1-Methylcyclopropene Concentration and Timing of Postharvest Application Alters the Ripening of 'McIntosh' Apples during Storage

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SUMMARY. This study evaluated the effects of 1-methylcyclopropene (1-MCP) concentration (1000 vs. 625 ppb) and treatment delays (3, 7, and 10 days after harvest) on the ripening and incidence of storage disorders in 'McIntosh' apples from three harvest times in 2004. Apples were stored in air at 0 °C to 1 °C for 3 and 6 months or in controlled atmosphere (CA) storage at 3 °C for 6 and 9 months. Apples treated with 1-MCP and held in air or CA storage were firmer than those not treated, but this difference in firmness was less with later harvests, more delay before 1-MCP treatment, and longer storage time. Apples treated with 1000 ppb 1-MCP were often firmer than those treated with 625 ppb after 6 months of storage and/or 7 days at 22 °C. Ethylene and carbon dioxide (CO₂) production were reduced in apples treated with 1-MCP, especially in fruit from the first harvest and those treated 3 days after harvest. Fruit treated with 1000 ppb 1-MCP showed a slower increase in ethylene production than those treated with 625 ppb during 14 days at 22 °C after storage. CO₂ production was the lowest in 'McIntosh' apples treated with 1000 ppb 1-MCP 3 days after harvest, but fruit treated with 625 ppb also exhibited lower respiration than those not treated. Storage disorders were most prevalent in 'McIntosh' apples stored for 6 months in air at 0 °C to 1 °C, whereas fruit from the first harvest treated with 1-MCP 3 days after harvest developed the fewest disorders. 1-MCP reduced the incidence of superficial scald, flesh browning, core browning, and senescent breakdown, while 1-MCP concentration and treatment delay had varying effects. This research has provided the basis for Canadian registration of SmartFreshSM use on apples at 1000 ppb 1-MCP and for the requirement that treatment be within 3 days of harvest.

1-Methylcyclopropene (1-MCP) inhibits the action of ethylene and, therefore, it has the unique ability to maintain quality and extend the shelf-life of many fresh fruit and vegetables. The postharvest gaseous application of 1-MCP has been shown to improve many physiological characteristics of apples, such as reduced ethylene production and respiration, enhanced fruit firmness and acidity retention, and reduced peel greasiness and various physiological disorders (Blankenship and Dole, 2003; DeEll et al., 2007; Fan et al., 1999a, 1999b; Watkins, 2006).

1-MCP affects the incidence of storage disorders in a variety of ways, depending on apple cultivar and storage regime. Superficial scald is generally reduced by 1-MCP (DeEll et al., 2002; Fan et al., 1999b; Moran, 2006; Rupasinghe et al., 2000; Watkins et al., 2000), as is peel greasiness (Fan et al., 1999b; Watkins and Nock, 2005) and senescent breakdown (DeLong et al., 2004; Watkins et al., 2000). There is often no effect of 1-MCP on internal browning in 'Empire' apples (DeEll et al., 2007;

Fawbush et al., 2008; Watkins and Nock, 2005). Core browning is reduced by 1-MCP in 'McIntosh' apples held in air storage at 0.5 °C (Watkins et al., 2000), but is increased in 'Delicious' apples stored long-term in controlled atmosphere (CA) (DeEll et al., 2007). 1-MCP also increases susceptibility to external CO₂ injury in 'Empire' and 'McIntosh' apples (DeEll et al., 2003; Fawbush et al., 2008). Watkins (2007) recently reviewed the effect of 1-MCP on the development of physiological storage disorders in horticultural crops.

There are many factors that can influence the response of apples to 1-MCP. Each cultivar tends to behave differently and responses often vary with storage conditions (Bai et al., 2005; DeEll et al., 2005a; Fan et al., 1999a, 1999b; Watkins et al., 2000). 1-MCP treatment temperature is important when application is less than 9 h (DeEll et al., 2002), whereas temperature has little effect in the case of 24-h treatments (Watkins and Nock, 2005). A dose response of 1-MCP has been found in some cultivars but not in others (Watkins et al., 2000). Application delays of up to 8 d can have no effect on 1-MCP efficacy or it can markedly reduce it (Watkins and Nock, 2005).

