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Interactions between 1-MCP concentration, treatment interval and storage time for 'Bartlett' pears

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Abstract

Storage trials were carried out over two seasons to determine a suitable treatment protocol for the use 1-methylcyclopropene (1-MCP) with 'Bartlett' (Williams) pears. In the 2000 season, pears were exposed to 0, 0.01, 0.1, 0.5 or 1.0 $\mu l\,l^{-1}$ 1-MCP at 0 °C, then stored at −1 °C for up to 24 weeks before ripening at 20 °C. The effects of the lower concentrations dissipated after a time, allowing fruit to reach eating ripeness. Superficial scald development was delayed, but not prevented, in these fruit. Although 1.0 $\mu l\,l^{-1}$ effectively prevented scald, these fruit failed to soften. Overall, concentrations of 0.1–0.5 $\mu l\,l^{-1}$ 1-MCP appeared to have the most potential as storage treatments. In the 2001 season, fruit were exposed to 0, 0.2 or 0.4 $\mu l\,l^{-1}$ 1-MCP at 0 °C. After 4 or 6 weeks at −1 °C, half the fruit were re-treated at 0 °C and stored at −1 °C for a further 4 or 6 weeks. Re-treatment after 4 weeks had a greater effect on color development and softening after storage than did the initial 1-MCP application. In contrast, fruit re-treated after 6 weeks showed little response to the additional 1-MCP exposure. These results suggest that green fruit recover ethylene sensitivity more slowly when re-treated with 1-MCP after a period of storage. However, if fruit have started to ripen they are relatively insensitive to additional 1-MCP. Treatment with 1-MCP reduced fruit sensitivity to handling damage, even after ripening. The results are discussed in terms of the practical difficulties with application of 1-MCP to 'Bartlett' pears as well as potential commercial benefits.
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1. Introduction

Storage of 'Bartlett' pears is typically limited to 2–3 months in air, even under ideal storage conditions at −1 °C. In most cases, the end of storage life is due to the onset of physiological disorders, particularly superficial scald and core breakdown. Ethylene produced by the fruit can exacerbate these disorders, as well as cause premature yellowing and softening during storage. Late harvested fruit are particularly susceptible to these disorders, which may begin to appear within a month of harvest (Ju et al., 2001).

Methods used to extend the storage life of pears include treatment with ethoxyquin, fruit coatings, and low oxygen atmospheres. There are some

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environmental concerns with the use of ethoxyquin and it is not registered for use on pears in California. While fruit coatings have been found to reduce rates of ripening and scald development, they can result in uneven ripening and blotchy color development (Meheriuk and Lau, 1988). Storing pears in 1–1.5% O_2 can effectively reduce the rate of ripening and the incidence of physiological disorders, thereby extending storage life (Yoshida et al., 1986; Kader, 1989). However, accumulation of CO_2 can increase internal browning, with susceptible fruit unable to tolerate >1% CO_2 during storage (Claypool, 1973).

An alternative method of slowing ripening is treatment with an inhibitor of ethylene action. One such compound, 1−methylcyclopropene (1-MCP), is now registered for use on apples in the US, with applications pending for wider use on other fruit and vegetables (Agrofresh, USA). 1-MCP is thought to act by binding irreversibly to ethylene receptors in the fruit, thereby preventing the effects of ethylene in the plant tissues (Sisler and Serek, 1997). Exposure to 1-MCP can inhibit ripening of climacteric fruit such as apples, avocados, bananas, kiwifruit, stonefruit and mangos (Watkins and Miller, 2003). Furthermore, treating apples with 1-MCP can reduce the incidence of superficial scald and other physiological disorders (Fan and Mattheis, 1999; Watkins et al., 2000). Pears have been shown to respond to 1-MCP, typical effects include delays in degreening and softening and reduced respiration and ethylene production (DeWild et al., 1999; Baritelle et al., 2001). It seemed possible that 1-MCP could also reduce superficial scald on pears.

Unlike apples, ‘Bartlett’ pears only reach full dessert quality when they soften. As the effects of 1-MCP are not readily reversible by exposure to ethylene, treatments must be applied in such a way that the fruit ripen normally after a period of storage. The rate at which fruit regains ethylene sensitivity is primarily dependent on the concentration of 1-MCP applied and the duration of storage (Watkins et al., 2000).

We conducted a series of experiments during 2000 and 2001 examining the effects of different concentrations of 1-MCP with different storage durations. In the first experiment, ‘Bartlett’ pears were exposed to 0–1 $\mu l\,l^{-1}$ of 1-MCP. From this work, we determined that concentrations between 0.1 and 0.5 $\mu l\,l^{-1}$ were likely to be the most suitable for pear fruit, as pears ripened within a reasonable time after removal from storage. However, such low concentrations are likely to lose their effectiveness within a relatively short period. It could be possible to extend the effects of 1-MCP as well as improve marketing flexibility by applying the gas more than once during storage. Therefore, the second season’s experimental work used concentrations of 0.2 and 0.4 $\mu l\,l^{-1}$ 1-MCP, and repeated these applications after 4 or 6 weeks of cold storage. The results are discussed in terms of the potential to implement a commercial treatment of 1-MCP for ‘Bartlett’ pear fruit.

