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Tolerance of peach and nectarine fruits to insecticidal controlled atmospheres as influenced by cultivar, maturity, and size

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Abstract

Tolerances of peach and nectarine fruits to insecticidal controlled atmospheres were determined by the time before occurrence of visual injury and/or off-flavor. The tolerances of 'John Henry' peaches, 'Fantasia' nectarines, 'Fire Red' peaches, 'O'Henry' peaches, 'Royal Giant' nectarines, and 'Flamekist' nectarines to 0.25% O_2 (balance N_2) at 20°C were 2.8, 4.0, 4.0, 4.4, 5.1, and 5.2 days, respectively. 'Fairtime' peaches tolerated 0.21% O_2 + 99% CO_2 at 20°C for 3.8 days, 0.21% O_2 + 99% CO_2 at 0°C for 5.0 days, 0.21% O_2 at 20°C for 6.0 days, and 0.21% O_2 at 0°C for up to 19 days. Soluble solids content, pH, titratable acidity, and vitamin C content of 'Fairtime' peaches were not significantly influenced by the low O_2 and/or high CO_2 treatments. There was a good correlation between tolerances of peaches and nectarines to the insecticidal atmospheres and the accumulation rates of acetaldehyde ($r = -0.94$, $P < 0.01$) and ethanol ($r = -0.88$, $P < 0.01$). The lower tolerance of 'John Henry' peaches to 0.25% O_2 was associated with a higher respiration rate, a more mature and larger fruit, and faster accumulation rates of acetaldehyde, ethanol, and ethyl acetate. Generally, accumulation rates of anaerobic volatiles were higher in more mature and larger fruits of 'O'Henry' peaches and 'Fantasia' nectarines kept in 0.25% O_2, air + 35% CO_2, or 0.25% O_2 + 35% CO_2 at 20°C. Comparison of fruit tolerance and published information on the time to reach 100% mortality of some insects suggests that 0.25% O_2 at 20°C is probably not feasible for postharvest insect disinfestation while 0.21% O_2 with or without 99% CO_2 at 0°C merits further investigation.

Key words: Peach; Nectarine; *Prunus persica*; Controlled atmosphere; Anaerobic volatile

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1. Introduction

Since the removal of ethylene dibromide from the list of approved chemicals in 1984, much research has been done to develop non-chemical alternative methods for postharvest insect disinfestation to meet quarantine requirements. Controlled atmospheres (CA) with O_2 concentration below 1% and/or CO_2 concentration above 20% have been reported to effectively kill certain insects in some fresh fruits and vegetables (Morgan and Gaunce, 1975; Aharoni et al., 1979, 1981; Gaunce et al., 1982; Benshoter, 1987; Soderstrom et al., 1987, 1990; Ali Niazee et al., 1989). CA treatments can be used as quarantine procedures only when they can completely kill the insects of concern before detrimental effects occur in the host commodities (Ke and Kader, 1992a).

Changes in quality of peaches and nectarines in response to CA vary according to cultivar, maturity, storage temperature and duration, and atmospheric composition. Long-term storage of peaches and nectarines in 1% O_2 + 5% CO_2 with intermittent warming reduced internal breakdown (chilling injury), extended storage life, and maintained their contents of sugars, organic acids, and unsaturated fatty acids (Wang and Anderson, 1982). Treatments with low O_2 and/or high CO_2 retarded softening and color changes and reduced respiration and ethylene production rates of peaches and nectarines (Wang and Anderson, 1982; Smilanick and Fouse, 1989). While 'Fairtime' peaches tolerated 0.25% O_2 at 0°C for up to 40 days, storage of the fruits at 5°C caused internal breakdown in 14 days (Ke et al., 1991b). When stone fruits were exposed to stress O_2 and/or CO_2 levels for longer than their tolerance limits, detrimental effects such as abnormal ripening, flesh browning, and accumulation of ethanol and acetaldehyde occurred (Kader, 1986; Smilanick and Fouse, 1989; Kerbel et al., 1990; Ke et al., 1991b; Ke and Kader, 1992b).

In this research, we studied the physiological responses and quality attributes of selected cultivars of peaches and nectarines (various maturity stages and fruit sizes) stored in CA of 0.25% or 0.21% O_2 and/or 35% or 99% CO_2 at 0 or 20°C. Our objective was to determine the tolerances of the fruits to the insecticidal atmospheres and to evaluate the potential of using CA treatments as quarantine procedures for postharvest insect control.

