Effects of Rapid Consecutive Postharvest 1-Methylcyclopropene Treatments on Fruit Quality and Storage Disorders in Apples

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Abstract. The objective of this study was to investigate the effects of rapid consecutive 1-methylcyclopropene (1-MCP) treatments on apple quality and disorders in storage. 'McIntosh' and 'Spartan' apples were harvested twice from commercial orchards and 1-MCP ($1 \mu\text{L}\cdot\text{L}^{-1}$) was applied postharvest either 1 day after harvest or 1 and 2 days after harvest. Similar fruit from both cultivars were also not treated with 1-MCP, plus an additional treatment of $2 \mu\text{L}\cdot\text{L}^{-1}$ (double rate) 1-MCP was used on 'McIntosh'. Fruit were held in either air storage at 0.5°C for three or six months or in controlled-atmosphere (CA) storage for six or nine months. Overall, 1-MCP treatment improved firmness and acidity retention and reduced internal ethylene in both cultivars. However, 'Spartan' stored in CA often maintained these attributes without 1-MCP. 'McIntosh' apples treated twice with 1-MCP were often firmer than those treated just once. All 1-MCP treatments substantially reduced superficial scald and there was no difference in scald incidence among the treatments. Core browning was generally reduced by 1-MCP, but fruit treated once with $2 \mu\text{L}\cdot\text{L}^{-1}$ or twice with $1 \mu\text{L}\cdot\text{L}^{-1}$ 1-MCP sometimes had higher incidence than fruit treated only once with $1 \mu\text{L}\cdot\text{L}^{-1}$. 'Spartan' treated twice with 1-MCP also had higher incidence of internal browning after nine months. 1-MCP increased the incidence of external CO_2 injury in 'McIntosh' from the first harvest, with fruit treated with $2 \mu\text{L}\cdot\text{L}^{-1}$ having the highest incidence after six months of CA storage and those treated once with $1 \mu\text{L}\cdot\text{L}^{-1}$ having the highest incidence after nine months. Storage rots were greatest after six months of air storage and 1-MCP treatments usually reduced the incidence, regardless of treatment. These results suggest that using more than the traditional single application of $1 \mu\text{L}\cdot\text{L}^{-1}$ 1-MCP may improve firmness retention, but there is also some risk associated with increased disorders, especially when storing apples long-term, such as for six months in air or nine months in CA storage.

1-MCP is an inhibitor of ethylene perception that can delay fruit ripening and extend storage life. 1-MCP is marketed as Smart-Fresh™ for postharvest treatment and its use has become common practice in many apple-growing regions. 1-MCP reduces ethylene production and respiration rate, improves firmness and acidity retention, and controls senescent-related disorders in apples (DeEll et al., 2007; Fan et al., 1999a, 1999b; Watkins, 2007). 1-MCP has also been shown to increase the risk of stress-related disorders in apples; increased incidence of CO_2 injury or flesh browning has been found in 1-MCP-treated 'McIntosh' and 'Empire' apples (DeEll et al., 2003; Fawbush et al., 2008; Jung and Watkins, 2011). Efficacy of 1-MCP treatment depends

on apple cultivar (Bai et al., 2005; Watkins et al., 2000), harvest maturity (DeEll et al., 2008; Toivonen and Lu, 2005), and temperature and timing of application (DeEll et al., 2002; Watkins and Nock, 2005). Effects of 1-MCP on 'McIntosh' apples are reduced in later harvests and with longer delays between harvest and treatment (DeEll et al., 2008).

Postharvest treatment of 1-MCP ($1 \mu\text{L}\cdot\text{L}^{-1}$) has traditionally involved a single application soon after harvest. It is recommended that 'McIntosh' be treated with 1-MCP within 3 d of harvest for maximum effectiveness (AgroFresh, 2012; DeEll et al., 2008). This has been difficult for small growers with storages that can take 1 week or more to fill.

The SmartFresh™ label in Canada was expanded in 2011 to allow up to four applications of 1-MCP ($1 \mu\text{L}\cdot\text{L}^{-1}$) within 240 d of harvest. Without such restrictions, the label in the United States was modified to include multiple applications in 2009. As a result, many storage operations are treating rooms with 1-MCP more than once during filling. This has provoked interest in the possibility that more than one application of 1-MCP could enhance the fruit quality benefits, but

also potentially increase the development of disorders that are aggravated by 1-MCP.

Preliminary studies have shown that a second 1-MCP treatment after four or eight months of CA storage can improve firmness retention and reduce ethylene production and respiration rate in 'Empire' apples harvested at optimum maturity (DeEll and Murr, 2005). Response to 1-MCP was better when apples were held in low O_2 CA ($1.2 \text{ kPa O}_2 + 1.0 \text{ kPa CO}_2$) than in standard CA ($2.5 \text{ kPa O}_2 + 2.0 \text{ kPa CO}_2$) at 2°C , and the effects diminished with increased time after removal from CA before 1-MCP treatment. This same study found little effect of 1-MCP on 'Empire' and 'Delicious' apples when the treatment followed air storage instead of CA. DeLong et al. (2004) found no effect of an additional 1-MCP application after 4.5 months on 'Cortland' and 'McIntosh' apples held in air and CA storage, but the concentration of 1-MCP was less than that used commercially. Mir et al. (2001) found the most effective 1-MCP treatment frequency was once per week in 'Redchief Delicious' apples at elevated temperatures (5 to 20°C). More recently, Watkins et al. (personal communication) showed little advantage of repeated 1-MCP applications at 4 or 7 d after harvest in addition to treatment 1 d after harvest.