2. Materials and methods

2.1. Fruit material

Pears were harvested from a commercial orchard in the Sacramento area on 2 August 2000 and 18 July 2001. In the initial experiment, harvested fruit were divided into six replicate groups for treatment. The second set of experiments used three replicate groups comprising pears selected from different harvest bins. In both seasons, the harvested fruit were transported to UCDavis by air-conditioned vehicle. After sorting to obtain undamaged fruit of uniform size and color, the pears were cooled overnight to 0 °C.

2.2. Treatments

The pears were placed into steel tanks for treatment. A small electric fan was also placed inside each tank to ensure even distribution of the 1-MCP gas around the fruit. The tank lids were constructed so as to fit into water filled troughs, forming a hermetic seal. Warm water was injected into a sealed flask containing a measured amount of the Ethylbloc powder (0.14% a.i., Floralife Inc., Walterboro, SC, USA) to generate 1-MCP gas. By continuing to inject water until the flask was full, the gas was forced out of the flask and into the tank.

The first set of experiments examined the effects of different 1-MCP concentrations on quality and ripening of pears after various periods of cold storage. Fruit were treated with 0, 0.01, 0.1, 0.5 or 1.0 $\mu l\,l^{-1}$ 1-MCP for 12 h at 0 °C. Immediately after treatment, 18 fruit from each group were exposed to 100 $\mu l\,l^{-1}$ ethylene for 42 h then placed at 20 °C for up to 19 days. The

remaining fruit were stored at −1 °C for 6, 12, 18 or 24 weeks before ripening at 20 °C for at least 8 days.

The second set of experiments used only low 1-MCP concentrations, but repeated the applications. Fruit assigned to both the 4 and 6 week treatment schedules were given an initial exposure to 0, 0.2 or 0.4 μl l^{-1} 1-MCP for 12 h at 0 °C. Ten additional fruit from each replication were assessed immediately after treatment, with a further 10 assessed after 1 week at 20 °C. After either 4 or 6 weeks at −1 °C, we removed half of the fruit from the appropriate schedule for assessment. Measurements were taken immediately or following 1 week of ripening at 20 °C. The remaining fruit were re-treated with the same 1-MCP concentration as had been used previously (0, 0.2 or 0.4 μl l^{-1}) for 12 h at 0 °C. The re-treated fruit were evaluated after a second storage period of the same duration as each group had already completed (4 or 6 weeks), both before and after 1 week of ripening at 20 °C.

2.3. Quality assessment

During initial experiments, we recorded pear attributes on removal from cold storage and then every 2 days during subsequent ripening at 20 °C. At each assessment, three fruit were destructively evaluated from each of the six replicate groups. Fruit in the second set of experiments were assessed on removal from storage and again after a week at 20 °C. In this case, each assessment used 10 fruit from each of three replicate groups.

2.3.1. Color

Skin color was measured using a Minolta Chroma Meter (Model CR300, Minolta Co., Japan) in the $L^*a^*b^*$ mode under standard CIE illuminant C. Measurements were taken on opposite sides of each fruit, and the mean value calculated. Color changes from green to yellow were indicated by calculating the hue angle (H°), from $\tan^{-1}\ b^*/a^*$.

2.3.2. Flesh firmness

Firmness was measured using an Ametek penetrometer (Ametek Inc., Hatfield, PA USA) mounted in a drill press stand and fitted with an 8 mm probe. Sections of pear skin were removed at the equator on either side of the fruit to allow two separate readings of each pear.

2.3.3. Disorders

We evaluated the pears for incidence and severity of scald, decay and internal breakdown. Scald, decay and internal breakdown were ranked subjectively as 0: none; 1: slight; 2: moderate; or 3: severe, and the percentage of the fruit that were affected was calculated. In the case of scald, the percentage of each fruit's surface that was affected (0–100%) was visually estimated.

2.4. Gas exchange

Measurements of respiration rate and ethylene production were made in both seasons using three replicate groups of six fruit per treatment. The fruit were sealed into 3.75 l glass jars, allowing CO_2 to accumulate to 0.1–0.3%. This took from 10 min to 3 h, depending on the ripeness stage and temperature. Concentrations of CO_2 and ethylene in the headspace of each jar were determined by rapid gas analysis (VIA510, Horiba, Japan) or gas chromatography (Model AGC Series 400, Hach-Carle Co., USA). In the first experiment, we calculated the rates of CO_2 and ethylene evolution daily for at least 8 days during ripening at 20 °C. The following season, measurements were made weekly while fruit were stored at −1 °C.

