Volatile Compound Production by Bisbee Delicious Apples after Sequential Atmosphere Storage

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Bisbee Delicious apples were stored for 6 months in controlled atmosphere (CA) where oxygen concentration was increased from 1 to 2% after 3, 4, or 5 months. Volatile emission after storage was highest in late-harvest apples. Increasing the oxygen concentration during storage did not increase loss of firmness, soluble solids content, or titratable acidity, and volatile emission was not enhanced. All CA treatments reduced volatile emission compared to that of air-stored fruit. Esters were the majority of volatiles detected. Emission of lipid-derived esters was inhibited more by CA treatments than were esters resulting from amino acid metabolism.

Keywords: *Controlled atmosphere; esters; aldehydes; alcohols; fruit quality*

INTRODUCTION

Controlled atmosphere storage (CA) is an effective means of retarding apple ripening (Smock, 1979). Although many processes of ripening are slowed, apples recover after returning to air and soften, lose acidity, change color, and produce more ethylene. Synthesis of compounds contributing to apple flavor and aroma can be inhibited by prolonged controlled atmosphere storage (Patterson *et al.*, 1974). The suppressive effect increases with lower O_2 and higher CO_2 concentrations and longer storage duration (Streif and Bangerth, 1988; Brackman *et al.*, 1993), and only partial recovery after return to air may be observed (Yahia *et al.*, 1990b). Decreased apple sensitivity to ethylene has been suggested as a mechanistic explanation for this effect (Bangerth, 1984; Bangerth and Streif, 1987). The terminal steps of the ester synthesis pathway are active after fruit is removed from CA (Berger and Drawert, 1984; Bartley *et al.*, 1985; Knee and Hatfield, 1981). Apple maturity at harvest also influences postharvest aroma production with less developed fruit producing lower amounts of aroma compounds throughout the storage period (Brackman *et al.*, 1993; Hansen *et al.*, 1992a; Yahia *et al.*, 1990a).

Smith (1984) demonstrated improvement in production of volatiles by Cox's Orange Pippin apples after CA, with minimal firmness loss, by raising O_2 from 1.25 to 2% during storage. Significant firmness loss was observed after O_2 concentrations were increased during storage of Jonagold, and McIntosh apples (Lidster *et al.*, 1983; Hansen *et al.*, 1992b). The present study was conducted using Delicious apples to determine if volatile synthesis could be enhanced in response to increasing oxygen concentration (sequential atmosphere) during storage without excessive firmness loss.

MATERIALS AND METHODS

Bisbee Delicious apples were obtained from a research orchard near Wenatchee, WA, in 1989, 1990, and 1991. Storage treatments were identical during the 3 year study; however, apples from a single harvest were stored in 1989 and 1990. Results from those two seasons indicated harvest maturity was a possible factor determining apple response to the CA treatments; therefore, apples were harvested 144, 158, and 172 days after full bloom (DAFB) in 1991. Fruit maturity was determined before and after storage by analyses of internal ethylene concentration, starch hydrolysis, flesh firmness, soluble solids content, titratable acidity and non-ethylene volatile production. Gas samples removed from the fruit core were analyzed for ethylene (Williams and Patterson, 1962). Gas analyses were conducted isothermally at 50 C using a gas chromatograph (Hewlett-Packard 5880, Avondale, PA) equipped with a 50 cm, 0.32 cm i.d. glass column packed with 80–100 mesh Porapak Q (Supelco, Bellefonte, PA). N_2 carrier, H_2, and air flows were 25, 25, and 300 mL mn^{-1}, respectively. Starch hydrolysis was rated visually using a 1–6 scale (1, full starch; 6, no starch) after staining an equatorial section with a 0.5% I–KI solution. Flesh firmness was measured on two pared surfaces per fruit using a penetrometer with an 11 mm tip (Lake City Technical, Kelowna, BC, Canada). Soluble solids content (SSC) and titratable acidity (TA) were determined using freshly prepared juice. The SSC was measured using a hand refractometer (Atago, Tokyo, Japan) and TA was determined by titrating 10 mL of juice to pH 8.2 using an autotitrator (Radiometer, Copenhagen, Denmark).

