Effects of Delays between Harvest and 1-Methylcyclopropene Treatment, and Temperature during Treatment, on Ripening of Air-stored and Controlled-atmosphere-stored Apples

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Abstract. The effects of temperature during 1-MCP treatment, and the effects of delays of up to 8 d after harvest before treatment, have been investigated using ‘Cortland’, ‘Delicious’, ‘Jonagold’, and ‘Empire’ (normal and late harvest) apple [*Malus sylvestris* (L.) Mill. var. *domestica* (Borkh.) Mansf.] cultivars stored in air for 2 and 4 months and in controlled atmosphere (CA) storage for 4 and 8 months. Fruit were treated with 1 $\mu\text{L}\cdot\text{L}^{-1}$ 1-MCP for 24 hours on the day of harvest (warm) or after 1, 2, 3, 4, 6, or 8 days at cold storage temperatures. CA storage was established by day 10. Little effect of temperature during treatment (warm fruit on the day of harvest compared with cold fruit after 24 hours of cooling) was detected. Major interactions among cultivars, handling protocols before 1-MCP treatment, storage type and length of storage were observed. Delays of up to 8 days before 1-MCP treatment either did not affect efficacy of treatment, or markedly reduced it, depending on cultivar, storage type and length of storage. The results indicate that, depending on cultivar, the importance of minimizing the treatment delay increases as storage periods increase.

The development of 1-methylcyclopropene (1-MCP), a gaseous inhibitor of ethylene perception by plant cells (Sisler and Serek, 1997), has great potential for maintaining storage quality of horticultural products. 1-MCP has been registered for use on flowers as Ethyl-Bloc, and for use on apple fruit as SmartFresh. Registration for food use of SmartFresh has been obtained in several countries, including the U.S. (Watkins and Miller, 2005a). A large body of literature dealing with the effects of 1-MCP on postharvest responses of fruits, vegetables and flowers is available (Blankenship and Dole, 2003; Watkins, 2002; Watkins and Miller, 2005b).

1-MCP can dramatically inhibit ethylene production and softening of apples in both air and controlled atmosphere (CA) storage (Fan et al., 1999; Mir et al., 2001; Rupasinghe et al., 2000; Watkins et al., 2000; Zanella, 2003). The effectiveness of 1-MCP is affected by cultivar. Few comparisons of the effects of physiological ripening stage at the time of treatment within a single cultivar are available although Mir et al. (2001) found that the effectiveness of 1-MCP declined slightly with advancing harvest date of ‘Delicious’ apple. Information about how

the effects of 1-MCP are modulated under commercial postharvest manipulations is also limited with most published studies reporting results where 1-MCP applications have been made at about 20 °C within a day of harvest (DeLong et al., 2004; Fan et al., 1999; Mir et al., 2001; Rupasinghe et al., 2000; Watkins et al., 2000). DeEll et al. (2002) have shown that efficacy of 1-MCP can be affected by treatment temperature and duration, with longer exposure periods being necessary at lower temperatures than warmer temperatures. Commercial recommendations for treatment are for 1 $\mu\text{L}\cdot\text{L}^{-1}$ 1-MCP for 24 h, and these are typically applied at storage temperatures. Another difference between the commercial operations and published studies is that fruit are accumulated over time after harvest before storage rooms are filled. Although rapid CA storage, in which O_2 levels in the room are reduced to <2.5% within 4 to 7 d (Watkins, 2003), is commonly used, actual room loading periods can be shorter or longer depending on the size of the storage operation.

The objectives of the present study were to examine the effects of temperature during 1-MCP treatment, and the effects of delays after harvest before 1-MCP treatment, on four cultivars. The effect of harvest date on the responses to these treatments of one cultivar, ‘Empire’, was also studied.

Materials and Methods

Fruit were harvested from mature trees of each cultivar growing at the Cornell research orchard at Ithaca, New York in 2000. Fruit of ‘Cortland’, ‘Delicious’, and ‘Jonagold’ were harvested on 25 Sept., 6 Oct., and 9 Oct.,

respectively, representing midharvest dates for each cultivar (Blanpied and Silsby, 1992). ‘Empire’ apples were harvested on two occasions, 28 Sept. and 12 Oct., which represent a normal and a late harvest date.