2.5. Data analysis

Changes in color and firmness in the initial experiments were plotted as sigmoidal curves and the number of days at 20 °C before each attribute reached a predetermined limit was calculated (Sigma Plot scientific software, Version 4, SPSS Inc., IL, USA). The limits used were $H^\circ = 102$ and firmness = 18 N, as these values indicated that fruit were essentially yellow and fully softened, respectively. The number of days taken for fruit to reach these limits was subjected to analysis of variance (ANOVA). Data was analyzed by time as well as by treatment. The percentage of the fruit that were affected by scald and/or internal breakdown was calculated based on data from day 8 of ripening only. The severity scores for both disorders and the percentage of the surface area of each fruit that was scald affected were compared and analyzed by ANOVA.

In the second set of experiments, data was analyzed by ANOVA according to time of storage and

treatment, and all time/treatment combinations were compared. All ANOVAs were performed using SAS statistical software (Version 7, SAS Institute Inc., USA) to conduct a series of factorial analyses. Means were separated using the Student–Newman–Keuls test to calculate the least significant difference.

3. Results

3.1. 1-MCP concentration and storage time

3.1.1. Color and firmness

Application of 1-MCP had no effect on color development during storage at −1 °C. Untreated fruit were softer than pears treated with 0.5 or 1.0 μl l^{-1} 1-MCP, but this difference was only apparent after 24 weeks storage at −1 °C (data not shown).

In contrast, large differences in color and firmness occurred during ripening at 20 °C. As the fruit were measured at 2 day intervals, it was possible to generate a relatively continuous relationship between fruit attributes and time. An example is shown in Fig. 1.

Both magnitude and duration of the effects of 1-MCP were related to treatment concentration (Table 1). Treatment with 0.01 μl l^{-1} 1-MCP did not affect the rate of color development or softening of pear fruit. However, increasing the 1-MCP concentration had progressively greater effects on softening and yellowing, and for longer periods.

None of the fruit treated with 1.0 μl l^{-1} 1-MCP and stored for up to 18 weeks at 0 °C fully softened to 18 N within 14 days at 20 °C (Table 1). A number

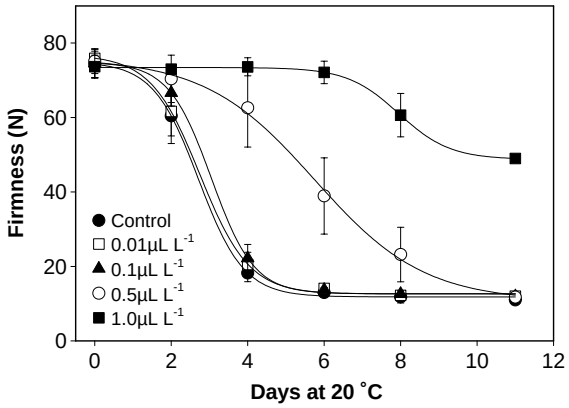

Fig. 1. Changes in firmness of pears during ripening at 20 °C. Fruit were treated with 0, 0.01, 0.1, 0.5 or 1.0 μl l^{-1} 1-MCP and stored for 6 weeks at −1 °C before ripening. Error bars indicate the standard deviation of each mean value ($n = 6$).

of fruit treated with1.0 μl l^{-1} 1-MCP softened to near 18 N when storage time was increased to 24 weeks at −1 °C; however, others remained firm and therefore the mean value (33 N) remained greater than the 18 N ripeness threshold.

As the time in storage at −1 °C increased, color development preceded softening to a greater extent. Yellow color development and softening were synchronized when fruit were ripened immediately after harvest. In contrast, pears kept at −1 °C for 18 or 24 weeks yellowed fully during storage yet still required 5–6 days at 20 °C to soften (Table 1). Loss of synchronization in ripening parameters was greatest in the 1-MCP treated fruit, but also occurred in untreated control fruit. The effect was greatest in the

Table 1
Days at 20 °C to soften (mean firmness = 18 N) and for skin color to become yellow (mean $H^\circ = 102$) for pears treated with 1-MCP at 0 °C then stored for up to 24 weeks at −1° C before ripening at 20 °C

1-MCP (μl l^{-1})	Firmness (weeks)					Color (weeks)				
	0[a]	6	12	18	24	0[a]	6	12	18	24
0	4.9 aB	4.0 aA	4.2 aA	5.1 aB	6.2 bC	5.2 aD	3.4 aC	2.4 aB	0.5 aA	0 aA
0.01	4.8 aA	4.2 aA	4.1 aA	6.4 bC	5.9 bB	5.2 aD	3.6 aC	2.1 aB	0 aA	0 aA
0.1	5.9 bB	4.4 aA	4.3 aA	6.6 bB	6.0 bB	6.0 bD	3.8 aC	1.9 aB	0.4 aA	0 aA
0.5	13.8 cC	8.6 bB	7.5 bB	5.2 aA	4.9 aA	9.4 cD	5.7 bC	3.0 bB	0.1 aA	0 aA
1.0	>14.0 dA	>14.0 cA	>14.0 cA	>14.0 cA	>14.0 cA	11.7 dD	8.6 cC	5.1 cB	0 aA	0 aA

Values are means from six replicate groups calculated using sigmoidal regression of data collected at 2 day intervals during ripening. Different letters indicate significant ($P = 0.05$) differences between treatment (a–d) or between evaluation times (A–D).