The commercial formulation of 1-MCP for use on food is SmartFreshSM (AgroFresh, Spring House, PA). Application in the United States is at a concentration of 1000 ppb 1-MCP, whereas in United Kingdom it is 625 ppb. Due to the diverse responses of apples to 1-MCP, these concentrations could result in different effects under various conditions. The objectives of this work were to investigate the effects of 1-MCP concentration (1000 vs. 625 ppb) and

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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
0.3048	ft	m	3.2808
3.7854	gal	L	0.2642
25.4	inch(es)	mm	0.0394
0.4536	lb	kg	2.2046
4.4482	lbf	N	0.2248
1	ppb	nL·L ⁻¹	1
0.001	ppm	mL·kg ⁻¹	1000
1	ppm	μL·kg ⁻¹	1
1	ppm	μL·L ⁻¹	1
(°F - 32) ÷ 1.8	°F	°C	(1.8 × °C) + 32

treatment delays after harvest (3, 7, and 10 d) on the ripening and incidence of storage disorders in 'McIntosh' apples from three harvest times. Apples were stored in air at 0 °C to 1 °C for 3 and 6 months, as well as in CA storage at 3 °C for 6 and 9 months.

Materials and methods

APPLE HARVEST. 'McIntosh' apples ('Summerland' strain) were harvested from a mature orchard in Norfolk County, Ontario, on the first (Harvest 1), sixth (Harvest 2), and 11th (Harvest 3) days of the commercial harvest in 2004. There were 108 boxes of fruit (≈ 20 kg each) harvested at each time. All apples were drenched with diphenylamine [1000 ppm a.i. (ShieldBrite; Pace International, Seattle)] and thiabendazole [500 ppm a.i. (Mertect; Syngenta, Wilmington, DE)] at a local commercial packinghouse and then transported to the postharvest physiology laboratory at the University of Guelph.

POSTHARVEST TREATMENTS. Apples were cooled overnight at 0 °C to 1 °C and held for 3, 7, or 10 d before treatment with 1-MCP. Boxes from each harvest and holding delay combination were placed in sealed air-tight plastic bags (6 mil) and exposed to 0, 625, or 1000 ppb of 1-MCP (SmartFreshSM) for 24 h at 0 °C to 1 °C. The 1-MCP concentration was calculated according to the percentage a.i. and release from the SmartFreshSM powder into the free headspace of the sealed bags.

Immediately after treatment with 1-MCP, apples were held in air at 0 °C to 1 °C for 3 and 6 months or in standard CA storage [2.5% oxygen (O₂) + 2.5% CO₂ for 30 d, 4.5% CO₂ thereafter] at 3 °C for 6 and 9 months. There were three box replicates of apples per treatment and storage combination. In addition, 25 fruit per treatment combination were held at 22 °C for 14 d immediately after 1-MCP treatment and were then evaluated as a confirmation test of 1-MCP effectiveness.

The O₂ concentration within the CA chambers (≈ 1000 L each) was established within 4 to 5 h of sealing, after flushing with nitrogen (N₂) until 2.5% O₂ was reached. The CO₂ levels were then established gradually

Table 1. Internal ethylene concentration (IEC), starch index, firmness, and soluble solids concentration (SSC) of 'McIntosh' apples at harvest.

	IEC (ppm) ^a	Starch index (1–8 scale) ^y	Firmness (lbf) ^x	SSC (%)
Harvest 1	0.06	5.0	15.4	10.8
Harvest 2	0.03	5.1	14.9	11.3
Harvest 3	0.13	6.3	14.0	10.1

^aIEC = internal ethylene concentration; 1 ppm = 1 $\mu\text{L}\cdot\text{L}^{-1}$.

^yStarch staining using charts by Blanpied and Silsby (1992).

^x1 lbf = 4.4482 N.

