HortScience 32(7):1239–1241. 1997.

Initial Low Oxygen Stress Offers No Scald Control Benefits to 'Starkrimson Delicious' Apples in 0.7 kPa O_2 Storage

O.L. Lau

Industry Research Program, Okanagan Federated Shippers Association, c/o Agriculture and Agri-Food Canada, Pacific Agri-Food Research Centre, Summerland, British Columbia V0H 1Z0, Canada

Additional index words. Malus ×domestica, postharvest physiology, controlled atmosphere, physiological disorders

***Abstract.* In a 2-year study, the benefits and risks of an initial low O_2 stress treatment (ILOS; 0.04 kPa O_2 for 10 days) as a supplement to 1.5 or 0.7 kPa O_2 storage for controlling scald in 'Starkrimson Delicious' apples (*Malus ×domestica* Borkh.) were evaluated. The fruit were picked from 15 orchards and harvested over five successive weeks to generate a wide range in maturity. Storage in 0.7 kPa O_2 did not adequately control scald in fruit picked at starch index between 1.0 and 2.1 (10% to 35% scald), but reduced watercore-induced breakdown in fruit picked at starch index ≥2.4 (0–9 scale). The ILOS treatment gave a statistically significant but commercially nonsignificant scald control benefit to fruit held in 1.5 kPa O_2 in 1 year, but not to fruit held in 0.7 kPa O_2. ILOS did not increase alcoholic taste, but increased skin purpling in 0.7 kPa O_2-stored fruit from the final harvest in 1 year. ILOS decreased flesh firmness in fruit picked at starch index ≥1.7 and increased watercore-induced breakdown in fruit picked at starch index ≥2.1 in both years.**

British Columbia-grown 'Delicious' apples have benefited from low O_2 storage for retention of flesh firmness (Lau, 1985) and control of storage scald (Lau, 1990b). The cultivar is tolerant of both 0.5 (Lau, 1990a) and 0.7 kPa O_2 (Lau, 1990b, 1993). Depending on harvest maturity, a 0.7 kPa O_2 storage atmosphere is 94% to 99% effective in reducing scald in 'Starking Delicious' and 'Harrold Red Delicious' apples but only 67% to 97% effective in 'Starkrimson Delicious' apples after 8 months (Lau, 1993).

Little et al. (1982) have shown that exposure of 'Granny Smith' apples to an initial low O_2 stress (ILOS) treatment at or below 0.5 kPa for 9 d gives additional benefits in scald control over that of continuous storage in 1.5 kPa O_2. The objective of this research was to assess the benefits and risks of ILOS as a supplement to 1.5 and 0.7 kPa O_2 storage for controlling scald in 'Starkrimson Delicious' apples picked from 15 orchards and harvested over five successive weeks to generate a wide range in maturity.

Received for publication 19 Nov. 1996. Accepted for publication 6 May 1997. Appreciation is extended to C. Holmes, P. Schofield, R. Yastremski, S. Horton, and L. Ostergaard for their invaluable technical assistance. Special thanks are due to the Science Council of British Columbia for providing partial research funding and to the Agriculture and Agri-Food Canada, Pacific Agri-Food Research Centre, Summerland, B.C., for providing research facilities. The cost of publishing this paper was defrayed in part by the payment of page charges. Under postal regulations, this paper therefore must be hereby marked *advertisement* solely to indicate this fact.