[a] Fruit treated with 100 μl l^{-1} ethylene for 24 h prior to ripening at 20 °C.

pears treated with 1.0 $\mu l\,l^{-1}$ 1-MCP and stored for 18 weeks, which were yellow when transferred from −1 to 20 °C yet remained hard and inedible. In this case, storage life was ended not by softening, but by disease.

In general, the time taken for fruit to soften after transfer to 20 °C decreased with length of storage at −1 °C. However, when pears were stored for more than 12 weeks, this was reversed. On average, fruit treated with 0, 0.01 or 0.1 $\mu l\,l^{-1}$ 1-MCP took at least 2 days more to reach edible softness when they had been stored for 18 weeks compared to 12 weeks (Table 1). However, this loss of capacity to soften ($P < 0.0001$) was not found in fruit treated with 0.5 $\mu l\,l^{-1}$ 1-MCP. In this case, the time taken for fruit to reach edible softness decreased significantly between 12 and 18 weeks ($P < 0.0001$), and was still decreasing at the end of the experimental period.

3.1.2. Physiological disorders

Treatment with 1-MCP reduced the incidence and severity of superficial scald. All pears stored for 6 weeks remained free of scald after ripening (Fig. 2a). However, the incidence and severity of scald in fruit treated with 0 or 0.01 $\mu l\,l^{-1}$ 1-MCP increased considerably with storage time. After 24 weeks, symptoms of scald were already evident when the fruit were removed from storage. Treatment with 0.1 $\mu l\,l^{-1}$ 1-MCP reduced scald severity on ripe fruits for up to 18 weeks ($P < 0.0001$) (data not shown), but had less effect on scald incidence. Exposure to 0.5 $\mu l\,l^{-1}$ 1-MCP reduced both scald severity and number of fruit affected ($P < 0.0001$), while fruit treated with 1.0 $\mu l\,l^{-1}$ 1-MCP remained free of scald for the duration of the experiment.

1-MCP treatment also reduced internal breakdown (Fig. 2b). After 18 weeks storage, internal breakdown occurred more frequently in the controls than in pears treated with 0.1 $\mu l\,l^{-1}$ 1-MCP, and more frequently in these fruit compared to pears treated with higher 1-MCP concentrations ($P < 0.0001$). After 24 weeks storage and 8 days at 20 °C, 50% of the fruit treated with 0.5 $\mu l\,l^{-1}$ 1-MCP had symptoms of internal breakdown, and the mean grade was "1: slight". However, internal breakdown was more severe in fruit treated with lower 1-MCP concentrations ($P < 0.0001$), being "2: moderate" to "3: severe". No internal breakdown was found in any of the pears exposed to 1.0 $\mu l\,l^{-1}$ 1-MCP.

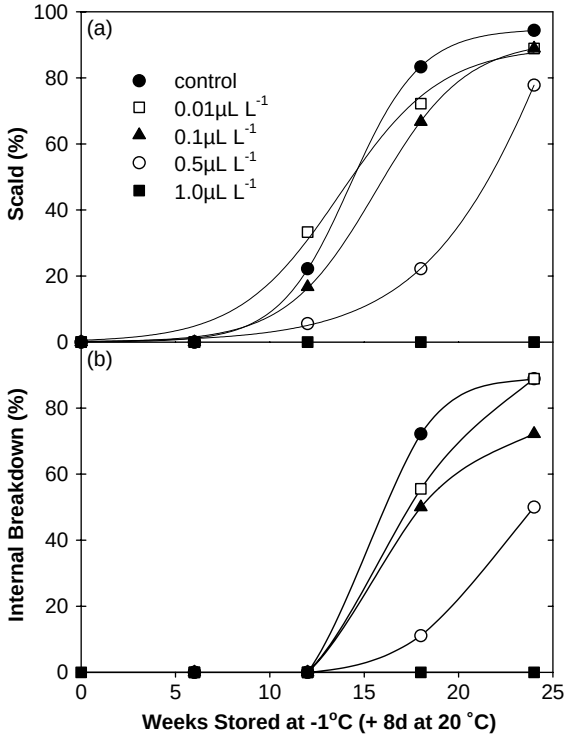

Fig. 2. Percentage of fruit with superficial scald (a) and internal breakdown (b) following treatment with 0, 0.01, 0.1, 0.5 or 1.0 $\mu l\,l^{-1}$ 1-MCP and storage at −1 °C for up to 24 weeks followed by 8 days of ripening at 20 °C. Error bars indicate the standard deviation of each mean ($n = 6$).