Table 2. Internal ethylene concentration (IEC), firmness, and soluble solids concentration (SSC) of 'McIntosh' apples from three harvests, treated with 1-methylcyclopropene (1-MCP; 0, 625, or 1000 ppb^a) 3, 7, or 10 d after harvest, and held 14 d at 22 °C (71.6 °F) (confirmation test).

	IEC (ppm) ^y	Firmness (lbf) ^x	SSC (%)
Harvest 1			
1-MCP 3 d after harvest			
0 ppb	1,163	11.1	11.3
625 ppb	169	15.1	11.2
1,000 ppb	1	15.2	11.4
1-MCP 7 d after harvest			
0 ppb	965	11.0	10.8
625 ppb	339	14.9	11.1
1,000 ppb	94	15.0	11.1
1-MCP 10 d after harvest			
0 ppb	860	10.6	10.8
625 ppb	738	14.1	10.8
1,000 ppb	742	13.8	11.3
Harvest 2			
1-MCP 3 d after harvest			
0 ppb	856	11.2	10.9
625 ppb	772	14.8	11.5
1,000 ppb	197	15.0	11.5
1-MCP 7 d after harvest			
0 ppb	905	9.6	10.1
625 ppb	709	12.8	11.6
1,000 ppb	496	13.6	11.6
1-MCP 10 d after harvest			
0 ppb	1,017	11.0	11.5
625 ppb	889	13.5	11.8
1,000 ppb	1,009	13.3	11.7
Harvest 3			
1-MCP 3 d after harvest			
0 ppb	776	9.6	10.2
625 ppb	717	12.1	10.3
1,000 ppb	551	12.9	10.3
1-MCP 7 d after harvest			
0 ppb	878	9.5	10.1
625 ppb	821	11.1	10.2
1,000 ppb	649	11.5	10.2
1-MCP 10 d after harvest			
0 ppb	818	9.9	9.8
625 ppb	747	11.1	9.7
1,000 ppb	779	11.4	9.9
SE	80.3	0.24	0.15
Significance ^w	T $\times$ M $\times$ H ^{**}	T $\times$ M ^{***}	T $\times$ H ^{***}
		T $\times$ H ^{***}	M ^{**}
		M $\times$ H ^{***}	

^a1 ppb = 1 $\text{nL}\cdot\text{L}^{-1}$.

^yIEC = internal ethylene concentration; 1 ppm = 1 $\mu\text{L}\cdot\text{L}^{-1}$.

^x1 lbf = 4.4482 N.

^w*, **, ***Significant at $P < 0.05$, $P < 0.01$, or $P < 0.001$, respectively, where T = treatment time, M = 1-MCP concentration, and H = harvest.

over a 72-h period by stepwise addition of CO₂ to the chambers. Gas levels were monitored daily with a gas analyzer (NOVA Analytical Instruments, Hamilton, ON) and adjustments using air, N₂, or CO₂ were made accordingly so that atmospheres never fluctuated more than $\pm 0.1\%$.

MATURITY AND QUALITY EVALUATIONS. Initial maturity was evaluated on three groups of 10-apple samples from each harvest. Starch content was determined using the Cornell Starch Chart (Blanpied and Silsby, 1992). Apples were cut in half at the equator and were rated on a scale of 1 to 8, where 1 = 100% starch staining and 8 = 0% staining. 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 gas chromatograph (CP-3800; Varian Canada, Mississauga, ON) equipped with a 0.5-mL sample loop, flame ionization detector (FID), and a 15 m $\times$ 0.32-mm Restek Rt-SPLITTM capillary column (Chromatographic Specialties, Brockville, ON). The injector, column, and detector temperatures were 120 °C, 35 °C, 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 (blush and green) of each apple after peel removal, using an electronic pressure tester fitted with an 11-mm tip (Lake City Technical Products, Kelowna, BC). Soluble solids concentration (SSC) in the juice expressed during firmness testing was determined using a hand-held temperature-compensated refractometer (Fisher Scientific, Nepean, ON).

