Controlled Atmosphere pO₂ Alters Ripening Dynamics of 1-MCP treated ‘d’Anjou’ Pear (*Pyrus communis* L.) Fruit

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Abstract. Ripening and development of physiological disorders and decay were assessed in ‘d’Anjou’ pear fruit after 1-methylcyclopropene (1-MCP) treatment and cold storage in air or controlled atmosphere (CA). Fruit were exposed after harvest to 0 or 12.6 $\mu\text{mol}\cdot\text{L}^{-1}$ 1-MCP and then stored at 0.5 °C in air or 1, 3, or 5 kPa O₂ with 0.5 kPa CO₂. Pears were held poststorage at 20 °C for 7 days before analysis. 1-MCP fruit usually had higher hue compared with controls. Softening after removal from storage was delayed in 1-MCP fruit regardless of storage atmosphere; however, control fruit stored in air or CA ripened to below 23 N, a minimum value for consumer acceptance, after all storage durations. 1-MCP fruit stored in air, 3, or 5 kPa O₂ softened in the outer cortex (fruit surface to 8 mm into the cortex) to below 23 N only after 9 m, however, only fruit stored in air softened to less than 23 N in the inner cortex (8 mm to coreline). 1-MCP treatment also delayed deformation in cortex tissue tensile strength (TTS); after six or more months, 1-MCP fruit TTS was lower compared with those for control fruit. After 9 m, 1-MCP fruit stored in air had TTS values similar to those of controls whereas values for fruit stored in CA increased with CA O₂ concentration. Titratable acidity was higher in 1-MCP-treated fruit stored in air (6 m only) or 3 or 5 kPa O₂ compared with controls. Superficial scald developed after 6 m on control fruit stored in air or 5 kPa O₂ and on control CA fruit regardless of O₂ concentration after 9 m. No 1-MCP fruit developed scald. The results indicate ‘d’Anjou’ pear ripening in response to 1-MCP is influenced by storage pO₂ as well as storage duration, and at the 1-MCP treatment concentration used, softening to a consumer standard for firmness occurred only in fruit cold stored in air for 9 months plus a 7-day poststorage ripening period. These fruit had peel hue less than 100, and the yellow peel color may not be consistent with current market expectations.

‘d’Anjou’ pears can develop the peel disorder superficial scald (scald) (Chen, 2016), and this defect can be prevented by 1-MCP application after harvest (Argenta et al., 2003; Calvo, 2003; Chen and Spotts, 2006). Although 1-MCP treatment can prevent scald, softening of treated fruit is delayed and may not predictably occur after fruit are removed from cold storage (Argenta et al., 2003; Bai et al., 2006; Baritelle et al., 2001; Calvo, 2003; Chen and Spotts, 2006; Xie et al., 2014). Fruit maturity at harvest, 1-MCP treatment concentration, postharvest storage environment (temperature and atmosphere),

and storage and poststorage duration influence ripening capacity of 1-MCP-treated fruit (Argenta et al., 2003; Chen and Spotts, 2006; Xie et al., 2014; Wang, 2016).

Uncertain ripen ability after storage limits the use of 1-MCP for scald control (Calvo, 2003; Chen and Spotts, 2006). Some of the ripening uncertainty is related to use of 1-MCP in addition to standard long-term storage conditions for ‘d’Anjou’ that include –0.5 °C and a CA with 1.5–2 kPa O₂ and 0.5–1 kPa CO₂ (Wang, 2016). Although a higher than typical storage temperature in air can allow softening of 1-MCP-treated fruit after long-term storage with no or a low incidence of scald development (Argenta et al., 2003; Xie et al., 2014), loss of peel green color limits commercial potential for this protocol (Chen, 2016).

‘d’Anjou’ CA efficacy to control scald and ripening depends in part on storage pO₂ and pCO₂ (Hansen, 1957). Progression of softening is delayed and scald control efficacy is enhanced as pO₂ is decreased (Chen et al., 1993). However, storage in pO₂ less than 1 kPa can enhance development of other disorders (Chen and Varga, 1989; Chen and Varga, 1997; Mattheis and Rudell, 2011;

Mattheis et al., 2013) limiting the use of low pO₂ for scald control. The antioxidant ethoxyquin is currently registered for ‘d’Anjou scald control in the United States but not in the EU (EFSA, 2013). Uncertainty regarding future U.S. ethoxyquin registration suggests a need for other scald control protocols. Due to efficacy for ripening and scald management, ease of use, and lack of residue, postharvest protocols that allow use of 1-MCP are desired by the commercial pear industry.