Storage treatments were applied in 0.145 m^3 controlled atmosphere chambers. Atmospheres were established within 24 h of harvest and maintained automatically (Techni-Systems, Chelan, WA). Apples were held initially in air (regular atmosphere, RA) or 1% O_2, 2% CO_2 at 1 °C, and the CA O_2 concentration was increased to 2% after 3, 4, or 5 months of storage. All apples were removed from storage after 6 months, and fruit quality and volatile production were analyzed after 1 or 10 days of ripening at 20 °C (20 fruit/harvest/treatment/ripening).

Analyses for headspace volatiles were as described previously (Mattheis *et al.*, 1991). Volatile compounds emitted from intact fruit were collected on Tenax TA (Alltech Associates, Deerfield, IL) traps and desorbed into a gas chromatograph (Hewlett-Packard 5890A) using thermal desorption and cryofocusing. Quantitative and qualitative analyses were performed using a mass selective detector (Hewlett-Packard 5971A, Palo Alto, CA). Putative identification was made using the Wiley NBS mass spectra library. Confirmatory identification and quantitation were accomplished using authentic standards. The experiment was analyzed as a factorial (3 harvest dates × 5 O_2 regimes × 2 ripening durations) using the ANOVA procedure of Systat (Systat Inc., Evanston, IL). Tukey's HSD was used to separate treatment means.

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Table 1. Internal Ethylene Concentration, Ester Emission Rate, and Fruit Quality Values[a] for Bisbee Delicious Apples at Harvest

harvest DAFB	internal C_2H_4 ($\mu L\ L^{-1}$)	ester synthesis ($nL\ kg^{-1}\ h^{-1}$)	starch[b] (1–6)	firmness (N)	soluble solids content (%)	titratable acidity (%)
144	0.00 ± 0.00	87 ± 50	1.4 ± 0.1	74.4 ± 3.6	8.8 ± 0.2	0.338 ± 0.035
158	0.14 ± 0.41	772 ± 110	1.6 ± 0.2	74.5 ± 4.0	10.4 ± 0.4	0.260 ± 0.018
172	0.08 ± 0.09	2499 ± 453	2.0 ± 0.3	70.8 ± 2.9	10.7 ± 0.4	0.258 ± 0.018

[a] Values are means and standard deviations calculated from 20 apples. [b] Starch rating: 1, full starch; 6, no starch.

Table 2. Bisbee Delicious Apple Firmness, Soluble Solids Content, and Titratable Acidity after 6 Months of Storage and 1 or 10 Days of Ripening at 20 °C[a]

		firmness (N)		soluble solids content (%)		titratable acidity (%)	
harvest DAFB	O_2 regime[b]	day 1	day 10	day 1	day 10	day 1	day 10
144	3/3	74.3a	67.0a	12.1	11.8	0.281a	0.232a
	2/4	76.2a	68.0a	11.7	12.1	0.249b	0.228a
	1/5	76.7a	69.5a	12.1	12.2	0.251b	0.234a
	0/6	74.4a	70.1a	12.5	12.8	0.245b	0.213a
	RA	61.5b	58.7b	11.9	11.7	0.205c	0.186b
158	3/3	71.1a	66.7a	12.9	11.7	0.273a	0.218a
	2/4	72.3a	69.3a	12.0	12.4	0.236b	0.216a
	1/5	70.7a	66.2a	11.8	11.4	0.241b	0.229a
	0/6	69.8a	66.8a	11.7	11.9	0.230b	0.215a
	RA	59.8b	59.8b	11.8	11.2	0.219b	0.212a
172	3/3	68.2a	66.4a	11.5	11.5	0.216b	0.210b
	2/4	67.7a	65.6a	12.3	12.2	0.236ab	0.236a
	1/5	71.5a	64.1a	12.1	11.8	0.242a	0.219ab
	0/6	68.7a	65.4a	11.9	12.0	0.215b	0.216ab
	RA	58.4b	57.4b	11.3	11.0	0.165c	0.155c

[a] All fruit were stored at 1 °C; CO_2 was 2% in all O_2 regimes. Means within columns within harvest DAFB followed by different letters indicate significant differences by Turkey's HSD test, $P \leq 0.01$ ($n = 20$). [b] O_2 regimes: 3/3, 3 months 1%/3 months 2%; 2/4, 2 months 2%/4 months 1%; 1/5, 1 months 2%/5 months 1%; 0/6, 0 months 2%/6 months 1%; RA, regular atmosphere.