For each cultivar, fruit were sorted to remove blemishes and small and over-sized fruit before being divided into 32 box lots of 50 to 60 fruit, plus additional sets of 10 fruit for assessment of internal ethylene concentration (IEC) and flesh firmness at the time of each 1-MCP treatment described below. Four boxes of each cultivar were treated with 1-MCP at 20 °C for 24 h using 135-L plastic containers. 1-MCP as a powder (SmartFresh, AgroFresh, Springhouse, Pa.; 0.14 % active ingredient by weight) was weighed into Erlenmeyer flasks to provide a final 1-MCP concentration in the containers of 1 $\mu\text{L}\cdot\text{L}^{-1}$. Water was added to liberate the 1-MCP from the powder, and the treatment containers were quickly sealed with wide duct tape. After 24 h, the containers were vented and placed in cold storage.

All other boxes were placed in cold storage (0.5 °C) on the day of harvest. For each cultivar, four boxes of fruit were left untreated, while four boxes of fruit were treated with 1 $\mu\text{L}\cdot\text{L}^{-1}$ 1-MCP for 24 h at 1, 2, 3, 4, 6, and 8 d after harvest, as described above. After 1-MCP treatment, the boxes of fruit were removed from the treatment containers and allowed to vent before being placed at the desired long term storage temperature.

On removal of the fruit from the last 1-MCP treatment (9 d after harvest), the boxes of fruit destined for CA storage were loaded into 850-L metal chambers (Watkins et al., 2000), while the remaining fruit were kept in air. CA was applied on day 10 and final atmospheres were obtained within 2 d. Atmospheres were maintained at 2% O_2 and 2% $\text{CO}_2 \pm 0.2\%$ using an Oxstat II CA system (David Bishop, England). Temperatures used were 0.5 °C for air- and CA-stored ‘Cortland’, ‘Jonagold’, and ‘Delicious’ and air-stored ‘Empire’ and 2.2 °C for CA-stored ‘Empire’. CA regimens and storage temperatures were the standard commercial recommendations for these cultivars in New York (Watkins, 2003).

Fruit from each box were removed to a constant temperature evaluation room maintained at 20 °C after 2 and 4 months for air-stored fruit, and 4 and 8 months for CA-stored fruit. The IEC, firmness and soluble solids concentration (SSC) of each of 10 fruit per replicate was assessed after 1 and 7 d. At the second removal all remaining fruit, together with the 10 fruit assessed on day 7 were checked for external and internal disorders on day 7. Greasiness was also noted subjectively by hand feel, as present or absent. The IEC of each individual fruit was assessed on 1-mL gas samples from the core cavity (Watkins et al., 2005). Firmness was measured on opposite sides of each fruit using an EPT-1 pressure tester (Lake City Technical Products, Kelowna, Canada) fitted with an 11.1-mm-diameter probe. The SSC was measured on combined juice collected from the penetrometer probe with a refractometer (Atago PR-100; McCormick Fruit Tech., Yakima, Wash.). Data were subjected to ANOVA to analyze effects

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Table 1. The internal ethylene concentration (IEC), flesh firmness and soluble solids concentration (SSC) of 'Cortland', 'Delicious', 'Jonagold', and 'Empire' (two harvest dates) apples treated with 1 $\mu\text{L}\cdot\text{L}^{-1}$ 1-MCP when warm (20 °C) on the day of harvest or after 1 d of cold storage (0.5 °C). Data are the means of two storage periods (2 and 4 months for air, and 4 and 8 months for controlled atmosphere (CA) storage) and two shelf life periods (1 and 7 d).