There have been no scientific reports on the effects of rapid consecutive 1-MCP treatments on apples at harvest, simulating daily 1-MCP applications as storage rooms are loaded with fruit. The objective of this study was to investigate the effects of rapid consecutive postharvest 1-MCP treatments (1 and 2 d after harvest) on fruit quality and storage disorders in apples. 'McIntosh' and 'Spartan' apples were studied through long-term storage in air and CA. 'McIntosh' was also used to determine if two consecutive treatments of the label rate ($1 \mu\text{L}\cdot\text{L}^{-1}$ 1-MCP) were equivalent to one application at double concentration ($2 \mu\text{L}\cdot\text{L}^{-1}$). There have been no scientific reports of 1-MCP treatment on 'Spartan' apples.

Materials and Methods

Plant material. 'McIntosh' apples were harvested on 12 Sept. (Harvest 1) and 19 Sept. (Harvest 2) in 2011 from the same commercial orchard located in Simcoe (Norfolk County), Ontario, Canada. There were 48 boxes of apples (more than 100 fruit in each) for each harvest time. Each box contained fruit from several trees and various locations within the trees. Apples were transported immediately to the nearby storage research facility and cooled overnight at 3°C .

'Spartan' apples were harvested on 20 and 29 Sept. in 2011 from commercial orchards located in Saint-Paul-d'Abbotsford and Sainte-Cécile-de-Milton (respectively), Quebec, Canada. There were 36 boxes of apples for each harvest time. Apples were transported overnight by refrigerated truck ($\approx 3^\circ\text{C}$) to the storage research facility in Simcoe, Ontario, Canada.

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Postharvest treatments. The following 1-MCP treatments were applied to 12 boxes of each cultivar from each harvest and orchard: 1) 1 $\mu\text{L}\cdot\text{L}^{-1}$ applied 1 d after harvest; 2) 1 $\mu\text{L}\cdot\text{L}^{-1}$ applied 1 and 2 d after harvest; and 3) no 1-MCP. In addition, 12 boxes of ‘McIntosh’

apples from each harvest were treated with 2 $\mu\text{L}\cdot\text{L}^{-1}$ 1-MCP at 1 d after harvest, to determine if one application at double concentration was equivalent to two consecutive treatments of 1 $\mu\text{L}\cdot\text{L}^{-1}$. All 1-MCP applications were made using SmartFresh™ tablets (AgroFresh Inc., Spring House, PA) within an air-tight treatment tent (Storage Control Systems Inc., Sparta, MI) and lasted for 24 h at 3 °C.

Three boxes from each treatment were then held in either air storage at 0.5 °C for three or six months or in CA storage for six or nine months. CA storage for ‘McIntosh’ consisted of 2.5 kPa O₂ + 2.5 kPa CO₂ for one

Table 1. Harvest dates and maturity of ‘McIntosh’ and ‘Spartan’ apples.

Harvest date	Firmness (N)	Internal ethylene ($\mu\text{L}\cdot\text{L}^{-1}$)	Soluble solids (%)	Malic acid (mg/100 mL)	Starch index (1–8)
<i>McIntosh</i>					
12 Sept.	66.6 ± 1.3	23 ± 100	10.5 ± 0.4	805 ± 95	4.7 ± 0.8
19 Sept.	57.6 ± 0.8	3 ± 12	10.6 ± 0.5	738 ± 0	6.0 ± 0.6
<i>Spartan</i> ^z					
20 Sept.	70.2 ± 1.2	2 ± 7	9.3 ± 0.1	536 ± 77	2.3 ± 0.4
29 Sept.	63.0 ± 1.1	44 ± 73	10.7 ± 0	486 ± 19	4.3 ± 1.2

^z‘Spartan’ apples were harvested from two different orchards.

Table 2. Quality and disorders of ‘McIntosh’ apples treated without or with 1-MCP 1 d (1 or 2 $\mu\text{L}\cdot\text{L}^{-1}$) or 1 and 2 d (1 $\mu\text{L}\cdot\text{L}^{-1}$) after harvest and stored for three or six months in air at 0.5 °C plus 1 or 7 d at room temperature (RT, ≈18 to 22 °C).