‘d’Anjou’ fruit are typically eaten when ripe and a firmness of 14–23 N is needed for consumer acceptance (Chen et al., 1996, 2003). Fruit firmness is typically measured using a penetrometer to assess resistance to penetration in the outer cortex after peel tissue has been removed (Chen, 2016). This value is used to indicate whole fruit firmness, but as the measurement is limited to the outer cortex, firmness in this fruit region may not reflect properties of the fruit interior (Evans et al., 2010). As fruit softening and texture are critical to consumer acceptance of ‘d’Anjou’ (Zhang et al., 2010), assessment of interior fruit firmness and texture may provide additional insight as to potential consumer response and acceptability of stored fruit.

Along with softening, green peel color when soft is a consumer expectation for ‘d’Anjou’ (Chen, 2016). Whereas fruit stored long-term in CA can maintain peel green color during ripening to 23 N or less (Chen and Varga, 1997), 1-MCP-treated fruit can develop yellow peel color after long term storage under conditions where softening occurs after removal from storage (Argenta et al., 2003; Wang et al., 2015). A postharvest management regime using 1-MCP, cold storage, and/or CA optimally results in fruit that soften and maintain green peel color but do not develop scald after removal from storage.

CA partial pressure of oxygen (pO₂) and 1-MCP are factors that influence ‘d’Anjou’ fruit ripening after storage but poststorage behavior of 1-MCP fruit stored in a range of CA pO₂ has not been reported previously. The objective of this research was to characterize how CA pO₂ and 1-MCP impact ‘d’Anjou’ fruit ripening and physiological disorders after removal from cold storage.

Materials and Methods

Plant material. ‘d’Anjou’ (*Pyrus communis* L.) pear fruit were obtained from three commercial orchards in central Washington State. Pears determined to be commercially mature by the growers were harvested into bulk bins and transported to the laboratory the day of harvest. Fruit absent visible external defects were placed onto pressed fiber trays and the trays packed into cardboard boxes. Fruit were cooled for 24 h at 0.5 °C then trayed pears to be exposed to 1-MCP were removed from cardboard boxes and placed inside an 800-L steel cabinet located in an adjacent 0.5 °C cold room. Fruit were exposed to 12.6 $\mu\text{mol}\cdot\text{L}^{-1}$ 1-MCP

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Table 1. 'd'Anjou' maturity at harvest. Fruit were obtained from three commercial orchards in central Washington State.

Lot	Wt (g)	Starch 1–6	SSC (%)	TA (%)	Hue	Firmness		TTS (mm)
						Outer cortex N	Inner cortex N	
A	225 ± 7	1.5 ± 0.1	13.5 ± 0.1	0.339 ± 0.008	114 ± 0.3	59.9 ± 0.9	73.5 ± 2.5	≤0.003 ²
B	224 ± 10	1.7 ± 0.2	13.1 ± 0.1	0.332 ± 0.009	114 ± 0.4	60.9 ± 1.3	72.8 ± 2.3	≤0.003
C	225 ± 6	1.6 ± 0.2	13.3 ± 0.1	0.336 ± 0.006	114 ± 0.2	58.9 ± 0.8	73.1 ± 1.7	≤0.003
all lots	225 ± 8	1.6 ± 0.2	13.3 ± 0.1	0.336 ± 0.008	114 ± 0.3	59.9 ± 1.0	73.1 ± 2.2	≤0.003

SSC = soluble solids content; TA = titratable acidity. Outer cortex firmness measured in cortex region from pared surface to 8 mm. Inner cortex firmness measured in cortex region 8 mm to coreline. Tissue tensile strength (TTS) deflection at 8-mm depth into the fruit. Values are means ± SE (*n* = 3 replicates of 6 fruit each lot). ²Minimum detection limit = 0.003 mm.

(AgroFresh, Inc., Spring House, PA) for 16 h, then the chamber was opened and after 4 h fruit was removed. All fruit was stored at 0.5 °C for up to 9 m. Control and 1-MCP-treated fruit for CA storage were placed into 0.14 m³ CA chambers and after 24 h, atmospheres containing 1, 3, or 5 kPa O₂ and 0.5 kPa CO₂ were established and maintained as previously described (Mattheis and Rudell, 2011).