2. Materials and methods

Materials and treatments

Fruits of peaches (cv. 'Carnival', 'Fairtime', 'Fire Red', 'John Henry', and 'O'Henry') and nectarines (cv. 'Fantasia', 'Flamekist', 'Royal Giant', and 'September Red') were obtained on the day of harvest from Fresno County, California, and transported in an air-conditioned car to our laboratory at Davis. The fruits were used for experiments immediately or after overnight storage at 0°C. Fruits with defects were sorted out and 5–6 good fruits were put into a 4-liter glass jar as one replicate with three replicates used per treatment. The fruit samples were kept under a continuous flow of air, 0.25% (±0.02%) O_2, 0.21% (±0.02%) O_2, air + 35% CO_2, 0.25% O_2 + 35% CO_2, or 0.21% O_2 + 99% CO_2 for 1, 2, 4, or 6 days at

20°C or for 1, 3, 5, 10, 14, or 19 days at 0°C. After each period, the jars were opened and the fruits were evaluated immediately or placed in a tray and transferred to air at 0°C for 4–7 days to mimic commercial transport conditions and then to air at 20°C for 3 days to allow the fruits to ripen before final quality evaluation.

Gas analysis

The O_2 and CO_2 concentrations were measured by analysis of a 10-ml sample using an O_2 analyzer in series with an infrared CO_2 analyzer. Respiration rate of the fruits kept in air was estimated by detecting the CO_2 concentration from the outlet of the jar holding the fruits. A vacuum extraction method was used to determine internal CO_2 concentration and resistance to gas diffusion (Ke and Kader, 1990). Resistance to CO_2 diffusion was calculated by the ratio: $[(CO_2)_{Int.} - (CO_2)_{Ext.}]/CO_2$ production rate.

Determination of quality attributes

Three initial samples of 5–6 fruits each were evaluated for size, skin and flesh color, flesh firmness, soluble solids content (SSC), pH, titratable acidity, concentrations of anaerobic volatiles, vitamin C content, and flavor score. Similar measurements were done as part of the quality evaluations when the fruits were removed from treatment and after ripening. Skin and flesh color was measured with a color difference meter (Minolta Chroma Meter, Model CR-2000) using "a" color value (green to red). Flesh firmness was measured as penetration force using a U.C. firmness tester with an 8-mm plunger tip. Fruit juice was extracted with a hand-press juicer. SSC was measured with an Abbe refractometer and pH and titratable acidity were measured by a pH meter connected to an automatic titrator. To measure acidity, the juice sample was titrated to pH 8.2 using 0.1 *N* NaOH. The rest of the juice was frozen in a freezer at −40°C until use for analysis of volatiles and vitamin C.

Determination of anaerobic volatiles

Frozen juice was thawed and a 5-ml sample was put in a 10-ml screw-cap test tube. The test tube was closed with a plastic cap and incubated in a water bath at 60°C. After 60 min, a headspace sample was taken with a 1-ml glass syringe for measurements of acetaldehyde, ethanol, and ethyl acetate concentrations using a HP5890A gas chromatography equipped with a flame ionization detector (at 250°C) and a glass column (2 mm × 1.0 m) containing 5% Carbowax on 60/80 Carbopack as a stationary phase (at 85°C).

Determination of vitamin C content

Frozen fruit juice was thawed and a 2-ml sample was diluted with 18 ml of 0.1% oxalic solution. The sample solution was centrifuged for 20 min at 25,000 *g* at 0°C and about 2 ml of the supernatant was filtered through a 0.45-mm microfilter. The filtrate was used to determine vitamin C content using a Bio-Rad high performance liquid chromatography system with an ion exclusion HPX-87H column and a Bio-Rad UV monitor (Model 1306) at a 245-nm wavelength. Mobile phase was 0.1 *N* H_2SO_4 and flow rate was 0.8 ml min^{-1}.

Estimation of flavor score

Flavor of three fruits per treatment was evaluated by tasting as previously described (Ke et al., 1991a), using a scale of 1 to 7 where 7 = excellent, 6 = good, 5 = fair, 4 = slight off-flavor, 3 = moderate off-flavor, 2 = severe off-flavor, and 1 = extreme off-flavor.

Estimation of low O_2 and/or high CO_2 injury

Severity of external and internal injuries were visually estimated using a pretransformed scale of 1 to 5 according to the percentage of injured area of the fruit's surface and longitudinal section, respectively: 1 = no injury; 2 = slight injury, 1% to 15% of the area injured; 3 = moderate injury, 16% to 50% of the area injured; 4 = severe injury, 51% to 85% of the area injured; and 5 = extreme injury, 86% to 100% of the area injured. The injury was estimated after the fruits were ripened in air at 20°C.