Samples of 25 apples from each harvest and 1-MCP treatment combination were held at 22 °C for 14 d immediately after 1-MCP application. These fruit were then evaluated as a confirmation test for the 1-MCP treatment. IEC, firmness, and SSC were measured using the methods described above.

After each storage regime, 10 fruit per box replicate from each treatment combination were also measured for firmness after 1 and 7 d at 22 °C. In addition, the incidence of core browning, internal browning, senescent breakdown, and superficial

scald were determined using 25 apples per box replicate from each treatment combination. Incidence was calculated as a percentage of fruit with the disorder, regardless of severity.

ETHYLENE AND CO₂ PRODUCTION. After each storage regime, a representative 1 to 1.5-kg sample of nine fruit was removed from each treatment combination (three fruit per box rep) and placed in 4.9-L glass jars. CO₂ and ethylene in the headspace of the jars were measured after 1, 4, 7, 11, and 14 d at 22 °C. Apples in the jars were aerated with a stream of ethylene-free air for 20 min and the jars were then sealed gas-tight for 30 min. At this time, a 3-mL gas sample was withdrawn from the headspace of the jar with a syringe inserted through a rubber septum in the lid and the gas sample was analyzed for ethylene as described above. Immediately after injection of the ethylene sample, the headspace was sampled again and analyzed for CO₂ by injecting

another 3-mL gas sample into an ADC IR gas analyzer (Nortech Control Equipment, Etobicoke, ON).

STATISTICAL ANALYSES. Data from air- and CA-stored fruit were analyzed separately, using the analysis of variance procedure of Genstat 5 (Payne, 2000). Within each storage type, the effects of harvest time (Harvests 1–3), delay in 1-MCP application (3, 7, and 10 d), 1-MCP concentration (0, 625, and 1000 ppb), storage duration (3 and 6 months in air or 6 and 9 months in CA), and days at 22 °C (1 and 7 d) were determined. Sources of variation were considered significant at $P \leq 0.05$.

Results and discussion

‘McIntosh’ apples from the first two harvests were of optimum maturity for long-term storage (Table 1). IEC was less than 1 ppm and the starch index was between 5 and 6, which is the recommended range

Table 3. Firmness of ‘McIntosh’ apples from three harvests treated with 1-methylcyclopropene (1-MCP; 0, 625, or 1000 ppb) 3, 7, or 10 d after harvest, and stored for 3 or 6 months in air at 0 °C to 1 °C (32.0 °F–33.8 °F). The highest levels of significant effects (interactive) are presented and the data are the means of two evaluations after storage [1 and 7 d at 22 °C (71.6 °F)].

	Firmness (lbf) ^a		
	1-MCP concentration (ppb)		
	0	625	1000
3 Months			
Harvest 1	12.3	14.0	14.1
Harvest 2	11.8	13.1	13.3
Harvest 3	12.1	13.0	13.3
6 Months			
Harvest 1	10.6	12.7	13.2
Harvest 2	10.3	11.1	11.0
Harvest 3	10.0	11.3	11.9
SE = 0.17			
Significance ^x M $\times$ H $\times$ O [*]			
3 Months			
Time from harvest to 1-MCP treatment (d)			
3	12.0	13.5	13.9
7	12.1	13.3	13.5
10	12.2	13.4	13.3
6 Months			
Time from harvest to 1-MCP treatment (d)			
3	10.5	11.9	11.9
7	10.0	11.5	12.4
10	10.4	11.7	11.8
SE = 0.17			
Significance ^x T $\times$ M $\times$ O [*]			

^a1 ppb = 1 nL·L⁻¹.

^x1 lbf = 4.4482 N.

^{*}Significant at $P < 0.05$, where T = treatment time, M = 1-MCP concentration, H = harvest, and O = months.

for CA storage of 'McIntosh' (Blanpied and Silsby, 1992). Apples from Harvest 3 had an average starch index higher than 6 and thus were a little overmature for successful long-term storage. Fruit firmness ranged from 15.4 lbf for the first harvest to 14.0 lbf for the third harvest (Table 1).