Materials and Methods

'Starkrimson Delicious' apples were obtained from the same 15 orchards (five in Osoyoos-Oliver, five in Summerland, and five in Kelowna, B.C.) in 1990 and 1991. These orchards were <100 km apart in the Okanagan Valley. Fruit from each location were harvested five times at weekly intervals from selected trees (210 apples per harvest). The fruit were then randomized into 10-fruit samples for maturity determination and 50-fruit samples for each of the four storage treatments (1.5 kPa O_2 ± ILOS and 0.7 kPa O_2 ± ILOS) in four sets of cabinets. Fruit sampling commenced on 23 Sept. in 1990 and 15 Sept. in 1991, ≈2 weeks before the commercial harvest. The storage samples were arranged in a 5 × 2 × 2 factorial design: five harvests × two initial treatments during the first 10 d (0.04 or 1.5 kPa O_2; 0.04 or 0.7 kPa O_2) × two O_2 levels during storage (1.5 or 0.7 kPa O_2, both with 1.0 kPa CO_2). Each location was considered a replication. The 10-fruit samples for maturity determination were evaluated for starch index value, internal C_2H_4 concentration (IEC), flesh firmness, and watercore, using methods described previously (Lau, 1985, 1990b; Smith et al., 1979). Starch index values of 0, 1.0, 2.0, 3.0, 4.0, 5.0, 6.0, 7.0, 8.0, and 9.0 represent 0%, 9%, 20%, 38%, 51%, 66%, 81%, 90%, 96%, and 100%, respectively, of the cross-sectional area of fruit clear of starch.

After harvest, the storage samples were cooled in air at 0 °C for 1 d before placement in 3.7-m^3 metal cabinets held in a 0 °C room. The 1.5 and 0.7 kPa O_2 storage atmospheres in "control" cabinets were established by use of N_2 within 36 h of sealing. Storage CO_2 of 1.0 kPa was achieved within 7 d by fruit respiration. The 10-d 0.04 kPa O_2 ILOS treatment was applied to fruit held in a second set of cabinets by additions of N_2. Carbon dioxide in these cabinets was allowed to rise over time to 1.0 kPa. Following the ILOS treatment, air was added to increase storage O_2 to 1.5 or 0.7 kPa within 0.5 h. Storage atmospheres were monitored twice daily by a paramagnetic O_2 analyzer and an infrared CO_2 analyzer. The desired atmospheres were maintained within 0.1 kPa of target partial pressures by additions of N_2 or air venting and additions of CO_2 or lime scrubbing. Storage temperatures were maintained at 0.2 ± 0.3 °C.

After 6 months in controlled atmosphere at 0.2 °C, the fruit were examined for scald and skin purpling. The 9-month samples were removed on 19 June 1991 and 24 June 1992 and, after seven additional days in air at 20 °C, 50-fruit samples were assessed for scald, skin purpling, watercore-induced breakdown, flesh firmness, and alcoholic taste by methods described previously (Lau, 1985, 1990b).

Analysis of variance (ANOVA) was performed on storage data to test for main effects and interactions. Treatment means were separated by Duncan's new multiple range test at $P < 0.05$. Percentage values were arcsin transformed before variance analysis.

Results and Discussion

Starch index, IEC, percent ripening fruit, and watercore of the sampled fruit all increased, while flesh firmness decreased, as harvest was delayed (Table 1). Sampling of the 1991 'Starkrimson Delicious' samples was 1 week ahead of that of the 1990 samples. Consequently, the 1991 samples had more scald (first pick) but less watercore-induced breakdown (last pick) than the 1990 samples (Tables 2 and 3).

0.7 vs. 1.5 kPa O_2 storage. Storage in 0.7 kPa O_2 was more effective than in 1.5 kPa O_2 in reducing watercore-induced breakdown (1990 only), scald, and firmness loss (Tables 2 and 3). The results are in agreement with previous reports that show beneficial effects of low O_2 on scald control and firmness retention in 'Delicious' (Anderson, 1967; Chen et al., 1985; Lau, 1985, 1990b), 'McIntosh' (Smock, 1947), 'Gallia Beauty' (Patterson and Workman, 1962), 'Cox's Orange Pippin' (Fidler and North, 1961), and 'Granny Smith' (Little et al., 1982) apples. The beneficial effect of 0.7 kPa O_2 on scald control was observed in the first three picks of the 1990 samples (starch index 1.3–2.1; Table 2) while the benefit was observed in all five picks of the 1991 samples (starch index 1.0–2.1; Table 3). This probably accounted for the significant interaction (harvest × O_2) on scald in 1990 but not 1991.