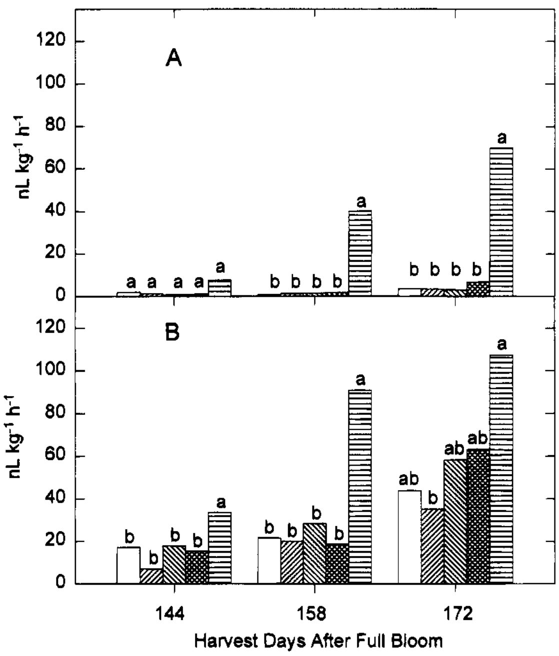

Figure 1. Total non-ethylene volatile emission after 6 months of storage of Bisbee Delicious apples. (A) day 1 and (B) day 10 after removal from storage. Temperature was 1 °C in all storage treatments which included the following: regular atmosphere; 3 months 1%/3 months 2% O_2; 4 months 1%/2 months 2% O_2; 5 months 1%/1 month 2% O_2; 6 months 1% O_2. CO_2 was held at 2% in all CA storage treatments. Different letters accompanying treatments within a harvest date are significantly different ($P = 0.05$) using Tukey's HSD test. Values are means of four replicate samples each containing four or five apples (~1 kg).

RESULTS AND DISCUSSION

The response of Bisbee Delicious apples to sequential atmosphere storage was considerably different in 1989 and 1990 (Mattheis and Fellman, 1992). Comparing the two years, ester and alcohol emission was higher after storage in 1991, while aldehyde emission was highest after the 1989–1990 season. Because apples were preclimacteric at harvest in 1989 and postclimacteric in 1990, harvest maturity was added as an additional variable for the 1991 experiment.

Fruit matured slowly during the fall of 1991 in central Washington (Table 1). Internal ethylene values at harvest did not indicate onset of climacteric ripening through 172 DAFB. The late onset of the ethylene climacteric in this orchard was unusual, internal ethylene concentrations exceeding 1 $\mu L\ L^{-1}$ were measured 165, 162, and 147 DAFB in 1990, 1992, and 1993, respectively. Ester emission increased significantly over the 4 week harvest period in the absence of the ethylene climacteric. A significant increase in starch hydrolysis and decrease in firmness were observed between 158 and 172 DAFB, whereas SSC and TA changed the most between 144 and 158 DAFB.

Harvest DAFB and oxygen regime significantly affected apple firmness and TA but not SSC after CA storage (Table 2). Treatment effects within harvest dates were significant between apples stored in CA and air. Apple firmness was similar between CA regimes within harvest dates, indicating storage at 2% O_2 after 3, 4, or 5 months at 1% O_2 was insufficient to result in significant additional softening. Residual effects of the initial storage period at 1% O_2, limited storage duration at 2% O_2 (3 months maximum), and fruit harvest maturity could be factors contributing to the lack of firmness loss. The TA of air-stored fruit was usually lower than that of CA-stored fruit. CA treatment effects on TA retention were inconsistent, indicating the change to 2% O_2 was insufficient to result in enough additional metabolic activity to increase acid loss. Lack of significant harvest date, treatment or ripening effects on SSC indicates sugar utilization by ripening Delicious apples was slow.