After 1-MCP treatments and 14 d at 22 °C, 'McIntosh' apples from the first harvest treated 3 d after harvest had the lowest IEC and highest fruit firmness (Table 2). These quality benefits were gradually reduced with later harvests and more delay before 1-MCP treatment. The higher concentration of 1-MCP (1000 ppb) resulted in less IEC but not always greater firmness in fruit from the first two harvests when treated within 7 d compared with 625 ppb. Overall, these results confirm that the 1-MCP applications were effective.

Apples treated with 1-MCP and held in air storage for 3 or 6 months at 0 °C to 1 °C or in CA storage for 6 or 9 months at 3 °C were firmer than those not treated (Tables 3 and 4). However, this difference in firmness was less with later harvests, more delay before 1-MCP treatment, and longer storage time. Apples treated with 1000 ppb 1-MCP were firmer than those treated with 625 ppb in certain situations. Fruit from Harvest 3 or those treated with 1-MCP 7 d after harvest were slightly firmer with 1000 than 625 ppb after 6 months of air storage (Table 3). 'McIntosh' apples from the first two harvests treated 3 d after harvest and held in CA storage were also firmer with 1000 than 625 ppb 1-MCP (Table 4). This additional firmness benefit with 1000 ppb was more prominent after 6 months of CA or 7 d at 22 °C.

Improved firmness retention is a well-documented response of apples to 1-MCP (Bai et al., 2005; DeEll et al., 2007; Watkins et al., 2000; Watkins and Nock, 2005). The results of this study show the importance of 1-MCP concentration and time between harvest and application. Since a specific amount of 1-MCP is used for a range of commercial room sizes (SmartFreshSM application by AgroFresh), in certain commercial situations the concentration of 1-MCP can be less than the expected 1000 ppb, and for cultivars like

'McIntosh' this can reduce the beneficial effect on firmness. The SmartFreshSM label in Canada states that application must be made within 3 d of harvest, whereas the window for treatment in the United States is 7 d. Firmness retention in 'McIntosh' apples due to 1-MCP would be better with application closer to harvest, as indicated by the results of this study.

Ethylene production was reduced in apples treated with 1-MCP

and held in air storage at 0 °C to 1 °C, especially in fruit from the first harvest and those treated 3 d after harvest (Table 5). Apples not treated with 1-MCP had less ethylene production after 6 months than 3 months of air storage, suggesting that these fruit were post-climacteric. Fruit treated with 1000 ppb 1-MCP showed a slower increase in ethylene production than those treated with 625 ppb during 14 d at 22 °C after 3 and 6 months of air storage at 0 °C to 1 °C

Table 4. Firmness of 'McIntosh' apples from three harvests treated with 1-methylcyclopropene (1-MCP; 0, 625, or 1000 ppb²) 3, 7, or 10 d after harvest, stored for 6 or 9 months in CA at 3 °C (37.4 °F), and held 1 or 7 d at 22 °C (71.6 °F). The highest levels of significant effects (interactive) are presented.

	Firmness (lbf) ¹		
	Time from harvest to 1-MCP treatment (d)		
	3	7	10
Harvest 1			
0 ppb 1-MCP	12.9	12.0	12.1
625 ppb	13.6	13.4	12.6
1,000 ppb	14.4	13.1	12.4
Harvest 2			
0 ppb 1-MCP	12.0	11.5	11.5
625 ppb	12.5	12.5	12.5
1,000 ppb	12.9	12.5	12.4
Harvest 3			
0 ppb 1-MCP	11.8	11.7	11.5
625 ppb	12.4	12.2	12.2
1,000 ppb	12.2	12.4	12.0
SE = 0.10			
Significance ^x	T × M × H***		
6 mo.			
0 ppb 1-MCP	12.6	12.3	12.0
625 ppb	13.4	13.1	12.9
1,000 ppb	13.9	13.3	12.8
9 mo.			
0 ppb 1-MCP	11.9	11.2	11.4
625 ppb	12.3	12.3	12.0
1,000 ppb	12.5	12.0	11.7
SE = 0.08			
Significance ^x	T × M × O*		
1 d at 22 °C			
0 ppb 1-MCP	13.5	12.5	12.5
625 ppb	14.3	13.9	13.4
1,000 ppb	14.4	13.9	13.1
7 d at 22 °C			
0 ppb 1-MCP	11.0	10.9	10.9
625 ppb	11.3	11.5	11.4
1,000 ppb	12.0	11.5	11.4
SE = 0.08			
Significance ^x	T × M × D*		

²1 ppb = 1 nL·L⁻¹.