	Firmness (N)	Internal ethylene ($\mu\text{L}\cdot\text{L}^{-1}$)	Soluble solids (%)	Malic acid (mg/100 mL)	Superficial scald (%)	Core browning (%)	Storage rots (%)
Air—three months							
Harvest 1							
1 d at RT							
No 1-MCP	38.3 ^{H-J}	587 ^B	11.9 ^{A-C}	726 ^{D-F}	—	—	—
1 $\mu\text{L}\cdot\text{L}^{-1}$ Day 1	44.6 ^D	5 ^C	11.9 ^{A-C}	816 ^{A-D}	—	—	—
2 $\mu\text{L}\cdot\text{L}^{-1}$ Day 1	53.1 ^A	49 ^C	12.0 ^{A-C}	894 ^A	—	—	—
1 $\mu\text{L}\cdot\text{L}^{-1}$ Days 1 and 2	49.1 ^B	7 ^C	12.4 ^A	805 ^{A-E}	—	—	—
7 d at RT							
No 1-MCP	36.0 ^J	968 ^A	11.6 ^{B-D}	704 ^{EF}	0	5 ^B	0 ^B
1 $\mu\text{L}\cdot\text{L}^{-1}$ Day 1	44.1 ^{DE}	2 ^C	12.3 ^{AB}	827 ^{A-D}	0	0 ^C	0 ^B
2 $\mu\text{L}\cdot\text{L}^{-1}$ Day 1	47.7 ^{BC}	5 ^C	12.0 ^{A-C}	872 ^{A-C}	0	0 ^C	2 ^A
1 $\mu\text{L}\cdot\text{L}^{-1}$ Days 1 and 2	45.9 ^{CD}	2 ^C	12.5 ^A	883 ^{AB}	0	0 ^C	0 ^B
Harvest 2							
1 d at RT							
No 1-MCP	33.8 ^K	658 ^B	11.0 ^{D-F}	637 ^{FG}	—	—	—
1 $\mu\text{L}\cdot\text{L}^{-1}$ Day 1	42.3 ^{EF}	37 ^C	11.1 ^{D-F}	749 ^{DE}	—	—	—
2 $\mu\text{L}\cdot\text{L}^{-1}$ Day 1	37.4 ^{IJ}	42 ^C	12.0 ^{A-C}	771 ^{C-E}	—	—	—
1 $\mu\text{L}\cdot\text{L}^{-1}$ Days 1 and 2	39.2 ^{G-I}	16 ^C	10.9 ^{D-F}	793 ^{A-E}	—	—	—
7 d at RT							
No 1-MCP	32.9 ^K	844 ^A	10.8 ^{EF}	603 ^G	0	10 ^A	1 ^B
1 $\mu\text{L}\cdot\text{L}^{-1}$ Day 1	40.5 ^{FG}	7 ^C	11.5 ^{C-E}	782 ^{B-E}	0	0 ^C	0 ^B
2 $\mu\text{L}\cdot\text{L}^{-1}$ Day 1	39.6 ^{GH}	5 ^C	11.4 ^{C-F}	782 ^{B-E}	0	0 ^C	0 ^B
1 $\mu\text{L}\cdot\text{L}^{-1}$ Days 1 and 2	37.8 ^{H-J}	4 ^C	10.7 ^F	771 ^{C-E}	0	1 ^C	0 ^B
Significance ^z	****	****	****	****	—	****	**
Air—six months							
Harvest 1							
1 d at RT							
No 1-MCP	33.8 ^{EF}	687 ^A	11.0 ^{A-E}	536 ^{A-D}	—	—	—
1 $\mu\text{L}\cdot\text{L}^{-1}$ Day 1	36.5 ^{CD}	77 ^F	11.3 ^{A-C}	592 ^{A-C}	—	—	—
2 $\mu\text{L}\cdot\text{L}^{-1}$ Day 1	39.2 ^{AB}	116 ^{EF}	11.6 ^A	648 ^A	—	—	—
1 $\mu\text{L}\cdot\text{L}^{-1}$ Days 1 and 2	37.8 ^{BC}	144 ^{EF}	11.5 ^{AB}	581 ^{A-C}	—	—	—
7 d at RT							
No 1-MCP	30.6 ^{GH}	624 ^A	11.0 ^{A-E}	436 ^{C-E}	64 ^A	88 ^A	6 ^A
1 $\mu\text{L}\cdot\text{L}^{-1}$ Day 1	39.6 ^{AB}	203 ^{C-F}	11.4 ^{AB}	570 ^{A-C}	7 ^C	46 ^C	2 ^B
2 $\mu\text{L}\cdot\text{L}^{-1}$ Day 1	38.7 ^B	217 ^{C-E}	11.0 ^{A-E}	626 ^{AB}	4 ^{CD}	47 ^C	1 ^B
1 $\mu\text{L}\cdot\text{L}^{-1}$ Days 1 and 2	41.0 ^A	329 ^C	11.1 ^{A-C}	548 ^{A-C}	3 ^{CD}	47 ^C	1 ^B
Harvest 2							
1 d at RT							
No 1-MCP	28.4 ^I	306 ^{CD}	10.2 ^{B-E}	380 ^{DE}	—	—	—
1 $\mu\text{L}\cdot\text{L}^{-1}$ Day 1	33.3 ^{EF}	93 ^{EF}	11.0 ^{A-E}	514 ^{A-D}	—	—	—
2 $\mu\text{L}\cdot\text{L}^{-1}$ Day 1	31.5 ^{GH}	90 ^{EF}	10.0 ^{C-E}	481 ^{B-E}	—	—	—
1 $\mu\text{L}\cdot\text{L}^{-1}$ Days 1 and 2	30.6 ^H	74 ^F	9.6 ^E	492 ^{A-D}	—	—	—
7 d at RT							
No 1-MCP	26.6 ^J	451 ^B	9.7 ^{DE}	335 ^E	41 ^B	85 ^A	8 ^A
1 $\mu\text{L}\cdot\text{L}^{-1}$ Day 1	36.5 ^{CD}	178 ^{D-F}	11.0 ^{A-D}	469 ^{B-E}	1 ^D	26 ^D	1 ^B
2 $\mu\text{L}\cdot\text{L}^{-1}$ Day 1	34.7 ^{DE}	281 ^{CD}	10.0 ^{C-E}	503 ^{A-D}	1 ^D	57 ^B	0 ^B
1 $\mu\text{L}\cdot\text{L}^{-1}$ Days 1 and 2	32.4 ^{FG}	223 ^{C-E}	10.2 ^{B-E}	503 ^{A-D}	0 ^D	57 ^B	0 ^B
Significance ^z	****	****	**	**	****	****	****

^zMeans within the same column for a given time with the same letter are not significantly different at $P < 0.05$.