Analysis of variance showed harvest DAFB, O_2 regime, and ripening after storage significantly affected total volatile emission. Fruit from the last harvest consistently emitted a greater amount of volatiles as was evident in apples ripened for 10 days after removal from storage (Figure 1). Apples stored in RA had the most volatile emission of the storage treatments. Esters were the largest quantitative group of non-ethylene volatiles detected (Figures 2–4). Storage treatment effects on ester emission were inconsistent other than the difference between RA and CA fruit. Lack of effects from increasing O_2 to 2% may indicate Bisbee Delicious apples fail to respond to treatments of this type or that increasing O_2 concentration to 2% was not high enough to produce a fruit response as has been previously

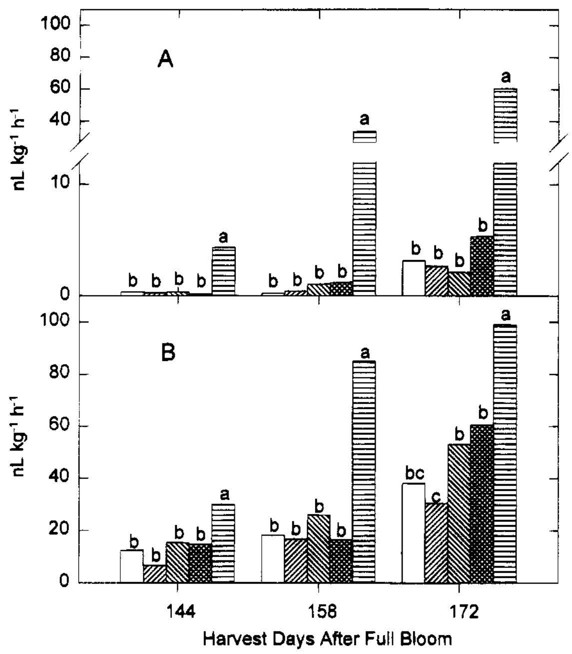

Figure 2. Ester emission after 6 months of storage of Bisbee Delicious apples: (A) day 1 and (B) day 10 after removal from storage. Storage conditions, sampling, and statistical analysis were the same as indicated in Figure 1 legend.

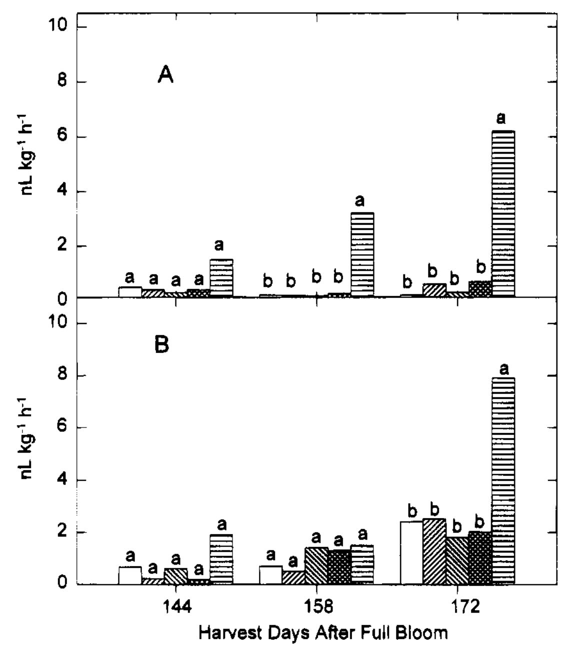

Figure 3. Alcohol emission after 6 months of storage of Bisbee Delicious apples: (A) day 1 and (B) day 10 after removal from storage. Storage conditions, sampling, and statistical analysis were the same as indicated in Figure 1 legend.

reported (Smith, 1984; Hansen *et al.*, 1992b). Ester emission increased, although not significantly, with duration at 2% O_2 in apples harvested 172 DAFB and ripened for 10 days; therefore an interaction of apple maturity and the amount and/or duration of O_2 change during storage may be what determines apple response. The initial storage duration at 1% O_2 may also be a factor determining subsequent response to changes in storage O_2 concentration.