3.1.3. Gas exchange

The degree and duration of the effects of 1-MCP on CO_2 and ethylene production at 20 °C were related to the treatment concentration (Fig. 3a and b). Ethylene production during ripening was inhibited by exposure to 0.1 $\mu l\,l^{-1}$ 1-MCP compared to untreated fruit when fruit were stored for 6 weeks at −1 °C ($P < 0.0001$), but not when the fruit was stored for longer periods. Similarly, treatment with 0.5 or 1.0 $\mu l\,l^{-1}$ 1-MCP reduced CO_2 and ethylene production by ripening fruit stored for 0, 6 or 12 weeks ($P < 0.0001$). However, after 18 weeks of storage, mean ethylene production was no longer affected by 1-MCP application, and only fruit treated with 1.0 $\mu l\,l^{-1}$ 1-MCP respired more slowly than the untreated controls during ripening. Interestingly, fruit treated with 0.5 $\mu l\,l^{-1}$ 1-MCP and stored for 24 weeks respired faster than fruit from other treatments ($P = 0.0004$), although ethylene production was less affected ($P = 0.2484$).

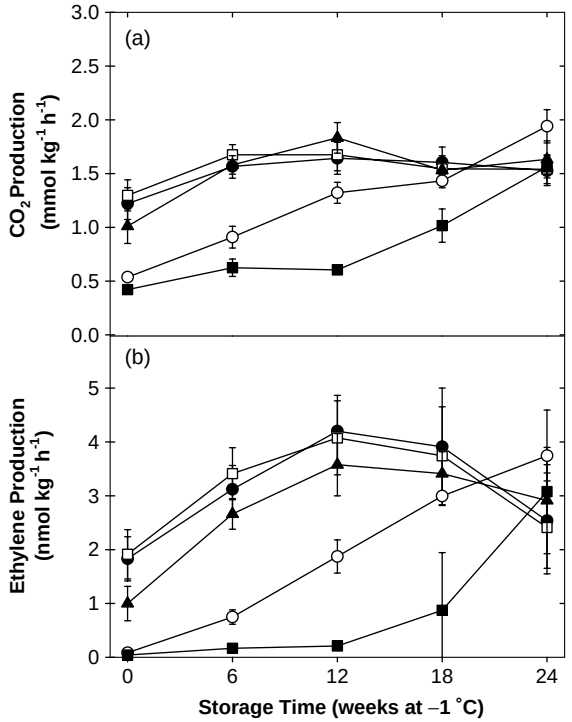

Fig. 3. Mean rates of CO_2 (a) and ethylene (b) production during ripening at 20 °C following treatment with 0, 0.01, 0.1, 0.5, or 1.0 μl l^{-1} 1-MCP and storage for up to 24 weeks at −1 °C. Error bars indicate the standard deviation of each mean ($n = 3$).

When data from all the storage times were considered, treatment with 0.5 or 1.0 μl l^{-1} 1-MCP reduced mean CO_2 production compared to untreated fruit ($P < 0.0001$). However, mean ethylene production during ripening was not reduced by exposure to 1-MCP.

Autocatalytic ethylene production during ripening was observed only in fruit stored for 0 or 6 weeks (data not shown). Ethylene production by fruit treated with 0, 0.01 or 0.1 μl l^{-1} of 1-MCP and then immediately ripened (with 42 h exposure to ethylene) increased from near 0 to 0.05–0.08 μl kg^{-1} h^{-1} during 8 days at 20 °C. Fruit treated with these same 1-MCP concentrations and stored for 6 weeks underwent approximately a doubling of ethylene production during ripening. However, when fruit were stored for longer than 6 weeks, their rate of ethylene evolution decreased during ripening at 20 °C. This effect was observed in all fruit, including those treated with the highest 1-MCP concentration.

The initial rate of ethylene production, measured when the fruit were first removed from storage, increased with storage time at −1 °C ($P < 0.0001$). For example, ethylene production by control fruit stored for 0, 6, 12, 18 and 24 weeks was 3.5×10^{-5}, 0.08, 0.16, 0.26 and 0.33 μl kg^{-1} h^{-1}. These increases in initial measurements at 20 °C were observed for all treatments.

3.2. Repeated 1-MCP application

3.2.1. Color and firmness

Results from fruit treated with 0.2 or 0.4 μl l^{-1} 1-MCP were intermediate between results obtained the previous season for fruit treated with 0.1 or 0.5 μl l^{-1} 1-MCP after the same storage time. This indicated that fruit were consistent between seasons.