3. Results and discussion

Tolerances of selected cultivars of peaches and nectarines to low O_2 atmosphere

Exposure of 'John Henry' peaches to 0.25% O_2 at 20°C for 2 days resulted in slight internal injury in some fruits after ripening (Table 1). The injury symptoms started as flesh browning close to the stone and extended outwardly. After 4 to 6

Table 1
Internal low O_2 injury of 'John Henry' and 'O'Henry' peaches. The fruits were kept in air or 0.25% O_2 (balance N_2) at 20°C for 1 to 6 days followed by transfer to air at 0°C for 4 days and then to air at 20°C for 3 days for ripening

Cultivar	Days under treatment	Internal injury severity[a]			
		At transfer		After ripening	
		Air	0.25% O_2	Air	0.25% O_2
'John Henry'	0	1.0	1.0	1.0	1.0
	1	1.0	1.0	1.0	1.0
	2	1.0	1.0	1.2	1.4
	4	1.0	2.0	1.6	5.0
	6	1.0	2.0	1.0	5.0
Pooled LSD (at P = 0.05)			0.4		
'O'Henry'	0	1.0	1.0	1.0	1.0
	1	1.0	1.0	1.0	1.0
	2	1.0	1.0	1.0	1.0
	4	1.4	1.0	1.0	1.4
	6	1.0	1.2	1.0	1.8
Pooled LSD (at P = 0.05)			0.2		

[a] Internal injury severity was visually estimated using a pretransformed scale of 1 to 5 according to the percentage of injured area of the fruit's longitudinal section: 1 = no injury; 2 = slight injury, 1% to 15% of the area injured; 3 = moderate injury, 16% to 50% of the area injured; 4 = severe injury, 51% to 85% of the area injured; and 5 = extreme injury, 86% to 100% of the area injured.

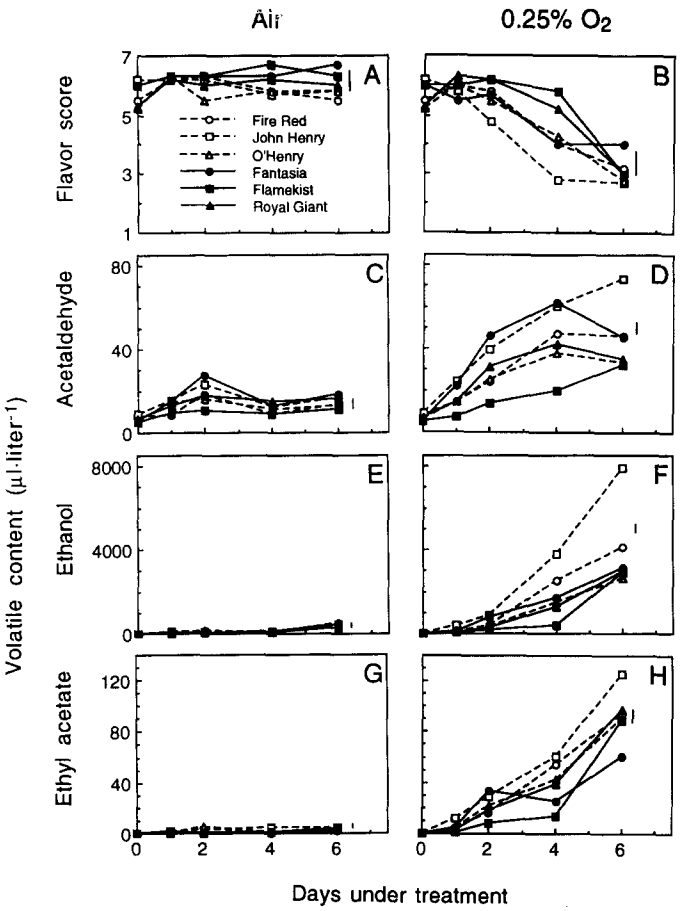

Fig. 1. Fruit flavor and contents of acetaldehyde, ethanol, and ethyl acetate of 6 peach and nectarine cultivars kept in air or 0.25% O_2 at 20°C for 1 to 6 days followed by transfer to air at 0°C for 4 days and then to air at 20°C for 3 days for ripening. Flavor was evaluated by tasting using a scale of 1 to 7 where 7 = excellent, 6 = good, 5 = fair, 4 = slight off-flavor, 3 = moderate off-flavor, 2 = severe off-flavor, and 1 = extreme off-flavor. Vertical bars represent pooled LSD at $P = 0.05$.

