Storage Humidity Influences Fruit Quality and Permeability to Ethane in 'McIntosh' Apples Stored in Diverse Controlled Atmospheres

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Abstract. Storage of 'McIntosh' apples (*Malus domestica* Borkh.) in high humidity (94% to 100% RH) or in 0.5% CO₂ plus 1.0% O₂ at 3C (LO) atmospheres decreased resistance to ethane diffusion relative to fruit stored in low humidity (75% RH) or in 5.0% CO₂ plus 3.0% O₂ at 3C (SCA), respectively. Loss of fruit firmness of SCA- or LO-stored 'McIntosh' apples, determined immediately after storage or after 7 days at 20C, decreased with increased storage humidity in each of three crop years. Storage humidity did not significantly affect ($P = 0.05$) fruit titratable acids or soluble solids contents. High storage humidity (96% to 100% RH) generally increased the incidence of senescent disorders (consisting of senescent breakdown and senile brown core) in SCA-stored fruit, while humidities of 92% to 100% RH decreased the incidence of low-O₂ injuries (epidermal bluing and cortical browning) in LO-stored fruit. Senescent disorders were found in SCA-stored fruit, but not in LO-stored fruit. The incidence of decay was not significantly affected by either storage humidity or atmosphere.

High storage humidity (RH) has been shown to predispose 'Cox's Orange Pippin', 'Bramley's Seedling', 'Delicious', and 'McIntosh' apples to senescent and/or low-temperature breakdown in air storage (Blanpied, 1981; Johnson, 1976; Rasmussen, 1963; Wilkinson, 1970). Breakdown of 'Jonathan' (Martin et al., 1967; Scott et al., 1964; Scott and Roberts, 1967) and 'Spartan' (Porritt and Meheriuk, 1973) fruit stored in air are similarly aggravated by high RH storage. Conversely, the reduction of storage RH by delays in storage temperature reduction (Scott and Roberts, 1968; Trout et al., 1940) or by raising the storage temperature to increase weight loss from the fruit (Smith, 1958) reduces the incidence of these disorders. Scott and Roberts (1968) report that a 1% increase in weight loss in response to low RH lowers the incidence of 'Jonathan' breakdown; they recommend a 4% weight loss for controlling breakdown without noticeable fruit shriveling.

'McIntosh' apples stored at 0 to 1C were found to be firmer when stored in air at high RH than similar apples (with greater weight loss) stored at low RH (Blanpied, 1981). The reason for lower firmness retention for apples stored in lower RH has not been reported, but may be, in part, due to advanced senility.

The incidence of low-O₂ injury in 'McIntosh' apples stored in CA has been shown to result from exposure to low-O₂ levels and the duration of exposure to these levels (Lau et al., 1987; Lidster et al., 1987). Internal O₂ concentrations maybe affected by changes in fruit permeability resulting from storage RH (Wilkinson, 1965), which, in turn, may affect fruit susceptibility to low-O₂ injury.

While the literature contains studies on the effects of humidity on apples stored in air, similar studies in controlled atmosphere storage were not found. The present study investigated the effects of storage RH on the retention of fruit firmness, titratable acids, soluble solids concentration (SSC), and on the incidence of storage disorders in 'McIntosh' apples stored in controlled

and in low-O₂ atmospheres. In addition, the effects of storage RH and atmospheres on fruit permeability to ethane exchange were investigated, the latter serving as a tool to follow permeability changes.

Materials and Methods

Preclimacteric 'McIntosh' apples were harvested from each of five orchards on 25 Sept. 1983, 21 Sept. 1984, and 23 Sept. 1985 at mean starch indices/internal C₂H₄ ($\mu\text{L}\cdot\text{kg}^{-1}\cdot\text{hr}^{-1}$) levels of 3.8/0.86, 3.9/0.34, and 3.6/0.32 and were precooled to 3C within 12 hr of harvest in vented plastic hampers that were randomly placed in each of 10 controlled atmosphere chambers maintained at 3C. In duplicate chambers, trays with a saturated solution of reagent grade NaCl, (NH₄)₂SO₄, or KCl were placed on top of the fruit within the chamber to maintain storage RH of 75%, 81%, and 89% RH, respectively (Rockland, 1960). Two chambers received empty trays (equilibrium humidity), while the other two received trays of distilled H₂O to maintain RH of 92% to 96% and 96% to 100%, respectively. A blade fan was attached to each tray to circulate air over the tray and within the chamber at a maximum velocity of 16.5 m·min⁻¹. In each of the three crop years, chambers were sealed and flushed with compressed N₂ to reduce O₂ levels to either 1% or 3% O₂ within 2, 3, and 5 days of harvest in 1983, 1984, and 1985, respectively. Levels of CO₂ were maintained by Ca(OH)₂ scrubbing and of O₂ by controlled venting to ambient atmospheres. Fruit were stored at 0.5% CO₂ plus 1.0% O₂ (LO) or 5.0% CO₂ plus 3.0% O₂ (SCA) at 3C in each of five chambers for 198, 225, and 255 days in the three crop years, respectively. In 1984 and 1985 trials, the preweighed fruit and trays were reweighed after chamber opening and the net water loss recorded.