Storage type	IEC ($\mu\text{L}\cdot\text{L}^{-1}$)		Firmness (N)		SSC (%)	
	Warm	Cold	Warm	Cold	Warm	Cold
'Cortland'						
Air	19.6	16.9	63.3	62.2	13.0	12.5
CA	8.0	1.9*	63.8	64.6	13.1	12.9
'Delicious'						
Air	24.7	26.4	67.4	68.2	13.1	13.1
CA	24.0	36.4	66.8	67.4	13.3	13.0
'Jonagold'						
Air	1.6	2.1*	61.0	60.5	13.9	13.8
CA	1.0	0.9	61.5	62.1	14.0	13.8
'Empire', harvest Sept. 28						
Air	1.3	1.5	76.1	74.5*	12.5	12.2
CA	11.7	16.2	75.4	72.4**	12.8	12.5
'Empire', harvest Oct. 12						
Air	7.7	9.5	67.5	66.7	12.4	12.5
CA	24.7	31.0	63.2	63.9	12.5	12.6

***Significance at $P \leq 0.05$ or 0.01, respectively, for comparisons of warm and cold treatment within each cultivar and storage type.

of warm and cold treatment with 1-MCP, and storage length and shelf life period for each cultivar and storage type. IEC and percentage disorder data were transformed to logarithms and arcsine, respectively, for analysis, but are presented as back-transformed means. Separate statistical analyses were carried out only on data from the 1-MCP treatment times (1, 2, 3, 4, 6, and 8 d after harvest) to dissect effects of treatment delays. Data for time of 1-MCP treatment were subjected to regression analysis to identify linear (L), quadratic (Q), and cubic (C) terms.

Results

Temperature of 1-MCP treatment. The data for fruit treated warm (20 °C) on the day of harvest compared with fruit cooled to 0.5 °C overnight before treatment were analyzed separately. No significant interactions among storage time (2 and 4 months for air storage, and 4 and 8 months for CA storage) and shelf life (1 and 7 d) were detected; therefore, only the overall means for IEC, firmness and SSC are provided (Table 1). IECs were lower and higher in cold-treated 'Cortland' stored in CA and 'Jonagold' stored in air, respectively, than when treated warm. Differences were minor, however. Treatment temperature effects were found for firmness only for 'Empire' from the first harvest, with softer fruit in cold than warm treatments. No effect of treatment temperature was detected for SSC.

Time after harvest before 1-MCP treatment. The IEC and firmness of 'Cortland', 'Delicious' and 'Jonagold' fruit at harvest were 15.2, 11.5, and 0.8 $\mu\text{L}\cdot\text{L}^{-1}$ and 63.5, 72.0, and 65.0 N, respectively. Although the IEC declined when fruit were placed into cold storage, neither the IEC nor firmness changed subsequently up to the maximum of 8 d of storage before 1-MCP was applied (Figs. 1–3).

With few exceptions, 1-MCP treated fruit had lower IECs and higher firmness values ($P \leq 0.001$) (Figs. 1–5). These exceptions occurred in fruit assessed 1 d after removal from CA

storage where little softening had taken place during storage.

The effect of delays between harvest and treatment time was affected by cultivar and storage type and length (Figs. 1–3; Table 2). In all experiments, the 1-MCP treatment delays before CA storage meant that the later treated fruit had shorter time periods before CA storage. It is assumed, but not certain, that this effect was minor compared with the effect of delays in 1-MCP treatment.

'Cortland' fruit stored in air for 2 months

plus the shelf life period of 7 d showed increased IEC and softening when treated 6 d after harvest (Fig. 1A and C). By 4 months of air storage, the IEC suppression was less consistent. Fruit were also generally softer with only a 2 d delay between harvest and 1-MCP treatment, although firmness stabilized from 3 to 6 d. In contrast, following CA storage IEC increased in fruit only after the 7-d shelf life period but after a 4- and 2-d delay in 1-MCP treatment for fruit stored for 4 and 8 months, respectively (Fig. 1B). Effects of treatment delay on firmness were statistically significant (Table 2) but overall firmness remained high (Fig. 1D).

The effects of delayed 1-MCP treatment on IEC and firmness of 'Delicious' apples was relatively small (Table 2). Most changes for both factors in air- and CA-stored were related to storage and shelf life periods rather than delay treatments (Fig. 2A–D).