days of exposure to low O_2, the internal injury became very severe and all the flesh showed both red and brown discoloration. For 'O'Henry' peaches, slight internal injury occurred in some fruits only after 4 to 6 days in 0.25% O_2 at 20°C. No internal injury occurred in 'Fire Red' peaches and 'Fantasia', 'Flamekist', and 'Royal Giant' nectarines even after 6 days in 0.25% O_2 at 20°C. For all the cultivars of peaches and nectarines tested, no external injury was observed.

Flavor was good for the peaches and nectarines kept in air at 20°C for up to 6 days but it declined in the fruits subjected to 0.25% O_2 at 20°C (Fig. 1). The decrease in flavor was fastest in 'John Henry' peaches and slowest in 'Flamekist' nectarines. After flavor score decreased to 4 (slight off-flavor), tasting quality of the fruits was considered unacceptable. Therefore, the days for flavor score to reach 4

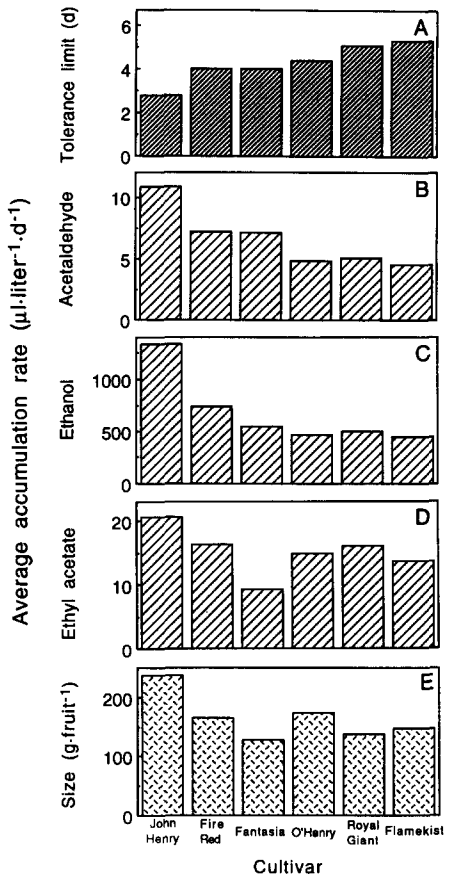

Fig. 2. Comparison of tolerance limits (days) of peach and nectarine fruits of 6 cultivars to 0.25% O_2 at 20°C with their accumulation rates of anaerobic volatiles and average fruit size. Data shown were means of three replicates.

is used as the tolerance limit (T_l) of the fruits to low O_2 atmospheres. The order of tolerances (T_l) of the tested cultivars from low to high was: 'John Henry', 'Fire Red' and 'Fantasia', 'O'Henry', 'Royal Giant', and 'Flamekist' (Fig. 2A).

A major effect of exposing peaches and nectarines to 0.25% O_2 at 20°C was the accumulation of anaerobic volatiles such as acetaldehyde, ethanol, and ethyl acetate (Fig. 1). The average accumulation rates ($\mu l\ kg^{-1}\ d^{-1}$) of these volatiles are shown in Fig. 2B, C, and D. There was a highly significant correlation between T_l and the accumulation rate of acetaldehyde ($r = -0.94$, $P < 0.01$) or ethanol ($r = -0.88$, $P < 0.01$). For example, 'John Henry' peaches had the highest accumulation rates of these two volatiles and the lowest tolerance to 0.25% O_2 among all the cultivars tested. T_l did not correlate well with the accumulation rate of ethyl acetate ($r = -0.45$, $P > 0.1$). Therefore, it seems that the occurrence of slight alcoholic off-flavor (a flavor score of 4 which determined T_l) was more likely caused by

acetaldehyde and ethanol than by ethyl acetate. On the other hand, ethyl acetate might be related to the occurrence of more severe and unpleasant off-flavor at a later stage since this volatile generally accumulated at a faster speed after 4 to 6 days in 0.25% O_2 at 20°C (Fig. 1H).