, ** Significant at $P < 0.01$ or $P < 0.0001$, respectively; each value represents the average of 15 apples for ethylene, 255 for disorders, and 30 for other indices. 1-MCP = 1-methylcyclopropene.

month, 3.5 kPa CO₂ for the next month, and then 4.5 kPa CO₂ thereafter at 3 °C. ‘Spartan’ apples were held in CA storage of 2.5 kPa O₂ + 2.5 kPa CO₂ at 0.5 °C.

The CA system consisted of small aluminium storage chambers (0.9 m³ volume) fitted with a circulating fan system (Storage Control Systems Inc.). Atmospheres were checked hourly and maintained within 0.2 kPa of target values using an ICA 61/CGS 610 CA Control System (International Controlled Atmosphere Ltd., Kent, U.K.), which was modified with flow controllers for the

experimental chambers (Storage Control Systems Inc.).

Fruit quality evaluations. Initial fruit maturity at the time of harvest was evaluated on a 10-apple sample for each cultivar at each harvest time. Internal ethylene concentration (IEC) was determined by withdrawing a 3-mL gas sample from the core of each fruit using a syringe and injecting the sample into a Varian CP-3800 gas chromatograph (Varian Canada Inc., Mississauga, Ontario, Canada) equipped with a 0.5-mL sample loop, flame ionization detector, and 15 m × 0.32 mm

Restek Rt-SPLIT™ capillary column (Chromatographic Specialties Inc., Brockville, Ontario, Canada). The injector, column, and detector temperatures were 120, 35, and 225 °C, respectively. High-grade helium was used as the carrier gas at a flow rate of 0.37 mL·s⁻¹ with a typical run time of 2 min.

Fruit firmness was determined on opposite sides of each apple after peel removal using an electronic texture analyzer fitted with an 11-mm tip (GÜSS, South Africa). Titratable acidity (expressed as mg equivalents of malic acid per 100 mL of juice) was

Table 3. Quality and disorders of ‘McIntosh’ apples treated without or with 1-MCP 1 d (1 or 2 µL·L⁻¹) or 1 and 2 d (1 µL·L⁻¹) after harvest and stored for six or nine months in CA (2.5 kPa O₂ + 2.5 to 4.5 kPa CO₂) at 3 °C plus 1 or 7 d at room temperature (RT, ≈18 to 22 °C).