1-MCP-treated 'Jonagold' fruit in both air and CA storage maintained low IEC despite delays in treatment (Fig. 3A and B), although small increases occurred due to a treatment delay after 4 months of storage (Table 2). The firmness of 1-MCP-treated fruit stored in air for 2 months declined over the shelf life period, but not fruit stored for 4 months (Fig. 3C). Firmness of CA stored fruit was not affected by storage or shelf life periods (Fig. 3D). Treatment delays did not affect the firmness of either air- or CA-stored fruit (Table 2).

The effects of fruit maturity on responses of fruit to delays in 1-MCP treatment were investigated using 'Empire' apples. Fruit har-

Fig. 1. Internal ethylene concentrations (IEC) and flesh firmness of 'Cortland' apples at harvest, untreated (U) or treated with 1 $\mu\text{L}\cdot\text{L}^{-1}$ 1-MCP at 0.5 °C for 24 h after delays of 1, 2, 3, 4, 6, or 8 d after harvest. Fruit were then stored in air for 2 and 4 months, or in controlled atmosphere (CA) storage for 4 and 8 months, and evaluated after 1 and 7 d at 20 °C. Regression analyses of data trends at each removal and evaluation time are provided in Table 2.

vested on 28 Sept. (Harvest 1) had IEC and firmness of $0.4 \mu\text{L}\cdot\text{L}^{-1}$ and 76.5 N , respectively, while those harvested on 12 Oct. (Harvest 2) had IEC and firmness of $12.1 \mu\text{L}\cdot\text{L}^{-1}$ and 71.9 N , respectively.

Although 'Empire' fruit from Harvest 1 softened slightly in air from 2 to 4 months (Fig. 4C), and IEC increased in fruit stored in CA for 8 months plus 7 d (Fig. 5A), no effects of treatment delay were detected (Table 2). In contrast, differences in responses of fruit from Harvest 2 to delays in 1-MCP treatment were marked (Figs. 4B and D; 5B and D; Table 2). In air storage, the IEC of fruit increased with longer delays before treatment, although overall concentrations remained relatively low except for the 4 month plus 7 d evaluation (Fig. 4B). Firmness was maintained for 2 months, but declined by the 4 month evaluation (Fig. 4D). Within this evaluation time, firmness declined beyond the 4-d delay treatment. For CA-stored fruit, IEC increased during the shelf life period after 4 months of storage, and especially during this period after 8 months of storage (Fig. 5B). No effects of delayed 1-MCP treatment were found for firmness at the first removal at 4 months, but at 8 months fruit softened rapidly if 1-MCP treatment was delayed >3 d (Fig. 5D).

No consistent effects of delay treatment on SCC were detected for any cultivar, storage period or shelf life period (data not shown).

Storage disorders. Overall, air- and CA-stored 'Cortland' apples had 5% and 8% bitter pit, respectively, with no effect of 1-MCP, delay treatment or storage time. In air storage, flesh browning increased from 1% after 2 months of storage to 6% after 4 months, but incidence was not affected by 1-MCP treatment (data not shown). In CA-stored apples, flesh browning increased from 2% to 14% from 4 to 8 months in the untreated control fruit. The incidence of browning increased with delay of 1-MCP treatment ($P = 0.038$), being 2%, 3%, 7%, 10%, 11%, and 15% for 1, 2, 3, 4, 6, and 8 d delays, respectively, after 8 months of storage. Superficial scald only occurred after 8 months of storage, and was affected by 1-MCP treatment ($P < 0.001$) but not by the delay treatments. Untreated control fruit had 42% scald, 2% in both warm and 1 d cold 1-MCP treatments, and 2%, 5%, 2%, 3%, and 3% in fruit treated with 1-MCP after 2, 3, 4, 6, and 8 d.

For 'Delicious', scald incidence was 30% in untreated control fruit, and 0% in all 1-MCP treatments, after storage in CA for 8 months. Slight incidences ($<5\%$) of core and flesh browning were detected in other storage treatments and times, but no treatment effects were detected.