Color and firmness changed from their values at harvest during storage at −1 °C. In particular, all fruit yellowed during storage at −1 °C. Even 4 weeks after harvest, the mean H° values of stored fruit had decreased from initial values of 115.1–113.0 ($P < 0.0001$). Yellowing of stored fruit continued for the duration of the experiment (Fig. 4a), all fruit stored for a total of 12 weeks being yellower than those removed from storage earlier ($P < 0.0001$). Softening at −1 °C occurred more slowly than color change. After a decrease ($P < 0.0001$) of approximately 17.4 N between weeks 0 and 6, fruit did not soften during storage at −1 °C (Fig. 5a). Overall, both yellowing and loss of firmness during storage at −1 °C were unaffected by 1-MCP treatment for the concentrations and storage times used.

However, significant variations were found among the treatments when the fruit were ripened at 20 °C. All of the 1-MCP treated fruit ripened after 4 or 6 weeks at −1 °C remained greener and firmer than the untreated controls ($P < 0.0001$) (Figs. 4b and 5b). Exposure to 0.4 μl l^{-1} had more effect than did 0.2 μl l^{-1} 1-MCP ($P < 0.0001$). Pears treated with either concentration and stored for 4 weeks at −1 °C did not become fully yellow or soft after 6 days of ripening. After 6 weeks storage, most of the fruit reached eating ripeness after the same period at 20 °C, although the 0.4 μl l^{-1} treated fruit remained firmer than ideal for eating quality (22 N).

The timing of re-application of 1-MCP affected pear color and firmness during subsequent ripening. Yellow

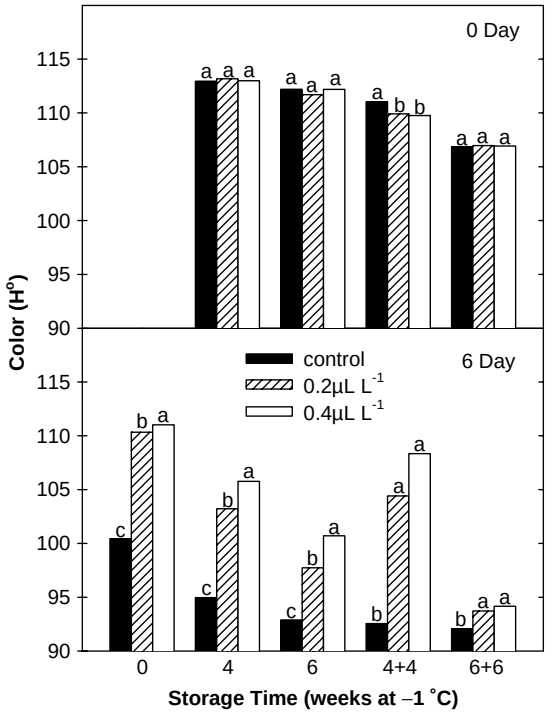

Fig. 4. Color (H°) of pears treated with 0, 0.2 or 0.4 $\mu l\,l^{-1}$ 1-MCP and stored for 4 or 6 weeks at $-1\,^{\circ}C$. Pears were either evaluated at 4 or 6 weeks, or re-treated with the same 1-MCP concentration as previously and stored for an additional 4 or 6 weeks. Measurements were taken immediately after removal from storage (Day 0) and following 6 days ripening at 20 °C (Day 6). Different letters indicate significant differences between the treatments at each assessment time. Color (H°) at harvest was 115.0.

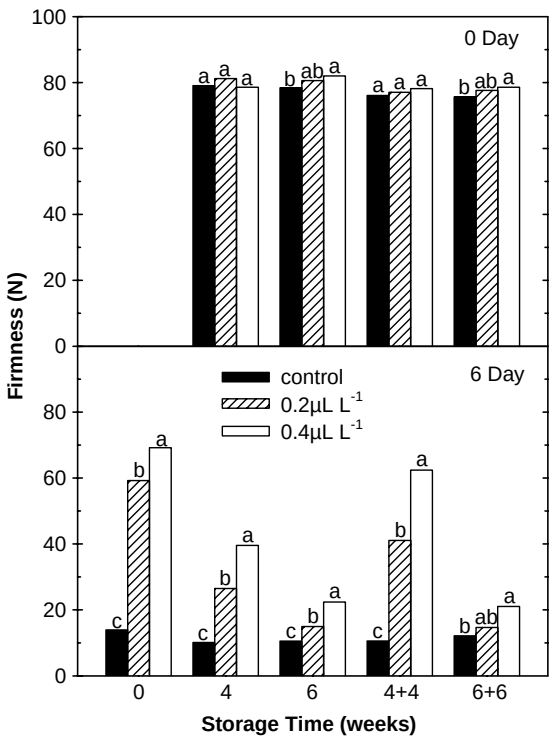

Fig. 5. Firmness (N) of pears treated with 0, 0.2 or 0.4 $\mu l\,l^{-1}$ 1-MCP and stored for 4 or 6 weeks at $-1\,^{\circ}C$. Pears were either evaluated at 4 or 6 weeks, or re-treated with the same 1-MCP concentration as previously and stored for an additional 4 or 6 weeks. Measurements were taken immediately after removal from storage (Day 0) and following 6 days ripening at 20 °C (Day 6). Different letters indicate significant differences between the treatments at each assessment time. Firmness at harvest was 84.4 N.

color development and softening were strongly inhibited when fruit were re-treated after 4 weeks and stored for a further 4 weeks (4 + 4) (Figs. 4b and 5b). These fruit remained green and hard after 6 days at 20 °C. However, application of 1-MCP had less effect when re-treatment was after 6 weeks. These fruit became fully yellow and soft during the ripening period.