Harvest maturity and fruit quality assessment. Starch content was rated visually (1 = full starch, 6 = no starch) at harvest after staining an equatorial section with a 30-mm solution of I-KI. Peel color was assessed as *L** *a** *b** on each fruit using a chromameter (CR-300; Minolta, Osaka, Japan) using CIE illuminant C, and values were converted to hue (McGuire, 1992). Firmness was measured on pared surfaces on opposite sides at the equator of each fruit with an MDT-1 analyzer (Mohr and Associates, Richland, WA) fitted with an 8-mm diameter probe. Maximum firmness in the outer 8 mm (outer cortex) and 8 mm to the core line boundary (inner cortex) as well as TTS at the 8-mm location were assessed. Soluble solids content (SSC) and titratable acidity (TA) in freshly prepared juice was measured using a refractometer (Atago N1, Atago, Tokyo, Japan) and a TIM850 titrator (Radiometer, Lyon, France), respectively. Juice was titrated to pH 8.2 using 0.1 N KOH. Superficial scald incidence, intensity (1 = light; 2 = dark), and severity (1 = symptoms on 1% to 25% peel surface; 2 = 26% to 50%; 3 = >50%) were visually assessed.

Experimental Design and Statistical Analysis

Statistical analysis. The experiment was conducted using a completely random design. Assessment of fruit quality attributes and physiological disorders used 3 replications of 6 fruit each for each lot-treatment-storage atmosphere-storage duration combination. All statistical analyses were performed using SAS 9.4 (SAS Institute Inc., Cary, NC). Analysis of variance was performed using the general linear model to identify main effects and interactions. Superficial scald incidence was arcsin square root transformed before analysis. Tukey's honestly significant difference test was used to compare means, *P* ≤ 0.05.

Results

Cortex firmness at harvest was similar among orchard lots and consistent with

Fig. 1. 'd'Anjou' pear firmness (N) in the outer 8 mm cortex after storage. Fruit were exposed to 0 (control) or 12.6 μmol·L⁻¹ 1-MCP for 16 h after harvest then stored at 0.5 °C in air or 1–5 kPa O₂ and 0.5 kPa CO₂ for 3, 6, or 9 months. Fruit held 7 d at 20 °C after removal from storage. Values are means, *n* = 9 replicates of 6 fruit. *All controls decayed after 9 months. Dashed line at 23 N is threshold of consumer acceptance for 'd'Anjou' firmness.

Fig. 2. 'd'Anjou' pear firmness (N) after storage in cortex region 8 mm to core line. Fruit were exposed to 0 (control) or 12.6 μmol·L⁻¹ 1-MCP for 16 h then stored at 0.5 °C in air or 1–5 kPa O₂ and 0.5 kPa CO₂ for 3, 6, or 9 months. Fruit held 7 d at 20 °C after removal from storage. Values are means, *n* = 9 replicates of 6 fruit. *All controls decayed after 9 months.

recommendations for commercial maturity (Table 1; Hansen and Mellenthin, 1979; Williams et al., 1978). All other measured attributes were also statistically similar among lots. TTS was at or below the detection limit for all lots.

Lot effects for stored fruit were not significant; therefore, data from all lots were combined. All control fruit stored in air for 9 m were decayed 7 d after removal from storage.

Control fruit softened to less than 23 N in the outer and inner cortex and TTS exceeded

0.6 mm after all storage durations (Figs. 1–3). Fruit treated with 1-MCP did not soften in the outer cortex relative to harvest after 3 m (Table 2), softened with increased pO₂ after 6 m but not to below 23 N, and to less than 23 N if stored in 3 kPa O₂ or higher after 9 m. Inner cortex firmness of 1-MCP fruit was less than at harvest after 3 m but was above 23 N. Inner cortex firmness was also above 23 N after 6 m although values decreased with increased pO₂. After 9 m, inner cortex firmness of 1-MCP fruit decreased with increased pO₂ but only fruit stored in air were less than 23 N. TTS for 1-MCP fruit increased with storage pO₂ after 6 and 9 m; however, only fruit stored 9 m in 3 or 5 kPa O₂ or air had values similar to control fruit.