In untreated air- and CA-stored 'Jonagold' fruit, greasiness incidence averaged 54% and 28%, for both storage periods, respectively. No effect of delay treatment was detected but the overall 1-MCP treatment greasiness incidence was 8% in air stored fruit. However, in CA-stored fruit incidences were reduced ($P = 0.05$) by a relatively smaller extent to 14%. Flesh browning was reduced by 1-MCP treatments, irrespective of delay, from 16% to $<3\%$ in air storage, but incidence in all CA stored

Fig. 2. Internal ethylene concentrations (IEC) and flesh firmness of 'Delicious' apples at harvest, untreated (U) or treated with $1 \mu\text{L}\cdot\text{L}^{-1}$ 1-MCP at 0.5°C for 24 h after delays of 1, 2, 3, 4, 6, or 8 d after harvest. Fruit were then stored in air for 2 and 4 months, or in controlled atmosphere (CA) storage for 4 and 8 months, and evaluated after 1 and 7 d at 20°C . Regression analyses of data trends at each removal and evaluation time are provided in Table 2.

Fig. 3. Internal ethylene concentrations (IEC) and flesh firmness of 'Jonagold' apples at harvest, untreated (U) or treated with $1 \mu\text{L}\cdot\text{L}^{-1}$ 1-MCP at 0.5°C for 24 h after delays of 1, 2, 3, 4, 6, or 8 d after harvest. Fruit were then stored in air for 2 and 4 months, or in controlled atmosphere (CA) storage for 4 and 8 months, and evaluated after 1 and 7 d at 20°C . Regression analyses of data trends at each removal and evaluation time are provided in Table 2.

Fig. 4. Internal ethylene concentrations (IEC) and flesh firmness of 'Empire' apples harvested on 28 Sept. (Harvest 1) and 12 Oct. (Harvest 2), and untreated (U) or treated with $1 \mu\text{L}\cdot\text{L}^{-1}$ 1-MCP at 0.5°C for 24 h after delays of 1, 2, 3, 4, 6, or 8 d after harvest. Fruit were then stored in air for 2 and 4 months for 4 and 8 months, and evaluated after 1 and 7 d at 20°C . Regression analyses of data trends at each removal and evaluation time are provided in Table 2.

Fig. 5. Internal ethylene concentrations (IEC) and flesh firmness of 'Empire' apples harvested on 28 Sept. (Harvest 1) and 12 Oct. (Harvest 2), and untreated (U) or untreated (C) or treated with $1 \mu\text{L}\cdot\text{L}^{-1}$ 1-MCP at 0.5°C for 24 h after delays of 1, 2, 3, 4, 6, or 8 d after harvest. Fruit were then stored in controlled atmosphere (CA) storage for 4 and 8 months, and evaluated after 1 and 7 d at 20°C . Regression analyses of data trends at each removal and evaluation time are provided in Table 2.

fruit was negligible. Bitter pit averaged 12% and 7% in air and CA storage, and was not affected by 1-MCP, storage type or length (data not shown).

No storage disorders were detected in air-stored 'Empire' from the first harvest, but in fruit from the second harvest a 4% incidence of flesh breakdown in fruit stored for 4 months was eliminated by 1-MCP treatment. Flesh browning of up to 3% was found at the 4 month evaluation. Incidence of flesh browning in CA fruit from Harvest 1 and Harvest 2 stored for 8 months averaged 17% and 83%, respectively. However, no effect of treatment on flesh browning was detected for either air or CA-stored fruit.

Discussion

1-MCP can markedly affect the ripening of apple fruit, but 'degrees of response' to the technology exist. This study has identified major interactions for each cultivar with handling protocols before 1-MCP treatment, storage type and length of storage, and for 'Empire', harvest date interactions. Cultivars such as 'Cortland' when stored in air, and late harvested 'Empire' stored in air or CA, show generally greater softening with increasing storage periods and shorter periods of optimal response to treatment. In contrast, 'Delicious', 'Jonagold' and early harvested 'Empire' apples, especially when stored in CA, show little effect of treatment delays up to 8 d.