Fruit firmness was determined on a 10-fruit subsample from each orchard/treatment using a Ballauf penetrometer (opposite sectors tested with an 11.1-mm tip on peeled flesh) immediately after storage and after an additional 7 days at 20C. Titratable acids were determined by titrating a 2-ml juice sample with 0.1N NaOH (pH 8.1 endpoint), and SSC was determined on juice with a hand-held refractometer. In 1985, resistance of whole fruits to ethane transfer was determined by the method of Cameron and Yang (1982) for each orchard/treatment on 10 indi-

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Table 1. Effects of humidity, SCA, and LO atmospheres on weight loss and fruit permeability to ethane in 'McIntosh' apples stored at 3C^z.

Storage humidity (%)	Fruit wt loss ^y (% w/w)				Fruit resistance to ethane (log ₁₀ s·cm ⁻¹)	
	1984		1985		SCA	LO
	SCA	LO	SCA	LO		
75	4.4	4.0	10.7	4.1	-3.19	-3.27
81	2.7	3.4	3.7	3.0	-3.49	-3.51
89	2.5	2.7	2.5	2.3	-3.67	-3.71
92-96	1.0	1.1	2.1	2.0	-3.77	-3.74
96-100	0.3	0.6	1.9	1.5	-3.71	-3.82
Mean					-3.57	-3.61
SEM (n = 5)					0.012	
SEM (n = 2)					0.019	
Significant effects ^x (P < 0.05)					A,H	

^zSCA = 5% CO₂ + 3% O₂; LO = 0.5% CO₂ + 1.0% O₂.

^yDetermined from total weight loss of five-orchard replicates.

*A = atmosphere, H = humidity.

vidual fruit taken from storage and equilibrated at 20C for 20 hr.

The incidence of disorders was determined on a 50-fruit subsample held at 20C for 7 days before examination. The disorders were classified either as senescent or low-O₂ disorders according to the descriptions of Smock (1977).

Data, except fruit weight loss, were tested by analyses of variance; the means and SE are presented in Tables 1-3. Polynomial regression components or orthogonal contrasts were calculated to test for significant trends of storage humidity (P = 0.05). Adequacy of the chosen model was assessed by an F test, which compared the fitted deviations with the residual mean square.

Results and Discussion

Fruit weight loss decreased with increased storage humidity in both years (Table 1). Fruit lost weight in all storage humid-

ities and was associated with weight gain by the saturated salt solutions placed in the individual CA chambers (data not presented) or with condensation on the chamber walls (96% to 100% RH). When RH was allowed to equilibrate under ambient atmosphere in chambers (92% to 96% RH), fruit lost 1% to 2.1% of their weight and, when distilled H₂O was stored in the chambers (96% to 100% RH), fruit lost slightly less. Water uptake by fruit stored at high RH (Wilkinson, 1965) was absent.

The weight losses for 'McIntosh' apples (Table 1) stored at 3C (0.3% to 10.7%, w/w) were much lower than the expected values calculated by Wilkinson (1965) for 'Cox's Orange Pippin' apples. He developed weight loss estimates of 0.6% and 0.25% (w/w) per week for apples stored at 3C in 80% and 90% RH, respectively. For the crop years of 1984 and 1985, fruit weight losses were about one-fifth to one-half of those calculated by Wilkinson, indicating a cultivar difference or increased fruit resistance to water loss with extended storage (Lentz and Rooke, 1964).

Fruit gas resistance after storage (determined by the ethane diffusion method) generally decreased in response to increasing storage RH and to reduction in storage CO₂ and O₂ concentrations (Table 1). An increase in permeability of apples stored in high RH was observed by Wilkinson (1965), who attributed it to an increase in fruit volume. Wilkinson (1965) further speculated that greater fruit permeability may have resulted from increased skin orifice size or increased internal air spaces resulting from a rounding of cortical cells.

Higher storage RH was associated with greater fruit firmness retention immediately after storage and after 7 days at 20C in both storage atmospheres, except after 7 days of shelf life in 1985 (individual year data not presented). These results contrast with those reported for 'Spartan' (Porritt et al., 1973), but are similar to those of Blanpied (1981) for 'McIntosh'.

Titrateable acids and SSC determined after storage or after 7 days at 20C were not significantly affected by RH (Table 2).

