booth 8', more than 2 months earlier than the actual harvest date. Avocados harvested late in the season have an inherently shorter delay to the initiation of ripening, and hence lower sensitivity to 1-MCP (Huber, 2008). Woolf et al. (2004) noted that, with increasing delay to harvest, avocados required less exposure time to ethylene to initiate ripening and were more tolerant of lower storage temperatures. Respiration rate and ethylene production for 'Booth 8' fruit supported the effect of the late harvest, where ripening in both control and 1-MCP-treated fruit initiated after only 6 d at

10°C (Fig. 2). By contrast, early harvested 'Monroe' fruit (Harvest Date A, before 23 Nov.) remained

preclimacteric during 14 d storage at 10 °C, possibly due to low sensitivity to 1-MCP.

In this study, Guatemalan-West Indian type avocados treated with aqueous 1-MCP (75 µg·L⁻¹ for 1 min) maintained better appearance during ripening under commercial conditions than untreated fruit. However, harvest maturity had a greater effect on the onset of ripening than treatment with 1-MCP. Determination of the full commercial potential of 1-MCP to delay ripening in these avocado hybrids will require further study of 1-MCP concentration, formulation (gaseous vs. aqueous), and exposure time for each cultivar and harvest date.

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