Peel hue decreased with increased storage duration except for 1-MCP fruit stored in 1 kPa O₂ (Fig. 4). Values for 1-MCP fruit usually were higher compared with those for controls for the same storage duration and pO₂. For 1-MCP fruit stored in 3 or 5 kPa O₂, hue was similar after 3 and 6 m but lower after 9 m. Hue was lowest for fruit stored in air regardless of storage duration for controls and 1-MCP fruit. TA decreased with storage duration (Fig. 5). Control fruit stored in air had the lowest value after 6 m, and values for controls stored in 3 or 5 kPa O₂ were lower compared with fruit stored in 1 kPa O₂ after 9 m. Values decreased with increased pO₂ for 1-MCP fruit after 9 m.

Superficial scald developed on control fruit stored in 5 kPa O₂ or air after 6 m and on all controls stored in CA after 9 m (Table 3). For fruit with scald, no treatment differences were present for intensity or severity. No 1-MCP fruit developed scald.

Discussion

Scald development on controls stored in 5 kPa O₂ or air for 6 m, and on all CA fruit after 9 m, it is consistent with a relationship between CA pO₂, storage duration, and scald development (Chen and Varga, 1997). Scald on control fruit also demonstrated disorder susceptibility in all lots as well as the efficacy of 1-MCP for scald prevention. Softening of control fruit at and after 3 m regardless of storage pO₂ indicated sufficient chilling had occurred for ripening to progress (Blankenship and Richardson, 1985).

The lack of scald development through 9 m on 1-MCP fruit stored in CA or air confirms 12.6 µmol·L⁻¹ 1-MCP can be sufficient for ‘d’Anjou’ scald control (Chen and Spotts, 2006). This 1-MCP concentration is consistent with the high range currently available commercially (F. Edagi, personal communication). Maintenance of fruit peel green color with hue above 100 occurred only for 1-MCP fruit stored in CA indicating cold storage at 1 °C alone for 9 m is not sufficient to slow chlorophyll degradation to meet market requirements (Chen, 2016).

Softening of 1-MCP fruit increased with storage pO₂ after 6 and 9 m indicating CA pO₂ is a factor that contributes to poststorage softening capacity of 1-MCP fruit. Whereas

Fig. 3. ‘d’Anjou’ pear tissue tensile strength after storage. Fruit were exposed after harvest to 0 (control) or 12.6 µmol·L⁻¹ 1-MCP for 16 h then stored at 0.5 °C in air or 1–5 kPa O₂ and 0.5 kPa CO₂ for 3, 6, or 9 months. Fruit held 7 d at 20 °C after removal from storage. Values are means, n = 9 replicates of 6 fruit. *All controls decayed after 9 months.

Table 2. Mean ‘d’Anjou’ firmness and tissue tensile strength (TTS) at harvest and after 3 mo. cold storage plus 7 d at 20 °C. Fruit were exposed to 0 or 12.6 µmol·L⁻¹ 1-MCP for 16 h after harvest then stored at 0.5 °C in air or 1–5 kPa O₂ and 0.5 kPa CO₂. Fruit held 7 d at 20 °C after removal from storage.

	kPa O ₂	Treatment	Firmness		TTS mm
			Outer cortex N	Inner cortex N	
Harvest 3 mo.	—	—	59.9 a	73.1 a	≤0.003 ²
	1	Control	12.0 b	17.8 c	0.73
		1-MCP	56.5 a	60.5 b	≤0.003
	3	Control	13.4 b	17.4 c	0.72
		1-MCP	57.9 a	60.1 b	≤0.003
	5	Control	11.6 b	16.9 c	0.69
		1-MCP	57.4 a	61.4 b	≤0.003
	Air	Control	10.2 b	12.5 c	0.76
		1-MCP	56.5 a	59.6 b	≤0.003

Means followed by different letters are significantly different, Tukey’s honestly significant difference, $P \leq 0.05$.

²Minimum detection limit = 0.003 mm.

Fig. 4. ‘d’Anjou’ pear peel hue after storage. Fruit were exposed after harvest to 0 (control) or 12.6 µmol·L⁻¹ 1-MCP for 16 h then stored at 0.5 °C in air or 1–5 kPa O₂ and 0.5 kPa CO₂ for 3, 6, or 9 months. Fruit held 7 d at 20 °C after removal from storage. Values are means, n = 9 replicates of 6 fruit. *All controls decayed after 9 months.