High RH increased the incidence of senescent disorders (senile brown core, senescent breakdown) in fruit stored in SCA (Table 3); results similar to those reported for 'McIntosh' and other cultivars stored in air at 0C (Blanpied, 1981; Johnson, 1976; Martin et al., 1967; Porritt and Meheriuk, 1973; Rasmussen, 1963; Scott et al., 1964; Scott and Roberts, 1967). For

Table 2. Effects of humidity, SCA, and LO atmospheres on fruit firmness, titrateable acids, and soluble solids contents of 'McIntosh' apples stored at 3C over three crop years^z.

Storage humidity (%)	After storage						After storage plus 7 days at 20C					
	Fruit firmness (N)		Titrateable acids (mg malic/100 ml)		Soluble solids (%)		Fruit firmness (N)		Titrateable acids (mg malic/100 ml)		Soluble solids (%)	
	SCA	LO	SCA	LO	SCA	LO	SCA	LO	SCA	LO	SCA	LO
75	45.8	64.0	502	531	11.2	11.3	41.9	54.1	436	480	11.1	11.3
81	48.3	63.3	511	552	11.0	11.3	42.3	56.5	455	459	11.1	11.2
89	51.8	63.1	483	557	11.1	11.2	43.9	59.0	424	494	10.8	11.2
92-96	55.1	69.0	530	575	11.2	11.0	47.3	60.9	456	511	10.9	11.0
96-100	52.9	72.1	522	535	11.3	11.1	44.9	63.1	445	493	10.6	11.2
SEM (n = 15)	1.74		15.7		0.112		2.34		25.5		0.185	
Significant effects ^y (P < 0.05)	A,H		Y,A		NS		Y,A,H		Y,A		Y,A	

^zSCA = 5% CO₂ + 3% O₂; LO = 0.5% CO₂ + 1.0% O₂.

^yY = year, A = atmosphere, H = humidity. ^{NS}Non-significant.

Table 3. Effects of humidity in SCA and LO atmospheres on the incidence of senescent disorders (senile brown core and senescent breakdown), low-O₂ injury (epidermal bluing and cortical browning) and decay of 'McIntosh' apples after storage at 3C plus 7 days at 20C, replicated over three crop years.

Storage humidity (%)	Storage atmosphere ^z					
	SCA			LO		
	Senile brown core (%)	Senescent breakdown (%)	Decay (%)	Epidermal bluing (%)	Cortical browning (%)	Decay (%)
75	5.4	2.1	6.1	6.3	7.3	3.9
81	7.2	6.0	4.8	14.6	3.8	5.6
89	6.7	4.5	5.0	8.1	2.1	5.4
92-96	8.9	4.2	5.8	1.3	1.1	3.7
96-100	22.9	13.7	8.9	1.1	2.2	6.7
SEM (n = 3) ^y	5.23	1.63	3.41	2.83	3.42	3.41
Linear	(P < 0.10)	(P < 0.01)	(P > 0.10)	(P < 0.01)	(P < 0.10)	(P > 0.10)

^zSCA = 5% CO₂ + 3% O₂; LO = 0.5% CO₂ + 1.0% O₂.

^yAnalysis of variance performed on percentages transformed to angles by $\sin^{-1} \sqrt{P/100}$. SEM values are in angles, but the means are back-transformed mean angles.

fruit held in SCA, low RH may reduce the incidence of senescent breakdown by increasing water and acetate ester loss, thereby decreasing tissue alcohol content (Wills, 1968). Senescent disorders were not observed in fruit stored in LO, which is consistent with previous reports (Lidster et al., 1985, 1987).

Low-O₂ injury observed in LO-stored fruit, consisting of epidermal bluing and cortical browning, was found to decrease in fruit at higher storage RH (Table 3). Storage of apples in low RH may increase fruit resistance to O₂ penetration into the tissue, especially from the LO-storage atmospheres, as evidenced by the increased resistance to ethane (Table 1). This effect may result in lower internal O₂ levels in the fruit that could aggravate the development of LO injury as compared with similar fruit stored in higher RH.

The present study determined that 'McIntosh' apples in SCA and LO required different humidity control for optimal CA storage. High storage RH will result in the firmest fruit from either storage atmosphere. However, very high RH may increase the incidence of senescent disorders in 'McIntosh' fruit stored in SCA, which suggests that a lower RH, near 89% to 94%, is best for SCA storage of 'McIntosh' apples. Fruit stored in LO at low RH (75% to 89%) were found to be less firm and more susceptible to low-O₂ injuries. Relative humidity of 96% to 100% proved beneficial for 'McIntosh' apples stored in LO. The benefits of storage humidity manipulation were not at the expense of losses due to decay (Table 3). Although these losses were variable over crop years, they were unaffected by storage atmosphere and humidity levels.

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