Harvest maturity, ripening, and storage treatment altered the synthesis pattern of individual esters (Tables 3 and 4). Qualitative as well as quantitative changes in ester synthesis occurred during ripening; the number

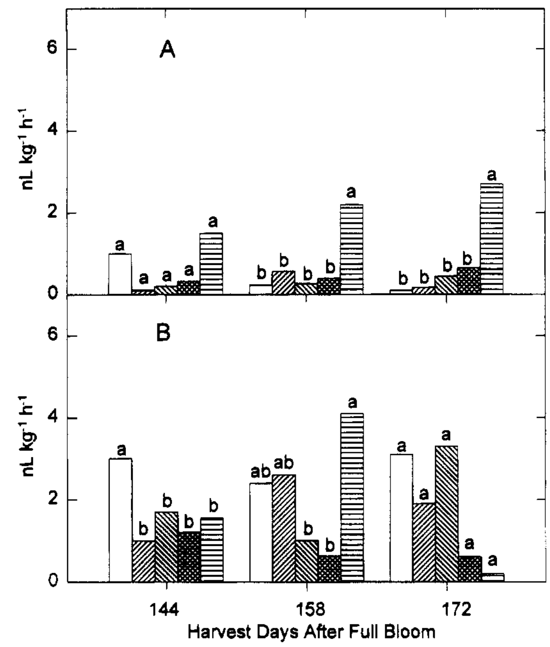

Figure 4. Aldehyde emission after 6 months of storage of Bisbee Delicious apples: (A) day 1 and (B) day 10 after removal from storage. Storage conditions, sampling, and statistical analysis were the same as indicated in Figure 1 legend.

of esters detected after 10 days was twice that after 1 day. Ethyl butyrate, ethyl 2-methylbutyrate, butyl propanoate, and 2-methyl propylacetate were detected only from RA fruit after 1 day of ripening. Ethyl butyrate, ethyl 2-methylbutyrate, and 2-methylpropyl acetate were only detected from apples harvested 158 and 172 DAFB, indicating the effect of harvest maturity. The lack of synthesis of specific compounds by CA fruit could be expected to have a direct impact on fruit flavor. For example, ethyl 2-methylbutyrate has been identified as a major contributor to Delicious apple flavor (Flath *et al.*, 1967). Ripening of CA fruit after storage improved the emission of ethyl 2-methylbutyrate only for fruit harvested 172 DAFB (Table 4). Although the number and concentration of esters increased during the 10 day ripening period, synthesis recovery was inconsistent. The concentration of esters originating from lipid degradation (Tressl *et al.*, 1970), specifically butyl acetate and hexyl acetate, was lower from CA- compared to RA-stored fruit while production of 2-methylbutyl acetate, a product of isoleucine degradation (Hansen *et al.*, 1993), increased during the 10 day ripening period of CA apples. Emission of 2-methylbutyl acetate by apples stored for 3 months in 1% O_2 and then for 3 months in 2% O_2 was similar to production by RA fruit. This differential effect of CA on subsequent volatile synthesis has been observed previously (Brackman *et al.*, 1993) and indicates residual impacts of CA are more pronounced on lipid than on amino acid metabolism. Alcohol and aldehyde concentrations were lower than ester concentration in apples from all harvest dates after ripening for 10 days (Figures 3 and 4). The interaction of harvest DAFB and O_2 treatments significantly affected alcohol emission after storage. Mean alcohol emission by RA apples was highest 1 day after removal from storage. Apple alcohol emission was qualitatively similar after 10 days of ripening (Tables 5 and 6), but quantitative differences were observed for 1-butanol (158 DAFB) and 2-methylbutyl alcohol (158 and 172 DAFB) from CA apples. Emission rates of the corresponding acetate esters increased in RA-stored apples

Table 3. Ester Emission (pL kg^{-1} h^{-1}) from Bisbee Delicious Apples after 6 Months of Storage at 1 °C plus 1 Day of Ripening at 20 °C[a]