Storage in 0.7 kPa O_2 did not increase alcoholic taste (data not shown) or skin purpling (Tables 2 and 3). Similar work also showed no increase in fermented flavors or skin purpling in 'Delicious' apples held in atmospheres containing 1 kPa or more O_2

Table 1. Characteristics of 'Starkrimson Delicious' apples at harvest (n = 15 orchard replicates per year).

Year	Harvest date	Starch index (0–9)	Internal ethylene concentration (IEC) ($\mu L \cdot L^{-1}$)	Percent ripening fruit (IEC >1 $\mu L \cdot L^{-1}$)	Watercore (% fruit affected)	Flesh firmness (N)
1990	23 Sept.	1.3 ± 0.6	2 ± 6	5 ± 12	0 ± 1	90 ± 4
	30 Sept.	1.6 ± 0.6	1 ± 3	10 ± 10	0 ± 0	86 ± 4
	7 Oct.	2.1 ± 0.8	56 ± 137	26 ± 33	3 ± 5	85 ± 3
	14 Oct.	2.4 ± 0.8	28 ± 55	30 ± 36	19 ± 19	83 ± 4
	21 Oct.	3.3 ± 1.0	12 ± 14	48 ± 55	56 ± 24	83 ± 4
	Significance	***	NS	***	***	***
1991	15 Sept.	1.0 ± 0.5	0.1 ± 0.1	1 ± 3	0 ± 0	90 ± 3
	22 Sept.	1.2 ± 0.5	0.2 ± 0.1	2 ± 4	0 ± 0	87 ± 2
	29 Sept.	1.5 ± 0.3	0.2 ± 0.4	3 ± 6	0 ± 0	86 ± 4
	6 Oct.	1.7 ± 0.5	0.7 ± 1.1	5 ± 9	6 ± 7	82 ± 3
	13 Oct.	2.1 ± 0.5	1.0 ± 1.5	12 ± 15	15 ± 18	81 ± 4
	Significance	***	*	**	***	***

NS, *, **, ***Nonsignificant or significant at $P = 0.05$, 0.01, or 0.001, respectively.

(Anderson, 1967) or 0.7 kPa O_2 (Lau, 1990b, 1993).

Initial low O_2 stress. An ILOS treatment at or below 0.5 kPa for 9 d has given additional benefits in scald control over that of continuous storage in 1.5 kPa or 0.7–1.0 kPa O_2 in some cultivars, including 'Granny Smith' (Little et al., 1982; Little and Peggie, 1987; Truter et al., 1994) and 'Jonathan' (Little and Peggie, 1987) apples. However, the benefits have varied with season, harvest maturity, and storage period (Truter et al., 1994).

In this study, storage in 0.7 kPa O_2 did not adequately control scald (14% to 35% scald) in 'Starkrimson Delicious' picked at starch index between 1.0 and 2.1 (Tables 2 and 3). The 10-d 0.04 kPa O_2 ILOS treatment did not offer any additional benefits on scald control in fruit picked over a 4-week period and held in 0.7 kPa O_2 for 6 (data not shown) or 9 months. The conclusions were the same whether ANOVA was done by region or by storage O_2 (data not shown). The only benefit of ILOS was a small decrease in scald in 1990 on fruit held in 1.5 kPa O_2 (Table 2), a marginal commercial benefit that would not warrant the extra cost of the ILOS treatment. ILOS reduced scald at 1.5 kPa, but not at 0.7 kPa, indicating a significant stress × O_2 interaction (Table 2).

The ILOS treatment did not increase alcoholic taste (data not shown) or skin purpling except in the last-picked, 0.7 kPa O_2-stored fruit in 1991 (Tables 2 and 3). However, the ILOS treatment increased watercore-induced breakdown in fruit picked at starch index between 2.1 and 3.3 in 1990 (Table 2) and in fruit picked at starch index 2.1 in 1991 (Table 3). It also decreased flesh firmness in fruit picked at starch index between 1.7 and 3.3 in 1990 and 1991 (Tables 2 and 3). Fidler and North (1971) showed that apples usually form ethanol during the anaerobic phase, but most of it will disappear upon return to aerobic conditions. However, accidental or deliberate anaerobiosis can lead to accumulation of alcohol and increase storage rots and perhaps the risks of coreflush and breakdown in 'Cox's Orange Pippin' apples (Fidler and North, 1971).