It is likely that cultivar effects and interactions with postharvest handling and storage procedures are mediated to a significant extent by the ethylene production by the fruit in terms of whether or not climacteric ethylene production has been initiated at the time of harvest, how effectively ethylene production before 1-MCP treatment is minimized after harvest, and the inherent ripening physiology of the specific apple cultivar. The literature on the effects of 1-MCP on apple fruit ripening shows that cultivar effects can be significant. In some cases, almost complete inhibition of softening occurs, while at the other extreme, softening is only delayed by 1-MCP treatment (DeLong et al., 2004; Fan et al., 1999; Pre-Aymard et al., 2003; Rupasinghe et al., 2000; Watkins et al., 2000). The reasons for differences in cultivar responses to 1-MCP are not fully understood, but because 1-MCP is thought to act by binding irreversibly to ethylene receptor sites (Sisler and Serek, 1997) then maximal effects should result from 1-MCP treatment before the initiation of ethylene production. Rates of ethylene production by fruit of different cultivars vary greatly over the harvest season (Blanpied and Silsby, 1992; Chu, 1988; Watkins et al., 1989). 'McIntosh', which appears less responsive to 1-MCP, often has high levels of ethylene at harvest and ripens rapidly (DeLong et al., 2004; Watkins et al., 2000). However, the effect of time of harvest around the ethylene climacteric was relatively small for 'Delicious' apples stored at 0°C (Mir et al., 2001). The recovery of ripening processes after 1-MCP treatment is probably related to the formation of new

Table 2. Regression analyses of internal ethylene concentration (IEC) and flesh firmness of 'Cortland', 'Delicious', 'Jonagold', and 'Empire' (two harvest dates) apples treated with 1 $\mu\text{L}\cdot\text{L}^{-1}$ 1-MCP after 1, 2, 3, 4, 6, or 8 d of cold storage (0.5 °C) and assessed after 2 and 4 months storage in air, or 4 and 8 months storage in CA, plus 1 and 7 d at 20 °C.

Cultivar	Factor	Air storage				CA storage			
		2 mo/1 d	2 mo/7 d	4 mo/1 d	4 mo/7 d	4 mo/1 d	4 mo/7 d	8 mo/1 d	8 mo/7 d
'Cortland'	IEC	L*	L**	L**, Q*C**	L*Q*	NS	L**Q**	NS	L***
	Firmness	NS	L***Q*C**	L*	L***	NS	L**	L**	L*
'Delicious'	IEC	NS	NS	NS	C*	NS	L*	NS	L*
	Firmness	NS	NS	NS	NS	L*	NS	NS	C*
'Jonagold'	IEC	NS	NS	L*	NS	NS	NS	NS	NS
	Firmness	NS	NS	NS	NS	Q*	NS	NS	NS
'Empire'	Harvest Sept. 28	IEC	NS	NS	NS	NS	NS	NS	NS
		Firmness	NS	NS	NS	NS	NS	NS	NS
	Harvest Oct. 12	IEC	NS	L*Q*	L***Q**	ns	L***Q***C**	L*	L*
		Firmness	NS	L***	Q*	NS	NS	L*Q*	L*Q*

NS,*,**,*Nonsignificant, or significant at $P < 0.05$, 0.01 or 0.001 for linear (L), quadratic (Q), or cubic (C) functions, respectively.

ethylene receptors (Blankenship and Sisler, 1993), but little is known about how this recovery differs among cultivars.