¹1 lbf = 4.4482 N.

, *Significant at $P < 0.05$ or $P < 0.001$, respectively, where T = treatment time, M = 1-MCP concentration, H = harvest, O = months, and D = days at 22 °C.

Table 5. Ethylene production of 'McIntosh' apples from three harvests treated with 1-methylcyclopropene (1-MCP; 0, 625, or 1000 ppb^z) 3, 7, or 10 d after harvest, and stored for 3 or 6 months in air at 0 °C to 1 °C (32.0 °F–33.8 °F). The highest levels of significant effects (interactive) are presented and the data are the means of two evaluations after storage [1 and 7 d at 22 °C (71.6 °F)].

	Ethylene production ($\mu\text{L}\cdot\text{kg}^{-1}\cdot\text{h}^{-1}$) ^y		
	1-MCP concentration (ppb)		
	0	625	1000
3 Months			
Harvest 1	224	75	42
Harvest 2	225	125	70
Harvest 3	206	176	142
6 Months			
Harvest 1	162	141	93
Harvest 2	144	134	105
Harvest 3	166	182	166
SE = 6.2			
Significance ^x M × H × O***			
3 Months			
Time from harvest to 1-MCP treatment (d)			
3	206	127	60
7	225	131	91
10	224	118	104
6 Months			
Time from harvest to 1-MCP treatment (d)			
3	175	150	102
7	147	146	123
10	150	161	139
SE = 6.2			
Significance ^x T × M × O*			

^z1 ppb = 1 nL·L⁻¹.

^y1 $\mu\text{L}\cdot\text{kg}^{-1} = 1 \text{ ppm}$.

^x*, ***Significant at $P < 0.05$ or $P < 0.001$, respectively, where T = treatment time, M = 1-MCP concentration, H = harvest, and O = months.

Fig. 1. Ethylene production of 'McIntosh' apples treated with 0, 625, or 1000 ppb 1-methylcyclopropene (1-MCP), stored for 3 and 6 months in air at 0 °C to 1 °C (32.0 °F–33.8 °F), and held 14 d at 22 °C (71.6 °F). Data are the means of three harvests and three 1-MCP treatment times (3, 7, and 10 d after harvest). The interaction of 1-MCP × Month × Day is significant at $P < 0.001$ (SE = 7.98). 1 ppb = 1 nL·L⁻¹, 1 $\mu\text{L}\cdot\text{kg}^{-1} = 1 \text{ ppm}$.

Fig. 2. Carbon dioxide (CO₂) production of 'McIntosh' apples from Harvests 1 and 2 treated 3, 7, or 10 d after harvest with 0, 625, or 1000 ppb 1-methylcyclopropene (1-MCP), stored for 3 and 6 months (data combined) in air at 0 °C to 1 °C (32.0 °F–33.8 °F), and held 14 d at 22 °C (71.6 °F). The interaction of Harvest × Treatment × 1-MCP × Day is significant at $P < 0.05$ (SE = 0.73). 1 ppb = 1 nL·L⁻¹, 1 mL·kg⁻¹ = 1000 ppm.

(Fig. 1). Also during this time, respiration (measured as CO₂ production) was the lowest in 'McIntosh' apples treated with 1000 ppb 1-MCP 3 d after harvest, but fruit treated with 625 ppb also exhibited lower respiration than those not treated (Fig. 2). Similar patterns were observed in apples from CA storage, but the differences in CO₂ production were not as great (Fig. 3).