Differences in ripening characteristics between the two re-treatment times were highly significant. For example, the fruit re-treated with 0.2 or 0.4 $\mu l\,l^{-1}$ 1-MCP after 4 weeks remained firmer after a total of 8 weeks storage and 6 days ripening than those treated once at harvest and ripened after 4 weeks, even though the total storage time was doubled ($P < 0.0001$). In contrast, firmness of fruit re-treated with 1-MCP after 6 weeks then stored for an extra 6 weeks before ripening was not different from fruit treated once and ripened after 6 weeks.

Control fruit softened and yellowed more than the fruit re-treated with 1-MCP in both treatment schedules ($P < 0.0001$). Fruit re-treated with 0.4 $\mu l\,l^{-1}$ 1-MCP after 4 weeks remained firmer during ripening than those re-treated with 0.2 $\mu l\,l^{-1}$ 1-MCP ($P < 0.0001$), although color development was unaffected. 1-MCP concentration did not affect changes during ripening when the fruit were re-treated after 6 weeks. All of these fruit attained full yellow color after 6 days of ripening.

As in previous experiments, control fruit took longer to soften when stored for 12 weeks compared to pears stored for shorter periods.

3.2.2. Physiological disorders

None of the fruit in these experiments developed storage scald, internal browning or significant decay. The fruit used were early season pears, which are generally less susceptible to such disorders, and the storage times used were relatively short. However, it was observed that fruit treated with 1-MCP were less susceptible to skin browning after ripening than were the control fruit. This was not evident when the fruit were first examined. However, handling during measurements of color was enough to cause noticeable skin browning in ripe, untreated fruit. The same handling caused less damage in the 1-MCP treated pears. This difference was still evident on fruit stored for 12 weeks, even though the effect of 1-MCP on ripening was minimal.

3.2.3. Gas exchange

Ethylene and CO_2 production at $-1\,^{\circ}C$ were significantly higher in the control fruit than the 1-MCP treated fruit (Fig. 6a and b) ($P < 0.001$). The untreated fruit underwent a climacteric rise in ethylene production during storage at $-1\,^{\circ}C$. Ethylene production by these fruit increased 10-fold between weeks 4 and 8, then subsequently decreased. Although treatment with 1-MCP suppressed ethylene production, rates continued to increase gradually while fruit were stored at $-1\,^{\circ}C$.

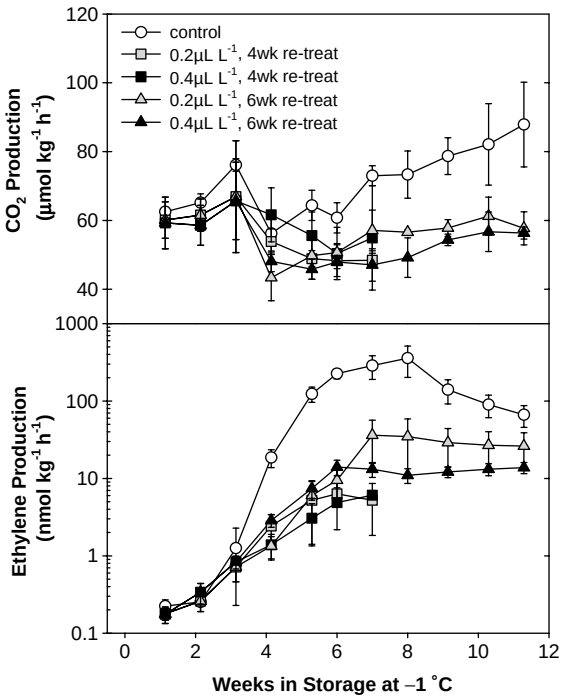

Fig. 6. CO_2 and ethylene production during storage at $-1\,^{\circ}C$ by pears treated with 0, 0.2 or 0.4 $\mu l\,l^{-1}$ of 1-MCP. Fruit were treated with 1-MCP after harvest and following 4 or 6 weeks storage at $-1\,^{\circ}C$. Error bars indicate the standard deviation of each mean ($n = 3$).

During the first 6 weeks of storage, no differences in rates of gas exchange were observed between fruit treated with 0.2 or 0.4 $\mu l\,l^{-1}$ 1-MCP. However, after 6 weeks at $-1\,^{\circ}C$, ethylene production and respiration rates had increased in fruit treated with 0.2 $\mu l\,l^{-1}$ 1-MCP compared with those treated with 0.4 $\mu l\,l^{-1}$ 1-MCP ($P = 0.0003$).