	Firmness (N)	Internal ethylene (µL·L ⁻¹)	Soluble solids (%)	Malic acid (mg/100 mL)	External CO ₂ injury (%)	Core browning (%)	Internal browning (%)
CA—six months							
Harvest 1							
1 d at RT							
No 1-MCP	59.4 ^C	256 ^{B-D}	10.2 ^{BC}	749 ^A	—	—	—
1 µL·L ⁻¹ Day 1	61.2 ^C	4 ^E	11.2 ^{AB}	592 ^{B-D}	—	—	—
2 µL·L ⁻¹ Day 1	65.3 ^{AB}	1 ^E	10.9 ^{A-C}	536 ^{B-D}	—	—	—
1 µL·L ⁻¹ Days 1 and 2	67.5 ^A	2 ^E	10.8 ^{A-C}	603 ^{BC}	—	—	—
7 d at RT							
No 1-MCP	37.4 ^G	1266 ^A	10.7 ^{A-C}	626 ^B	2 ^C	0 ^A	0
1 µL·L ⁻¹ Day 1	61.2 ^C	210 ^{B-D}	10.9 ^{A-C}	559 ^{B-D}	11 ^B	0 ^A	0
2 µL·L ⁻¹ Day 1	65.3 ^{AB}	116 ^{DE}	11.1 ^{A-C}	525 ^{CD}	15 ^A	0 ^A	0
1 µL·L ⁻¹ Days 1 and 2	64.8 ^B	132 ^{C-E}	11.6 ^A	581 ^{B-D}	12 ^{AB}	0 ^A	0
Harvest 2							
1 d at RT							
No 1-MCP	45.5 ^F	303 ^{BC}	10.6 ^{A-C}	525 ^{CD}	—	—	—
1 µL·L ⁻¹ Day 1	59.9 ^C	1 ^E	10.7 ^{A-C}	536 ^{B-D}	—	—	—
2 µL·L ⁻¹ Day 1	59.0 ^C	1 ^E	10.3 ^{BC}	514 ^{CD}	—	—	—
1 µL·L ⁻¹ Days 1 and 2	56.3 ^D	2 ^E	10.2 ^{BC}	548 ^{B-D}	—	—	—
7 d at RT							
No 1-MCP	36.5 ^G	1314 ^A	10.3 ^{BC}	503 ^D	0 ^C	0 ^A	0
1 µL·L ⁻¹ Day 1	55.4 ^D	364 ^{CD}	10.7 ^{A-C}	581 ^{B-D}	0 ^C	0 ^A	0
2 µL·L ⁻¹ Day 1	53.1 ^E	186 ^{E-I}	10.2 ^C	592 ^{B-D}	2 ^C	1 ^A	0
1 µL·L ⁻¹ Days 1 and 2	55.4 ^D	176 ^{E-I}	10.1 ^C	626 ^B	1 ^C	0 ^A	0
Significance ^z	****	****	*	***	****	NS	—
CA—nine months							
Harvest 1							
1 d at RT							
No 1-MCP	50.4 ^F	231 ^D	11.5 ^{BC}	402 ^H	—	—	—
1 µL·L ⁻¹ Day 1	63.5 ^{BC}	10 ^E	12.1 ^A	469 ^{FG}	—	—	—
2 µL·L ⁻¹ Day 1	64.8 ^{AB}	7 ^E	12.0 ^{AB}	503 ^{D-F}	—	—	—
1 µL·L ⁻¹ Days 1 and 2	67.5 ^A	6 ^E	11.9 ^{AB}	603 ^A	—	—	—
7 d at RT							
No 1-MCP	41.9 ^H	1265 ^A	10.9 ^{D-F}	458 ^{F-H}	1 ^C	1 ^D	4 ^A
1 µL·L ⁻¹ Day 1	49.5 ^F	711 ^C	11.5 ^{BC}	492 ^{E-G}	10 ^A	0 ^D	1 ^B
2 µL·L ⁻¹ Day 1	48.2 ^F	777 ^C	11.6 ^{A-C}	514 ^{C-F}	5 ^B	1 ^D	2 ^{AB}
1 µL·L ⁻¹ Days 1 and 2	54.0 ^E	702 ^C	11.7 ^{A-C}	536 ^{B-D}	7 ^B	2 ^{CD}	1 ^B
Harvest 2							
1 d at RT							
No 1-MCP	51.3 ^F	269 ^D	10.4 ^{FG}	514 ^{C-F}	—	—	—
1 µL·L ⁻¹ Day 1	62.1 ^{B-D}	3 ^E	11.3 ^{C-E}	570 ^{A-C}	—	—	—
2 µL·L ⁻¹ Day 1	60.3 ^D	4 ^E	10.8 ^{EF}	559 ^{A-D}	—	—	—
1 µL·L ⁻¹ Days 1 and 2	60.8 ^{CD}	4 ^E	10.5 ^{FG}	548 ^{A-E}	—	—	—
7 d at RT							
No 1-MCP	36.9 ^I	1311 ^A	10.2 ^G	436 ^{GH}	0 ^C	4 ^{BC}	5 ^A
1 µL·L ⁻¹ Day 1	45.0 ^G	754 ^C	11.3 ^{CD}	581 ^{AB}	0 ^C	0 ^D	1 ^B
2 µL·L ⁻¹ Day 1	43.7 ^{GH}	789 ^C	10.8 ^{EF}	514 ^{C-F}	1 ^C	5 ^B	1 ^B
1 µL·L ⁻¹ Days 1 and 2	41.4 ^H	1009 ^B	10.5 ^{FG}	514 ^{C-F}	1 ^C	13 ^A	2 ^B
Significance ^z	****	****	****	****	****	****	***

^zMeans within the same column for a given time with the same letter are not significantly different at $P < 0.05$.

NS, *, **, **** Nonsignificant and significant at $P < 0.05$, $P < 0.001$, or $P < 0.0001$, respectively; each value represents the average of 15 apples for ethylene, 255 for disorders, and 30 for other indices.

1-MCP = 1-methylcyclopropene; CA = controlled atmosphere.

determined by titrating a 2-mL juice sample with 0.1 N NaOH to an end point of pH 8.1 (as indicated by phenolphthalein), whereas soluble solids concentration (SSC) was determined using a digital refractometer (PR-32; Atago Co., Ltd., Japan). Starch index was determined using the Cornell Starch Chart (Blanpied and Silsby, 1992). Apples were cut in half at the equator, dipped in a potassium-iodine solution, and rated on a scale of 1 to 8, where 1 = 100% starch staining and 8 = 0% staining.

After the storage period plus 1 and 7 d at room temperature (RT, 18 to 22 °C), 10 fruit per box replicate of each treatment were also measured for IEC, firmness, SSC, and titratable acidity. The incidence of storage disorders and rots was determined after 7 d at RT using 85 apples per replicate of each

treatment. Incidence was calculated as a percentage of fruit with the disorder or rot regardless of severity.

Statistical analyses. Data were analyzed by generalized linear models procedures using the SAS program (Version 9.1.3; SAS Institute Inc., Cary, NC). Mean separations were examined using Duncan's separation test and only differences significant at $P \leq 0.05$ are discussed.

Results and Discussion

Fruit maturity at each harvest time for both cultivars is presented in Table 1. All harvests occurred within the commercial harvest period. One 'McIntosh' apple from the first harvest had unusually high IEC (489 $\mu\text{L}\cdot\text{L}^{-1}$), which affected the IEC average for that sample.

As expected, overall, 1-MCP treatment improved firmness and acidity retention and reduced internal ethylene in 'McIntosh' (Tables 2 and 3). Similar trends were observed in 'Spartan' stored in air, whereas those held in CA often maintained these attributes without 1-MCP treatment (Tables 4 and 5).