1-MCP blocks the ethylene receptors and consequently prevents the effects of ethylene, such as those associated with fruit ripening. Therefore, reduced ethylene production in fruit would be an expected response to 1-MCP treatment, and this has been confirmed for several apple cultivars under various conditions (DeEll et al., 2005a, 2005b, 2007; DeLong et al., 2004; Fan et al., 1999a; Rupasinghe et al., 2000; Watkins et al., 2000; Watkins and Nock, 2005). In this study, ethylene production increased with time at 22 °C, suggesting that the effect of

1-MCP may be temporary and/or other receptor sites may be synthesized.

Storage disorders were most prevalent in 'McIntosh' apples stored for 6 months in air at 0 °C to 1 °C and fruit from the first harvest treated with 1-MCP 3 d after harvest developed the fewest (Table 6). Extensive flesh browning developed in fruit from Harvest 3, but there was lower incidence with 1-MCP treatment 3 d after harvest (75% vs. 50%). These results are in contrast to previous studies where the incidence of internal browning in 'Empire' and 'Delicious' apples was unaffected by 1-MCP treatment (DeEll et al., 2007; Watkins and Nock, 2005). Watkins and Nock (2005) also found that flesh browning in 'Empire' apples increased dramatically in late harvested fruit and it was unaffected by 1-MCP,

Fig. 3. Ethylene and carbon dioxide (CO_2) production of 'McIntosh' apples treated with 0, 625, or 1000 ppb 1-methylcyclopropene (1-MCP), stored for 6 and 9 months in controlled atmosphere (CA) at 3 °C (37.4 °F), and held 14 d at 22 °C (71.6 °F). Data are the means of three harvests and three 1-MCP treatment times (3, 7, and 10 d after harvest). The interaction of 1-MCP $\times$ Month $\times$ Day is significant at $P < 0.01$ (SE = 0.34). 1 ppb = 1 nL·L⁻¹, 1 $\mu\text{L}\cdot\text{kg}^{-1} = 1 \text{ ppm}$, 1 mL·kg⁻¹ = 1000 ppm.

irrespective of delays before treatment (up to 8 d). The incidence of flesh browning did not increase with more time between harvest and 1-MCP treatment in this study, nor was there any effect of 1-MCP concentration (Table 6). There was little effect of time at 22 °C after storage on flesh browning except in apples from Harvest 2 where the disorder was only present after 7 d at 22 °C.

Substantial core browning and superficial scald developed after 7 d at 22 °C and there was greater incidence of both disorders in apples from Harvest 3 (Table 6). Typically, superficial scald is more prevalent in earlier harvests (Emongor et al., 1994) and core browning is reduced with advanced maturity (Meheriuk et al., 1994). 1-MCP reduced the

Table 6. Incidence of flesh browning, core browning, and superficial scald in 'McIntosh' apples from three harvests treated with 1-methylcyclopropene (1-MCP; 0, 625, or 1000 ppb^a) 3, 7, or 10 d after harvest, stored for 6 months in air at 0 °C to 1 °C (32.0 °F–33.8 °F), and held 1 or 7 d at 22 °C (71.6 °F).

	Flesh browning (%) ^y						Core browning (%)			Superficial scald (%)		
	1 d at 22 °C			7 d at 22 °C			7 d at 22 °C			7 d at 22 °C		
	Time to 1-MCP (d)			Time to 1-MCP (d)			Time to 1-MCP (d)			Time to 1-MCP (d)		
	3	7	10	3	7	10	3	7	10	3	7	10
Harvest 1												
0 ppb												
1-MCP	13	25	0	0	13	10	90	34	80	63	87	83
625 ppb	0	0	0	3	0	0	10	0	17	37	87	60
1,000 ppb	0	0	0	0	0	0	20	0	10	13	70	73
Harvest 2												
0 ppb												
1-MCP	0	0	0	3	17	13	100	100	100	73	70	83
625 ppb	0	0	0	13	3	0	100	53	50	50	47	63
1,000 ppb	0	0	0	0	4	13	33	11	57	37	18	67
Harvest 3												
0 ppb												
1-MCP	87	76	65	63	63	33	100	100	100	90	100	100
625 ppb	60	75	33	43	53	27	94	100	100	100	100	90
1,000 ppb	58	82	52	37	27	23	87	97	100	87	87	87
SE	4.7						3.8			4.5		
Significance ^x	T $\times$ M $\times$ O $\times$ D*						T $\times$ M $\times$ H $\times$ O $\times$ D**			T $\times$ H $\times$ O $\times$ D**		
	T $\times$ H $\times$ O*									M $\times$ H $\times$ O**		

^a1 ppb = 1 nL·L⁻¹.