	storage treatment														
	144 harvest DAFB					158 harvest DAFB					172 harvest DAFB				
compound	1	2	3	4	5	1	2	3	4	5	1	2	3	4	5
ethyl butyrate	nd[b]	nd	nd	nd	nd	nd	nd	nd	nd	72	nd	nd	nd	nd	542
ethyl 2-methylbutyrate	nd	nd	nd	nd	nd	nd	nd	nd	nd	85	nd	nd	nd	nd	72
butyl acetate	nd	nd	nd	nd	184	nd	nd	nd	nd	5390	146	nd	nd	nd	23300
butyl propionate	nd	nd	nd	nd	68	nd	nd	nd	nd	647	nd	nd	nd	nd	666
butyl butyrate	nd	7	nd	nd	132	nd	nd	nd	10	211	35	64	nd	17	211
pentyl acetate	nd	nd	nd	nd	408	10	nd	8	nd	1410	68	22	29	nd	1830
hexyl acetate	48	62	1042	140	2050	240	356	190	94	11100	499	281	93	153	16400
hexyl propionate	nd	nd	nd	nd	nd	16	nd	nd	nd	nd	nd	nd	nd	nd	nd
hexyl 2-methylbutyrate	nd	nd	nd	nd	nd	219	nd	nd	nd	nd	nd	nd	nd	nd	nd
2-methylpropyl acetate	nd	nd	nd	nd	nd	nd	nd	nd	nd	169	nd	nd	nd	nd	458
2-methylbutyl acetate	70	201	117	90	1530	580	565	183	112	13000	4230	1480	2160	2230	16600

[a] CA treatments were months in 1% then 2% O_2: (1) 3/3; (2) 4/2; (3) 5/1; (4) 6/0; (5) regular atmosphere cold storage. CO_2 concentration was 2% for all CA treatments. [b] nd, not detected.

Table 4. Ester Emission (pL kg^{-1} h^{-1}) from Bisbee Delicious Apples after 6 Months of Storage at 1 °C plus 10 Days of Ripening at 20 °C[a]

	storage treatment														
	144 harvest DAFB					158 harvest DAFB					172 harvest DAFB				
compound	1	2	3	4	5	1	2	3	4	5	1	2	3	4	5
ethyl acetate	nd[b]	nd	nd	nd	nd	nd	nd	nd	nd	503	nd	nd	nd	nd	13000
ethyl butyrate	nd	nd	nd	nd	nd	nd	nd	nd	nd	4030	10	12	23	nd	4030
ethyl 2-methylbutyrate	nd	nd	nd	nd	nd	nd	nd	nd	nd	5710	58	nd	67	41	6230
ethyl hexanoate	nd	nd	nd	nd	nd	nd	nd	nd	nd	638	nd	nd	nd	nd	418
ethyl octanoate	nd	nd	nd	nd	nd	nd	nd	nd	nd	1060	nd	nd	nd	nd	nd
propyl acetate	nd	nd	nd	52	nd	nd	nd	99	2720	822	822	1080	464	875	3170
propyl propionate	nd	nd	nd	14	nd	15	nd	nd	37	298	442	329	135	349	400
propyl hexanoate	68	30	277	1060	562	462	1620	373	975	1250	2480	4240	2220	1840	827
butyl acetate	125	301	31	152	2550	426	526	423	391	23900	7250	4830	1510	2350	22000
butyl propionate	209	153	nd	106	257	144	40	76	23	985	1270	1220	539	100	507
butyl butyrate	182	285	nd	180	377	86	453	134	223	505	936	nd	602	612	nd
butyl 2-methylbutyrate	142	355	nd	481	576	343	1290	302	538	807	1450	3260	1040	1170	479
butyl hexanoate	1750	nd	612	1230	817	872	nd	711	1430	887	1510	nd	872	1090	659
pentyl acetate	76	51	15	73	1250	119	132	153	127	1950	1090	890	457	417	1170
hexyl acetate	676	1270	559	807	10800	1720	1880	1490	1170	17000	7500	5320	2700	2200	11500
hexyl propionate	453	390	229	481	571	339	813	365	508	741	849	1460	398	547	207
hexyl butyrate	23	nd	201	587	677	231	nd	197	679	355	277	nd	246	349	105
hexyl 2-methylbutyrate	1550	2290	730	986	1030	799	777	565	1130	543	688	994	325	570	95
hexyl hexanoate	59	nd	150	nd	116	235	nd	165	nd	nd	129	nd	nd	nd	nd
2-methylpropyl acetate	nd	nd	nd	36	nd	nd	nd	nd	112	1270	650	334	191	549	438
2-methylbutyl acetate	8740	9640	3640	5220	10500	10100	17500	11100	9270	29200	31600	26900	20500	22300	31200
2-methylbutyl acetate	nd	nd	219	625	nd	276	nd	303	613	nd	598	nd	nd	770	nd

[a] CA treatments were months in 1% then 2% O_2: (1) 3/3; (2) 4/2; (3) 5/1; (4) 6/0; (5) regular atmosphere cold storage. CO_2 concentration was 2% for all CA treatments. Values are means of four replicate samples each containing four or five apples (~1 kg). [b] nd, not detected.