The initial research on 1-MCP has been typically laboratory-based and carried out at temperatures close to ambient (Watkins and Ekman, 2005), and for apples 1-MCP applications have been made at about 20 °C within 1 d of harvest (DeLong et al., 2004; Fan et al., 1999; Mir et al., 2001; Rupasinghe et al., 2000; Watkins et al., 2000). In commercial practice, however, most products will be treated at close to the recommended storage temperature for that product. A limited number of studies suggest that treatment at low temperature is generally less effective than treatment at a higher temperature. For example, 1-MCP applied at 2 to 5 °C did not provide protection against ethylene for *Penstemon* and *Grevillea* flowers or bananas (Macnish et al., 2000; Serek et al., 1995). In apple fruit and broccoli the effectiveness of 1-MCP appears to decline as application temperature decreases (Ku and Wills, 1999; Mir et al., 2001). For 1-MCP to inhibit ethylene perception, it has to diffuse to, as well as bind to, the attachment sites, and Sisler and Serek (1997) suggested that more 1-MCP is attached to receptors at higher temperatures. Poorer binding could be due to conformational changes in a membrane-located protein that is the ethylene receptor (Macnish et al., 2000). In our study, however, the effects of treatment temperature on IEC and firmness of the cultivars were small or absent. DeEll et al. (2002) showed that treatment temperature and duration can affect efficacy of 1-MCP on fruit quality, but significant differences in duration times were 9 hours or less. A 4 h treatment at 20 °C was as effective as a 24 h treatment of cold fruit for 'Anna', 'Queen Cox' and 'Bramley' apple fruit (Dauny and Joyce, 2002; Pre-Aymard et al., 2003). Under commercial conditions, rapid treatment of warm fruit is not practical and cooling is desirable to prevent the onset of ethylene production and fruit softening.

Interestingly, cold temperatures induce ethylene production in some apple cultivars (Knee et al., 1983; Larrigaudiere et al., 1997), but none of the cultivars used in our study showed higher IECs during the 8 d of this experiment. Possible effects of longer delay times are needed to investigate these effects

further. However, enhanced capacity for ethylene biosynthesis by cold storage underscores the importance of applying 1-MCP rapidly to arrest the development of competency of fruit to produce and respond to ethylene.

Of the storage disorders found in this study, only flesh browning in CA-stored 'Cortland' apples increased with the delay before 1-MCP treatment. Browning symptoms were consistent with senescent breakdown, which increases with CA storage period and is reduced by 1-MCP (DeLong et al., 2004), but suggests that risk of injury development can increase even in 1-MCP-treated fruit if treatment is delayed and the storage period is extended. The browning symptoms in 'Empire' apples, which were not affected by 1-MCP, irrespective of delays before treatment, were more consistent with those of chilling injuries, with moist and firm cortical flesh. The incidence of flesh browning increased dramatically in late harvested fruit suggesting that a maturity factor is involved in susceptibility of fruit to the disorder. However, the incidence of chilling-associated flesh browning in Empire apples was not affected by 1-MCP.

Disorders affected by 1-MCP, regardless of delay treatment, were superficial scald and greasiness. Superficial scald was dramatically inhibited by 1-MCP, supporting earlier observations (Fan and Mattheis, 1999; Rupasinghe et al., 2000; Watkins et al., 2000; Zanella, 2003). The mechanism of scald development is generally accepted to result from oxidation products of the sesquiterpene (E,E)- α -farnesene, probably the conjugated trienols (CTols) (Rowan et al., 1995; Whitaker et al., 1997). Control of superficial scald development is thought to be via inhibition of α -farnesene production, and thus reduced CTol accumulation (Lurie et al., 2005; Pechous et al., 2005; Rupasinghe et al., 2000). Greasiness, a phenomenon associated with changes in the wax and oil fractions in the skin (Morice and Shorland, 1973), is a major storage disorder found commercially in 'Jonagold' apples. Greasiness development is associated with more mature fruit and longer storage periods (Leake et al., 1989a; Leake et al., 1989b). Inhibition of greasiness development by 1-MCP shown here and for 'Granny Smith' apples by Fan and Mattheis (1999) suggests that 1-MCP may be a useful tool to manage this problem.

Research such as this described here has provided the basis for recommendations by AgroFresh Inc., the suppliers of 1-MCP as the commercial formulation, SmartFresh, that fruit of most cultivars should be treated within 7 days of harvest in the US (SmartFresh, AgroFresh Inc., 2004). In this respect the recommendations are similar to those for 'rapid CA' (Watkins, 2003). However, under commercial conditions it is likely that the period after harvest before 1-MCP treatment that is necessary to ensure optimal responses to 1-MCP can be much shorter than those generally recommended. Depending on cultivar, the importance of minimizing delays increases as storage periods increase.

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