^yPercentage data were transformed to angles ($Y = \sin^{-1} \sqrt{\%/100}$) and back-transformed to percentage for presentation [$\% = 100 \times (\sin Y)^2$].

*, **Significant at $P < 0.05$ or $P < 0.01$, respectively, where T = treatment time, M = 1-MCP concentration, H = harvest, O = months, and D = days at 22 °C.

incidence of core browning and superficial scald, albeit neither disorder was completely controlled (Table 6). DeLong et al. (2004) also found that 1-MCP reduced the incidence of core browning and superficial scald in 'Summerland McIntosh' stored for 6 or 9 months in air at 3 °C plus 21 d at 20 °C. However, under these same conditions, 1-MCP reduced the incidence of core browning in 'Redmax McIntosh' after 6 months, but not after 9 months. There was little effect of 1-MCP concentration or time between harvest and treatment on disorders, except that apples from Harvest 2 treated 3 or 7 d after harvest had lower incidence of core browning with 1000 than 625 ppb (Table 6). Watkins and Nock (2005) found that superficial scald was reduced by 1-MCP in 'Cortland' and 'Delicious' apples, but there was no effect of delay before treatment (up to 8 d). 1-MCP has also been shown to control superficial scald in CA-stored 'McIntosh' from

four orchards in Maine (Moran, 2006).

Some senescent breakdown was also observed after 6 months of air storage at 0 °C to 1 °C plus 7 d at 22 °C, with lower incidence in the 1-MCP treated apples (29% vs. 13%). A similar reduction in senescent breakdown has been shown in 1-MCP treated 'Summerland McIntosh' after 9 months in air storage at 3 °C plus 21 d at 20 °C (DeLong et al., 2004). The incidence of senescent breakdown in 'Cortland' apples was found to increase with increasing delay between harvest and 1-MCP treatment (Watkins and Nock, 2005). However, the delay in 1-MCP treatment in this study had no consistent effect on senescent breakdown in 'McIntosh' apples (data not presented).

'McIntosh' apples stored for 3 months in air at 0 °C to 1 °C developed very few disorders (<2%). Similarly, few internal disorders (<1% flesh and core browning) were found

in 'McIntosh' apples stored in CA at 3 °C. Superficial scald developed in CA-stored fruit, with an incidence of 5% and 8% after 6 and 9 months, respectively, plus 7 d at 22 °C; however, there was no consistent effect of 1-MCP treatment, which was likely due to the low incidence observed. The fact that scald was observed in apples drenched with diphenylamine suggests that the concentration used in this study (1000 ppm a.i.) was not adequate for complete control during long-term storage. External CO₂ injury is often found in 'McIntosh' and 'Empire' apples treated with 1-MCP and stored in CA (DeEll et al., 2003; Fawbush et al., 2008). However, all fruit in this study were drenched with the antioxidant diphenylamine, which has been shown to control CO₂ injury in apples (Watkins et al., 1997), and thus no such injury was observed.

The research described here has provided the basis for the Canadian SmartFreshSM label and the recommendation by AgroFresh that 'McIntosh' apples should be treated within 3 d of harvest (AgroFresh Inc., 2007). The importance of minimizing 1-MCP treatment delays becomes greater as storage time increases and apples are pushed to their maximum life span. 1-MCP concentrations less than 1000 ppb due to application methods can also reduce the beneficial effects in 'McIntosh' fruit, especially with treatment delays or long-term storage periods. Therefore, storage operators should take care as to when and how their apples are treated with 1-MCP.

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