Table 5. Alcohol Emission (pL kg^{-1} h^{-1}) from Bisbee Delicious Apples after 6 Months of Storage at 1 °C plus 1 Day of Ripening at 20 °C[a]

	storage treatment														
	144 harvest DAFB					158 harvest DAFB					172 harvest DAFB				
compound	1	2	3	4	5	1	2	3	4	5	1	2	3	4	5
2-propanol	229	nd[b]	nd	nd	nd	16	nd	nd	nd	nd	nd	nd	nd	nd	nd
ethanol	nd	nd	nd	34	nd	nd	nd	nd	nd	515	nd	nd	nd	nd	nd
1-butanol	nd	nd	nd	19	246	nd	13	nd	nd	1525	101	13	116	11	4497
1-pentanol	nd	nd	nd	nd	425	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd
1-hexanol	49	37	105	107	723	105	69	113	71	1093	122	101	89	82	753
2-methyl-1-butanol	86	49	129	264	52	146	97	60	138		474	171	400	129	980
2-ethyl-1-hexanol	nd	nd	158	34	58	nd	nd	25	nd	32	nd	nd	nd	nd	nd

[a] CA treatments were months in 1 then 2% O_2: (1) 3/3; (2) 4/2; (3) 5/1; (4) 6/0; (5) regular atmosphere cold storage. CO_2 concentration was 2% for all CA treatments. Values are means of four replicate samples each containing four or five apples (~1 kg). [b] nd, not detected.

after 10 days, but alcohol content remained unchanged during the same period indicating increased capacity for ester synthesis.

Ripening after storage was the only significant effect identified by ANOVA for aldehyde emission. The lack of harvest date and treatment effects for aldehyde emission contrast with those observed for ester and alcohol emission. Conversion of aldehydes to alcohols may be less affected by low O_2 storage than ester or alcohol emission after ester emission begins during apple development. Nonanal and decanal were the only aldehydes detected 1 day out of storage, with the largest amounts generally produced by RA fruit (Table 7). Emission of nonanal and decanal by CA apples increased during 10 days of ripening (Table 8). Hexanal was detected only after 10 days of ripening. The

Table 6. Alcohol Emission (pL kg^{-1} h^{-1}) from Bisbee Delicious Apples after 6 Months of Storage at 1 °C plus 10 Days of Ripening at 20 °C[a]

	storage treatment														
	144 harvest DAFB					158 harvest DAFB					172 harvest DAFB				
compound	1	2	3	4	5	1	2	3	4	5	1	2	3	4	5
2-propanol	nd[b]	nd	nd	60	nd	748	nd	nd	nd	nd	70	nd	160	nd	nd
ethanol	nd	nd	nd	54	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	5203
1-butanol	nd	21	nd	69	1305	62	105	nd	nd	985	543	171	425	312	1325
1-pentanol	nd	nd	nd	nd	nd	nd	nd	nd	15	nd	nd	nd	20	31	nd
1-hexanol	38	62	30	82	253	74	nd	47	139	299	118	11	155	143	244
2-methyl-1-butanol	73	159	189	404	324	406	1253	445	527	247	1222	1619	1745	1909	981
2-ethyl-1-hexanol	nd	nd	nd	nd	nd	nd	nd	48	21	nd	nd	nd	nd	44.7	nd

[a] CA treatments were months in 1 then 2% O_2: (1) 3/3; (2) 4/2; (3) 5/1; (4) 6/0; (5) regular atmosphere cold storage. CO_2 concentration was 2% for all CA treatments. Values are means of four replicate samples each containing four or five apples (~1 kg). [b] nd, not detected.