After three months of air storage, 'McIntosh' from the first harvest treated once with 1 $\mu\text{L}\cdot\text{L}^{-1}$ 1-MCP were softer than those treated once with 2 $\mu\text{L}\cdot\text{L}^{-1}$ 1-MCP or treated twice with 1 $\mu\text{L}\cdot\text{L}^{-1}$ 1-MCP (Table 2). Fruit from these latter treatments were the only ones with firmness greater than 45 N and thus had potential for marketing. 'McIntosh' either from the later harvest or stored in air for six months were all less than 45 N, and 1-MCP treatments had varying effects on firmness. These low firmness levels are in contrast

Table 4. Quality and disorders of 'Spartan' apples treated without or with 1-MCP (1 $\mu\text{L}\cdot\text{L}^{-1}$) 1 d or 1 and 2 d after harvest and stored for three or six months in air at 0.5 °C plus 1 or 7 d at room temperature (RT, ≈ 18 to 22 °C).^z

	Firmness (N)	Internal ethylene ($\mu\text{L}\cdot\text{L}^{-1}$)	Soluble solids (%)	Malic acid (mg/100 mL)	Core browning (%)	Superficial scald (%)	Storage rots (%)
Air—three months							
Orchard 1							
1 d at RT							
No 1-MCP	62.6 ^C	225 ^C	12.7 ^{AB}	536 ^{BC}	—	—	—
1-MCP Day 1	71.1 ^A	9 ^D	11.9 ^{B-D}	704 ^A	—	—	—
1-MCP Days 1 and 2	68.4 ^B	5 ^D	12.9 ^A	760 ^A	—	—	—
7 d at RT							
No 1-MCP	51.8 ^F	525 ^B	12.3 ^{A-C}	492 ^C	0 ^A	0	0 ^A
1-MCP Day 1	68.9 ^B	17 ^D	12.2 ^{A-C}	760 ^A	0 ^A	0	0 ^A
1-MCP Days 1 and 2	68.0 ^B	2 ^D	12.7 ^{AB}	749 ^A	0 ^A	0	1 ^A
Orchard 2							
1 d at RT							
No 1-MCP	43.2 ^G	544 ^{AB}	12.1 ^{A-C}	525 ^{BC}	—	—	—
1-MCP Day 1	57.6 ^{DE}	41 ^D	12.0 ^{A-D}	548 ^{BC}	—	—	—
1-MCP Days 1 and 2	59.4 ^D	4 ^D	11.9 ^{B-D}	592 ^B	—	—	—
7 d at RT							
No 1-MCP	38.7 ^H	700 ^A	11.1 ^{DE}	536 ^{BC}	1 ^A	0	1 ^A
1-MCP Day 1	55.8 ^E	68 ^{CD}	11.4 ^{C-E}	693 ^A	0 ^A	0	0 ^A
1-MCP Days 1 and 2	55.8 ^E	9 ^D	10.9 ^E	738 ^A	0 ^A	0	1 ^A
Significance ^y	****	****	***	****	NS	—	NS
Air—six months							
Orchard 1							
1 d at RT							
No 1-MCP	41.9 ^E	438 ^C	11.8 ^{AB}	481 ^B	—	—	—
1-MCP Day 1	64.4 ^A	34 ^F	12.0 ^{AB}	603 ^A	—	—	—
1-MCP Days 1 and 2	59.0 ^B	30 ^F	11.9 ^{AB}	603 ^A	—	—	—
7 d at RT							
No 1-MCP	41.9 ^E	302 ^D	12.5 ^A	380 ^C	27 ^A	10 ^B	0 ^C
1-MCP Day 1	63.9 ^A	97 ^{EF}	12.1 ^{AB}	492 ^B	0 ^B	0 ^C	1 ^{BC}
1-MCP Days 1 and 2	59.9 ^B	197 ^{DE}	12.5 ^A	481 ^B	1 ^B	0 ^C	0 ^C
Orchard 2							
1 d at RT							
No 1-MCP	35.1 ^F	615 ^B	11.5 ^B	291 ^D	—	—	—
1-MCP Day 1	45.9 ^D	95 ^{EF}	12.3 ^{AB}	358 ^C	—	—	—
1-MCP Days 1 and 2	50.9 ^C	39 ^F	12.3 ^{AB}	358 ^C	—	—	—
7 d at RT							
No 1-MCP	34.7 ^F	776 ^A	9.7 ^D	201 ^E	26 ^A	27 ^A	6 ^A
1-MCP Day 1	47.7 ^D	160 ^{EF}	10.6 ^C	279 ^D	0 ^B	2 ^C	3 ^B
1-MCP Days 1 and 2	51.8 ^C	131 ^{EF}	10.5 ^{CD}	279 ^D	0 ^B	0 ^C	3 ^B
Significance ^y	****	****	****	****	****	****	****

^zOrchards 1 and 2 were harvested at optimum fruit maturity and late, respectively.

^yMeans within the same column for a given time with the same letter are not significantly different at $P < 0.05$.

NS, ***, **** Nonsignificant and significant at $P < 0.001$ or $P < 0.0001$, respectively; each value represents the average of 15 apples for ethylene, 255 for disorders, and 30 for other indices.

1-MCP = 1-methylcyclopropene.