The statistical interactions on skin purpling in 1991 (harvest × stress, harvest × O_2, stress × O_2, and harvest × stress × O_2; Table 3) were probably the result of 6.3% skin purpling in ILOS-treated, 0.7 kPa O_2-stored fruit harvested on 13 Oct. 1991. Since these interactions occurred in only one of the two years, their implications are not clear.

Storage in 0.7 kPa O_2 effectively controlled watercore-induced breakdown in non-ILOS fruit (with 56% watercore) picked on 21 Oct. 1990, but the ILOS treatment markedly increased the disorder in these watercore-afflicted fruit (Table 2). This probably accounted for the significant interactions (harvest × stress, harvest × O_2, stress × O_2, and harvest × stress × O_2) on watercore-induced breakdown in 1990 (Table 2). Incidence of watercore-induced breakdown was low in 1991, but results were very similar (Table 3).

The ILOS treatment increased flesh softening in fruit picked at a more advanced maturity (starch index ≥ 1.7), thus resulting in harvest × stress interactions in 1990 and 1991 (Tables 2 and 3).

In summary, the ILOS treatment gave no commercially relevant benefits in scald control in British Columbia-grown 'Starkrimson Delicious' held in 0.7 kPa O_2 + 1.0 kPa CO_2 at 0.2 °C. The ILOS treatment, which also decreased flesh firmness and increased watercore-induced breakdown in the treated fruit, does not appear to be a commercially viable treatment for 'Starkrimson Delicious' fruit stored at 0.7 kPa O_2.

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Table 2. Effects of harvest date, initial low O_2 stress (+S), and storage O_2 level on superficial scald, skin purpling, watercore (WC)-breakdown, and flesh firmness in 'Starkrimson Delicious' apples[z] after storage at 0.2 °C and 7 d in air at 20 °C (n = 15 orchard replicates, 1990).

Harvest date	Superficial scald (%)				Skin purpling (%)				WC-breakdown (%)				Flesh firmness (N)			
	1.5 kPa O_2		0.7 kPa O_2		1.5 kPa O_2		0.7 kPa O_2		1.5 kPa O_2		0.7 kPa O_2		1.5 kPa O_2		0.7 kPa O_2	
	–S	+S	–S	+S	–S	+S	–S	+S	–S	+S	–S	+S	–S	+S	–S	+S
23 Sept.	56	46	35	28	0.0	0.0	0.0	0.0	0.0	0.5	0.0	0.1	76	75	77	77
30 Sept.	50	37	28	27	0.0	0.0	0.0	0.3	0.3	0.1	0.0	0.0	74	72	77	75
7 Oct.	28	25	14	14	0.1	0.0	0.0	0.4	0.5	0.8	0.0	0.7	72	67	74	71
14 Oct.	18	11	10	11	0.0	0.4	0.1	0.4	4.9	11.8	0.3	7.4	69	64	72	67
21 Oct.	12	9	7	9	0.1	1.1	1.1	0.8	20.2	30.0	4.7	25.6	68	63	71	66
Treatment means[y]	33 c	26 b	19 a	17 a	0.1 a	0.3 ab	0.2 ab	0.4 b	5.2 b	8.7 c	1.0 a	6.8 b	72 b	68 a	74 c	71 b