4. Discussion

Treatment with 1-MCP had little or no effect on yellowing and softening of 'Bartlett' pear fruit during storage at $-1\,^{\circ}C$. However, exposure to 1-MCP slowed changes during ripening. Respiration and ethylene production before and during ripening were also inhibited, and the incidence and severity of superficial scald and internal breakdown were reduced. However, the response of fruit to treatment was highly dependent on the 1-MCP concentration applied and the period that fruit were stored prior to ripening.

In initial experiments, we treated fruit with between 0.01 and 1.0 $\mu l\,l^{-1}$ 1-MCP. Although exposure to 1.0 $\mu l\,l^{-1}$ completely inhibited the development of scald and internal breakdown, these fruit failed to soften normally even after 24 weeks in storage. Fruit treated with 0.5 $\mu l\,l^{-1}$ 1-MCP did ripen during the experimental period, although softening and color development were delayed. Treatment with 0.1 $\mu l\,l^{-1}$ had some benefit in terms of reducing scald and the rate of ripening in pears stored for up to 6 weeks. However, the effects were slight and lost relatively quickly. Exposure to 0.01 $\mu l\,l^{-1}$ 1-MCP had no effect compared with untreated fruit. From these results, we concluded that a 1-MCP treatment of between 0.1 and 0.5 $\mu l\,l^{-1}$ would be most likely to provide benefits in terms of maintaining firmness and reducing scald in storage, while still allowing pears to ripen in a similar period of time as untreated fruit for marketing and consumption.

In the subsequent set of experiments, we treated pears with 0.2 or 0.4 $\mu l\,l^{-1}$ 1-MCP. However, it was apparent that the effects of such low concentrations were likely to wear off within a relatively short time. To both counteract this problem and increase marketing flexibility, fruit were re-treated after either 4 or 6 weeks, then stored for an additional 4 or 6 weeks.

Re-treating fruit after 4 weeks had a greater effect on the subsequent rate of ripening than did the initial 1-MCP application; yellowing and softening were slower after a total of 8 weeks storage at $-1\,^{\circ}C$ than after 4 weeks. It would seem possible that regeneration of ethylene receptors was faster in freshly harvested fruit compared to pears stored for 4 weeks at $-1\,^{\circ}C$. This could explain why recovery of sensitivity to ethylene was slower after a second exposure to 1-MCP.

In contrast, re-treating fruit after 6 weeks had little additional effect on subsequent ripening. It has been found previously that 1-MCP has less effect when applied to pears that are already starting to ripen (Mattheis, 2001). In this case, ethylene production had increased from a rate of 1–3 $nmol\,kg^{-1}\,h^{-1}$ after 4 weeks storage to 9–13 $nmol\,kg^{-1}\,h^{-1}$ after 6 weeks storage. This suggests that ripening processes may have already been initiated in the fruit. The results support the conclusions of Harris et al. (2000), who found that fruit maturity can have a large influence on the effects of exposure to 1-MCP.

Some commercial buyers of pears use skin color as an indicator of the remaining post-harvest life of stored fruit. For pears to be marketed successfully to these buyers, they need to be predominantly green when removed from storage, with ripening occurring afterward. Even 1.0 $\mu l\,l^{-1}$ 1-MCP failed to prevent yellow color development when pears were stored for more than 12 weeks. These results suggest that storage of 'Bartlett' pears for longer than 3 months may be limited, irrespective of 1-MCP treatment. However, this buyer bias against yellow pears may be changing as more ripe fruit are marketed.

Use of 1-MCP could prove beneficial for European pears. Reducing the rate of ripening at ambient temperatures may increase the marketable life of the fruit, particularly in markets where the cold chain is interrupted. Also, although the early season fruit used in the second set of treatments did not develop superficial scald within the experimental period, it would seem likely from previous results that even 0.4 $\mu l\,l^{-1}$ 1-MCP could reduce the incidence of this disorder.

Finally, the observed reduction in skin browning during handling of ripe pears warrants further investigation. Ripe pears are extremely sensitive to handling, which is the primary reason why fruit are usually sold partially green. However, in this case, 1-MCP considerably reduced skin damage without affecting normal ripening. This could prove of considerable benefit to the industry by reducing losses and improving the appearance of marketed pears.

5. Conclusion

'Bartlett' pears are extremely sensitive to exposure to 1-MCP. However, the effects of 1-MCP are both time and concentration dependent. Further research is needed to understand the factors affecting the responses of pears to re-treatment with 1-MCP. However, exposure to 0.2–0.4 $\mu l\,l^{-1}$ 1-MCP could prove beneficial by reducing physiological disorders and skin browning, and slowing the rate of ripening at room temperature.

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