Table 5. Quality and disorders of ‘Spartan’ apples treated without or with 1-MCP ($1 \mu\text{L}\cdot\text{L}^{-1}$) 1 d or 1 and 2 d after harvest and stored for six or nine months in CA ($2.5 \text{ kPa O}_2 + 2.5 \text{ kPa CO}_2$) at 3°C plus 1 or 7 d at room temperature (RT, ≈ 18 to 22°C).^z

	Firmness (N)	Internal ethylene ($\mu\text{L}\cdot\text{L}^{-1}$)	Soluble solids (%)	Malic acid (mg/100 mL)	Core browning (%)	Internal browning (%)
CA—six months						
Orchard 1						
1 d at RT						
No 1-MCP	68.9 ^A	1 ^D	12.2 ^{AB}	581 ^{BC}	—	—
1-MCP Day 1	68.9 ^A	1 ^D	12.0 ^{AB}	671 ^A	—	—
1-MCP Days 1 and 2	69.3 ^A	1 ^D	12.1 ^{AB}	626 ^{AB}	—	—
7 d at RT						
No 1-MCP	66.6 ^B	81 ^C	12.3 ^A	469 ^D	0	0 ^A
1-MCP Day 1	70.7 ^A	1 ^D	12.2 ^{AB}	570 ^C	0	0 ^A
1-MCP Days 1 and 2	68.9 ^A	2 ^D	12.5 ^A	559 ^C	0	0 ^A
Orchard 2						
1 d at RT						
No 1-MCP	57.2 ^E	218 ^B	11.8 ^{AB}	447 ^D	—	—
1-MCP Day 1	61.2 ^C	1 ^D	11.4 ^B	458 ^D	—	—
1-MCP Days 1 and 2	59.0 ^{DE}	1 ^D	12.2 ^{AB}	425 ^D	—	—
7 d at RT						
No 1-MCP	46.8 ^F	578 ^A	10.4 ^C	313 ^E	0	0 ^A
1-MCP Day 1	61.2 ^C	5 ^D	10.1 ^C	324 ^E	0	1 ^A
1-MCP Days 1 and 2	60.8 ^{CD}	11 ^D	10.5 ^C	335 ^E	0	0 ^A
Significance ^y	****	****	****	****	—	*
CA—nine months						
Orchard 1						
1 d at RT						
No 1-MCP	73.8 ^{AB}	11 ^D	12.2 ^{AB}	413 ^{BC}	—	—
1-MCP Day 1	71.6 ^{BC}	4 ^D	11.8 ^{B-D}	559 ^A	—	—
1-MCP Days 1 and 2	71.1 ^C	1 ^D	12.2 ^{AB}	570 ^A	—	—
7 d at RT						
No 1-MCP	64.8 ^D	485 ^A	12.4 ^A	358 ^{CD}	0 ^C	0 ^C
1-MCP Day 1	73.8 ^A	66 ^{CD}	12.0 ^{A-C}	559 ^A	1 ^{BC}	0 ^C
1-MCP Days 1 and 2	72.5 ^{A-C}	126 ^C	12.0 ^{A-C}	570 ^A	1 ^{BC}	1 ^{BC}
Orchard 2						
1 d at RT						
No 1-MCP	54.9 ^F	414 ^A	11.4 ^{EF}	413 ^{BC}	—	—
1-MCP Day 1	64.8 ^D	3 ^D	11.3 ^{E-G}	436 ^B	—	—
1-MCP Days 1 and 2	60.8 ^E	1 ^D	10.9 ^G	447 ^B	—	—
7 d at RT						
No 1-MCP	51.3 ^G	423 ^A	11.2 ^{FG}	313 ^D	1 ^{BC}	1 ^{BC}
1-MCP Day 1	64.4 ^D	233 ^B	11.7 ^{C-E}	369 ^C	2 ^{AB}	3 ^B
1-MCP Days 1 and 2	62.6 ^{DE}	133 ^C	11.4 ^{D-F}	369 ^C	3 ^A	6 ^A
Significance ^y	****	****	****	****	**	****

^zOrchards 1 and 2 were harvested at optimum fruit maturity and late, respectively.

^yMeans within the same column for a given time with the same letter are not significantly different at $P < 0.05$.

ns, **, **** Nonsignificant and significant at $P < 0.01$ or $P < 0.0001$, respectively; each value represents the average of 15 apples for ethylene, 255 for disorders, and 30 for other indices.

1-MCP = 1-methylcyclopropene; CA = controlled atmosphere.

with previous results, in which all 1-MCP-treated ‘McIntosh’ from three harvest times exhibited firmness greater than 49 N after three and six months of air storage at 0 to 1°C (DeEll et al., 2008).

After six months of CA storage, ‘McIntosh’ from the first harvest treated once with $1 \mu\text{L}\cdot\text{L}^{-1}$ 1-MCP were also softer than those treated once with $2 \mu\text{L}\cdot\text{L}^{-1}$ 1-MCP or treated twice with $1 \mu\text{L}\cdot\text{L}^{-1}$ 1-MCP (Table 3). Apples from the first harvest that received two applications of 1-MCP remained firmer than fruit from the other treatments after nine months of CA storage and 7 d at RT. All ‘McIntosh’ from the later harvest treated with 1-MCP had softened to 45 N or less at this time. These results suggest that using more than

the traditional single application of $1 \mu\text{L}\cdot\text{L}^{-1}$ 1-MCP may improve firmness retention in ‘McIntosh’ apples, especially during long-term storage.