Table 7. Aldehyde Emission (pL kg^{-1} h^{-1}) from Bisbee Delicious Apples after 6 Months of Storage at 1 °C plus 1 Day of Ripening at 20 °C[a]

	storage treatment														
	144 harvest DAFB					158 harvest DAFB					172 harvest DAFB				
compound	1	2	3	4	5	1	2	3	4	5	1	2	3	4	5
heptanal	nd[b]	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	46	nd	nd	nd
nonanal	127	51	158	228	627	192	84	231	80	776	207	116	62	67	600
decanal	93	154	305	535	736	193	139	241	149	1250	316	281	102	535	736

[a] CA treatments were months in 1% then 2% O_2: (1) 3/3; (2) 4/2; (3) 5/1; (4) 6/0; (5) regular atmosphere cold storage. CO_2 concentration was 2% for all CA treatments. Values are means of four replicate samples each containing four or five apples (~1 kg). [b] nd, not detected.

Table 8. Aldehyde Emission (pL kg^{-1} h^{-1}) from Bisbee Delicious Apples after 6 Months of Storage at 1 °C plus 10 Days of Ripening at 20 °C[a]

	storage treatment														
	144 harvest DAFB					158 harvest DAFB					172 harvest DAFB				
compound	1	2	3	4	5	1	2	3	4	5	1	2	3	4	5
hexanal	nd[b]	nd	nd	224	nd	nd	176	nd	176	659	nd	nd	nd	479	84
heptanal	nd	nd	nd	nd	nd	nd	nd	nd	nd	107	nd	nd	nd	nd	nd
nonanal	93	101	85	1113	1041	186	184	993	739	632	155	202	511	760	nd
decanal	132	105	82	1149	389	179	372	618	1068	1122	264	219	1047	1252	nd

[a] CA treatments were months in 1 then 2% O_2: (1) 3/3; (2) 4/2; (3) 5/1; (4) 6/0; (5) regular atmosphere cold storage. CO_2 concentration was 2% for all CA treatments. Values are means of four replicate samples each containing four or five apples (~1 kg). [b] nd, not detected.

absence of detectable amounts of aldehydes except nonanal and decanal may indicate the efficiency of aldehyde conversion to alcohols is sufficient enough to allow only small amounts of aldehydes to accumulate. The efficiency of aldehyde utilization by fruit alcohol dehydrogenase declines as carbon number increases (Bartley and Hindley, 1980; Bruemmer and Roe, 1971); this could account for the presence of nonanal and decanal.

The rate of apple ripening after harvest is determined by a combination of fruit maturity at harvest, postharvest storage environment, and storage duration. Ester emission is higher when apples are stored in air compared to low O_2, and ester synthesis decreases when apples are stored in low O_2 for long periods (Streif and Bangerth, 1988; Brackman *et al.*, 1993; Fellman *et al.*, 1993a). Our results confirm the influence of harvest maturity on subsequent quality retention and emission of volatile compounds (Brackman *et al.*, 1993; Brown *et al.*, 1966; Fellman *et al.*, 1993b; Hansen *et al.*, 1992a; Yahia *et al.*, 1990a), but ripening during storage was unaffected by increased O_2 concentration. Apple storage in low O_2 decreases metabolic activity markedly, and Gran and Beaudry (1993) reported a low O_2 tolerance level for Delicious apples of approximately 0.8%. If Delicious apples are subjected to anoxia for 30 days, substantial amounts of ethyl esters are produced (Mattheis *et al.*, 1991a), indicating the acetate-ester-forming enzyme system remains active regardless of oxygen concentration in storage. The lack of response to increased O_2 in our study may be due to a number of factors. Increasing O_2 concentration from 1 to 2% was not sufficient to promote firmness or TA or SSC loss or to enhance volatile emission. The O_2 concentration necessary to induce these responses is apparently higher than 2% with Delicious apples of the maturities used in this experiment. The length of initial storage at 1% O_2 may also determine, in part, subsequent response to increased O_2 concentration. The sequence of ripening events in apples is also subject to seasonal variation (Knee *et al.*, 1990). Fruit in 1991 matured slowly in the field remaining preclimacteric at harvest later than typically observed in this orchard. This developmental effect may also have been a factor determining subsequent response to manipulation of storage conditions.

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