Fig. 5. 'd'Anjou' pear titratable acidity after storage. Fruit were exposed after harvest to 0 (control) or 12.6 $\mu\text{mol}\cdot\text{L}^{-1}$ 1-MCP for 16 h then stored at 0.5 °C in air or 1–5 kPa O₂ and 0.5 kPa CO₂ for 3, 6, or 9 months. Fruit held 7 d at 20 °C after removal from storage. Values are means, $n = 9$ replicates of 6 fruit. *All controls decayed after 9 months.

Table 3. 'd'Anjou' pear disorders after storage. Fruit were exposed to 0 or 12.6 $\mu\text{mol}\cdot\text{L}^{-1}$ 1-MCP for 16 h after harvest then stored at 0.5 °C in air or 1–5 kPa O₂ and 0.5 kPa CO₂. Fruit held 7 d at 20 °C after removal from storage.

Months	O ₂ kPa	Treatment	Scald incidence (%)	Scald intensity (1–2)	Scald severity (1–3)
6	1	Control	0 d	—	—
		1-MCP	0 d	—	—
	3	Control	0 d	—	—
		1-MCP	0 d	—	—
	5	Control	11 cd	1.0	2.0
		1-MCP	0 d	—	—
9	Air	Control	28 c	1.4	2.2
		1-MCP	0 d	—	—
	1	Control	70 a	1.6	1.1
		1-MCP	0 d	—	—
	3	Control	67 a	1.8	1.5
		1-MCP	0 d	—	—
	5	Control	69 a	1.8	1.3
		1-MCP	0 d	—	—
	Air	Control	^z	^z	^z
		1-MCP	0 d	—	—

Scald intensity: 1 = light, 2 = dark; scald severity: 1 = 1% to 25% fruit surface with symptoms, 2 = 26% to 50%; 3 = >50%. Values are means, $n = 9$ replicates of 6 fruit. Means followed by different letters are significantly different, Tukey's honestly significant difference, $P \leq 0.05$.

^zAll controls decayed.

outer cortex firmness for fruit stored in 3 or 5 kPa O₂ was less than 23 N after 9 m, inner cortex firmness above 23 N could contribute to lack of consumer acceptance (Zhang et al., 2010). The TTS test is a standard engineering method whereby an item is subjected to a constant tensile or compressive stress, and the resulting strain of the material is measured. This is useful to measure the visco-elastic properties of the material under test. During the TTS test the penetrometer maintains a constant force against the fruit by varying the motion of the probe. The penetrometer does not move or moves very little for fruit with intact, elastic tissue; however, as the softening occurs the tissue gives way and the penetrometer advances the probe to maintain a constant force. Increased TTS with increased CA pO₂ and storage duration indicates texture change occurred in 1-MCP

fruit that approached that of controls stored in air or CA after all storage durations. As the TTS test reflects tissue properties only at 8 mm into the cortex, TTS in 1-MCP fruit stored in 3 or 5 kPa O₂ for 9 m similar to that in controls may be less of a factor determining consumer acceptance than inner cortex firmness above 23 N in the same fruit.

Although storage in CA and/or 1-MCP treatment resulted in higher TA compared with fruit stored in air, a clear relationship between TA and consumer preference has not been established. Chen et al. (1983) reported changes in TA associated with longer storage duration were not associated with changes in dessert quality determined by a taste panel.

Addition of 1-MCP to the standard 'd'Anjou' CA protocol (–1 to –0.5 °C, 1.5 kPa O₂; Chen, 2016) has proven to be of mixed success in meeting fruit quality objectives

for long term storage. This contrasts with the mostly ready adaptability of 1-MCP for scald susceptible (and nonsusceptible) apple cultivars where firm, crisp texture with no scald after long-term storage is consistent with apple postharvest management objectives (Watkins, 2006). The lack of predictable softening after 'd'Anjou' cold storage limits the utility of 1-MCP under these conditions when sufficient material is applied to control scald. However, factors that impact the duration of the 1-MCP impact on softening are known (1-MCP treatment concentration, storage temperature, storage duration, CA pO₂, and poststorage temperature and duration; Argenta et al., 2003; Bai et al., 2006; Calvo, 2003; Chen and Spotts, 2006; Wang et al., 2015) and a revised postharvest system using 1-MCP that prevents scald, maintains peel green color, and allows softening to a level acceptable to consumers may be feasible with changed postharvest management. Additional operational benefits may accrue from an altered protocol including reduced electricity use because of warmer storage temperature and higher CA pO₂ or storage in air rather than CA. Additional research to identify new best practices remains to be conducted.

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