‘Spartan’ from Orchard 2 (later harvest) and stored in air for six months had greater firmness with repeated 1-MCP treatments compared to only a single application after harvest (Table 4). In contrast, ‘Spartan’ from Orchard 1 (earlier harvest) and stored in air for three or six months were softer with repeated 1-MCP treatments compared to only a single application. This trend was also observed in ‘Spartan’ from Orchard 2 and stored in CA for six or nine months, but the effect was lost after 7 d at RT. Overall, there appears to be inconsistent effects of repeated

1-MCP treatments on ‘Spartan’ firmness, compared to those treated only once.

There was little effect resulting from the additional 1-MCP application on IEC, soluble solids, and malic acid content in air-stored ‘McIntosh’ and ‘Spartan’. Similarly, there was no difference or slight inconsistent differences in these attributes among apples with the various 1-MCP treatments and stored in CA.

All 1-MCP treatments substantially reduced superficial scald development in ‘McIntosh’ and ‘Spartan’ stored in air for six months plus 7 d at RT (Tables 2 and 4). There was no difference in the incidence of scald among the various 1-MCP treatments. Single post-harvest applications of 1-MCP have been previously shown to reduce scald development in ‘McIntosh’ (DeEll et al., 2008; DeLong et al., 2004; Rupasinghe et al., 2000). Low O_2 CA has been also shown to reduce superficial scald development in apples [Lurie and Watkins, 2012 (and references therein)]; however, Lau (1983) found that lowering O_2 concentration from 2.5% to 1.0% had no effect on the incidence of scald in ‘Spartan’ apples.

Core browning was also reduced by 1-MCP in air-stored ‘McIntosh’ (Table 2). However, after six months of air storage, ‘McIntosh’ from the second harvest treated once with $2 \mu\text{L}\cdot\text{L}^{-1}$ 1-MCP or twice with $1 \mu\text{L}\cdot\text{L}^{-1}$ 1-MCP had significantly higher incidence of core browning than fruit only treated once with $1 \mu\text{L}\cdot\text{L}^{-1}$ 1-MCP. This trend of increased core browning was also observed in ‘McIntosh’ from the later harvest stored in CA for nine months, with fruit treated twice having a higher incidence of the disorder. The fact that rapid consecutive applications of 1-MCP can augment core browning development is a risk of which commercial users need to be aware.

Core browning tends to be more prevalent in fruit that is high in nitrogen, large, shaded on the tree, or harvested after an extended period of cloudy, cool, or wet weather (Meheriuk et al., 1994). Single postharvest applications of 1-MCP typically reduce core browning in ‘McIntosh’, but this effect diminishes with advanced maturity at harvest time and 1-MCP concentrations below $1 \mu\text{L}\cdot\text{L}^{-1}$ (DeEll et al., 2008; Watkins et al., 2000).

‘Spartan’ had a high incidence of core browning after six months of air storage and 1-MCP controlled the disorder regardless of the number of applications (Table 4). This is in contrast to the increased incidence of core browning observed in ‘McIntosh’ treated twice with 1-MCP. After nine months of CA storage, however, ‘Spartan’ fruit treated twice with 1-MCP had a significantly higher incidence of internal browning than those treated once or not treated (Table 5). Some internal browning also developed in ‘McIntosh’ after nine months of CA storage and 1-MCP generally reduced the incidence. In previous studies, the effect of 1-MCP on internal browning has not been consistent, as sometimes it reduces (DeEll et al., 2008), increases (Jung and Watkins, 2011), or has no effect (DeEll et al., 2007) on its incidence.

'McIntosh' from the first harvest had notable amounts of external CO₂ injury after six and nine months of CA storage (Table 3). 1-MCP increased the incidence of CO₂ injury, with fruit treated with 2 µL·L⁻¹ having the highest incidence after six months and those treated once with 1 µL·L⁻¹ having the highest incidence after nine months. The symptoms of external CO₂ injury usually develop within the first few weeks of storage, so storage duration should not influence the disorder incidence. Increases in external CO₂ injury resulting from postharvest 1-MCP treatment have been reported previously for 'McIntosh' and 'Empire' apples (DeEll et al., 2003; Fawbush et al., 2008). However, this effect is not observed every year, especially when the incidence of external CO₂ injury is high (DeEll and Ehsani-Moghaddam, 2012a). Preharvest 1-MCP applications in the orchard have been also shown to result in higher levels of external CO₂ injury in 'McIntosh' and 'Empire' apples (DeEll and Ehsani-Moghaddam, 2012b). No CO₂ injury was observed in 'Spartan' apples.

Storage rots were greatest after six months of air storage and 1-MCP treatments usually reduced the incidence regardless of the number of applications (Table 3). 1-MCP often has no effect on the incidence of storage rots (DeEll et al., 2007).

In summary, all typical effects of 1-MCP treatments were observed throughout the various storage regimes with an occasional slight improvement to firmness retention (less than 4.5 N) when 'McIntosh' fruit were treated twice. There was an increased incidence of core browning in 'McIntosh' treated twice with 1 µL·L⁻¹ 1-MCP or once with 2 µL·L⁻¹, compared to the usual single application of 1 µL·L⁻¹. This indicates that there is some risk associated with using more than the traditional single 1 µL·L⁻¹ treatment, especially when storing apples long-term such as for six months in air storage or nine months in CA.

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