Analysis of variance

Source of variation	df	Superficial scald (MS)[x]	Skin purpling (MS)[x]	WC-breakdown (MS)[x]	Flesh firmness MS
Replicate	14	0.382***	0.006*	0.137**	220.215***
Harvest (H)	4	2.233***	0.007NS	1.694***	990.295***
Error A	56	0.035	0.003	0.054	19.071
Stress (S)	1	0.229***	0.005NS	0.502***	803.142***
H × S	4	0.018NS	0.000NS	0.145***	51.732***
O_2	1	1.679***	0.004NS	0.272***	510.883***
H × O_2	4	0.055*	0.000NS	0.067***	7.878NS
S × O_2	1	0.119*	0.000NS	0.045*	7.857NS
H × S × O_2	4	0.011NS	0.002NS	0.026*	2.709NS
Error B	210	0.019	0.002	0.008	5.014

[z]Examined on 26 June 1991.
[y]Mean separation within parameters by Duncan's new multiple range test at $P < 0.05$.
[x]Arcsin scale.
NS, *, **, ***Nonsignificant or significant at $P = 0.05$, 0.01, or 0.001, respectively.

Table 3. Effects of harvest date, initial low O_2 stress (+ S) and storage O_2 level on superficial scald, skin purpling, watercore (WC)-breakdown, and flesh firmness in 'Starkrimson Delicious' apples[z] after storage at 0.2 °C and 7 d in air at 20 °C (n = 15 orchard replicates, 1991).

Harvest	Superficial scald (%)				Skin purpling (%)				WC-breakdown (%)				Flesh firmness (N)			
	1.5 kPa O_2		0.7 kPa O_2		1.5 kPa O_2		0.7 kPa O_2		1.5 kPa O_2		0.7 kPa O_2		1.5 kPa O_2		0.7 kPa O_2	
date	–S	+S	–S	+S	–S	+S	–S	+S	–S	+S	–S	+S	–S	+S	–S	+S
15 Sept.	55	48	23	26	0.0	0.1	0.1	0.0	0.0	0.0	0.0	0.1	78	78	79	79
22 Sept.	62	59	30	27	0.5	0.0	0.0	0.5	0.0	0.3	0.0	0.0	76	75	77	77
29 Sept.	61	58	21	28	0.0	0.0	0.0	0.0	0.1	0.1	0.0	0.1	73	71	76	75
6 Oct.	44	42	16	21	1.3	0.4	0.3	0.3	0.3	0.8	0.8	1.5	71	69	75	71
13 Oct.	25	21	8	10	1.1	1.3	0.8	6.3	1.5	3.6	0.4	2.0	69	64	74	66
Treatment means[y]	50 b	46 b	19 a	22 a	0.6 a	0.4 a	0.2 a	1.8 b	0.4 ab	1.0 b	0.2 a	0.8 b	74 b	71 a	76 c	74 b

Analysis of variance

Source of variation	df	Superficial scald (MS)[x]	Skin purpling (MS)[x]	WC-breakdown (MS)[x]	Flesh firmness MS
Replicate	14	0.431^{***}	0.019^{*}	0.035^{***}	166.014^{***}
Harvest (H)	4	1.269^{***}	0.075^{***}	0.051^{***}	963.800^{***}
Error A	56	0.046	0.008	0.007	6.798
Stress (S)	1	0.000^{NS}	0.017^{*}	0.021^{**}	423.552^{***}
$H \times S$	4	0.012^{NS}	0.015^{**}	0.008^{**}	87.776^{***}
O_2	1	7.878^{***}	0.009^{NS}	0.001^{NS}	513.964^{***}
$H \times O_2$	4	0.055^{NS}	0.012^{*}	0.006^{*}	7.322^{NS}
$S \times O_2$	1	0.140^{*}	0.051^{***}	0.000^{NS}	2.374^{NS}
$H \times S \times O_2$	4	0.014^{NS}	0.015^{**}	0.000^{NS}	9.901^{*}
Error B	210	0.023	0.004	0.002	3.336

[z]Examined on 1 July 1992.

[y]Mean separation within parameters by Duncan's new multiple range test at $P < 0.05$.

[x]Arcsin scale.

[NS, *, **, ***]Nonsignificant or significant at $P = 0.05$, 0.01, or 0.001, respectively.

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