Effects of maturity and fruit size

The initial quality of peaches and nectarines was measured to estimate their maturity (Tables 2 and 3). Generally, changes in ground color of skin and flesh color from green to yellow, lower flesh firmness, higher SSC, and higher respiration rate indicated a more mature stage of peaches and nectarines. The flesh firmness, SSC, and respiration rate data indicated that 'John Henry' peaches were more mature than 'Fire Red' and 'O'Henry' peaches and 'Fantasia', 'Flamekist', and 'Royal Giant' nectarines (Table 2). Generally, more mature fruits of 'O'Henry' peaches and 'Fantasia' nectarines accumulated more acetaldehyde, ethanol, and ethyl acetate when kept in 0.25% O_2, air + 35% CO_2, or 0.25% O_2 + 35% CO_2 at 20°C (Fig. 3). The effects of 35% CO_2 on anaerobic volatiles were greater than those of 0.25% O_2.

Resistances to CO_2 diffusion (r_{CO_2}) were similar among the three cultivars of peaches and three cultivars of nectarines tested (Table 2). These r_{CO_2} values were about 0.1 units and they were much lower than the r_{CO_2} values of 1 to 2 units for apples and oranges (Ke and Kader, 1990; Ke et al., 1991a). Similarly, no significant differences in r_{CO_2} values were observed among different maturity stages of 'Carnival' peaches and 'September Red' nectarines (Table 2). Thus, it appears that resistance to gas diffusion is not a major factor in determining the variation

Table 2
Initial fruit quality and resistance to gas diffusion of selected peach and nectarine cultivars at indicated maturity stages. Flesh firmness and soluble solids content (SSC) were measured before storage while respiration rate and resistance to CO_2 diffusion (r_{CO_2}) were measured after 3 days in air at 0°C

Commodity	Cultivar	Maturity[a]	Firmness (N)	SSC (%)	Respiration rate (ml CO_2 kg^{-1} h^{-1})	r_{CO_2} [%·(ml kg^{-1} h^{-1})]
Peach	'Fire Red'	M2	52	10	2.4	0.09
	'John Henry'	M2	44	13	3.4	0.11
	'O'Henry'	M2	67	13	2.4	0.10
Nectarine	'Fantasia'	M2	54	10	2.4	0.13
	'Flamekist'	M2	51	11	1.9	0.10
	'Royal Giant'	M2	53	10	1.9	0.11
Pooled LSD at $P = 0.05$			9	1	0.4	0.04
Peach	'Carnival'	M1	56	13	2.1	0.12
		M2	52	13	2.3	0.11
		M3	45	14	2.6	0.13
Nectarine	'September Red'	M1	45	11	1.8	0.15
		M2	49	11	1.9	0.14
		M3	36	13	2.4	0.12
Pooled LSD at $P = 0.05$			8	1	0.2	0.03

[a] Based on skin ground color, M1 = light green, M2 = yellowish green, and M3 = greenish yellow.

Table 3
Initial quality of 'O'Henry' peach and 'Fantasia' nectarine fruits harvested at different maturity stages and sizes

Commodity and cultivar	Maturity [a]	Size [b]	Color (CDM "a") [c]		Firmness (N)	SSC (%)
			Skin	Flesh		
'O'Henry' peach	M1	M	−10.8	−7.8	58	8.8
	M2	M	−0.6	−4.8	56	9.3
	M3	M	22.1	4.0	43	11.2
'Fantasia' nectarine	M2	M	18.8	9.0	42	9.6
	M3	M	19.5	11.7	27	10.7
Pooled LSD at $P = 0.05$			7.8	4.4	10	0.7
'O'Henry' peach	M2	S	12.0	0.3	46	8.6
	M2	M	3.7	2.7	42	10.1
	M2	L	6.4	2.6	53	10.8
'Fantasia' nectarine	M2	S	2.9	1.2	48	9.9
	M2	M	3.4	3.2	40	9.4
	M2	L	5.1	4.9	41	11.0
Pooled LSD at $P = 0.05$			7.1	2.3	7	1.2

[a] See footnote to Table 2 for description of maturity.
[b] Average fruit weight (g) = 109 for small (S), 146 for medium (M), and 252 for large (L) fruits.
[c] CDM = color difference meter. On the "a" scale, negative values indicate greenness and positive values indicate redness.

in tolerance to low O_2 and/or high CO_2 atmospheres among cultivars and maturity stages of peaches and nectarines.

Another factor influencing fruit tolerance to CA treatments might be fruit size. 'John Henry' fruits were larger than those of the other cultivars tested and had the lowest tolerance (Fig. 2A and E). Experiments with both 'O'Henry' peaches and 'Fantasia' nectarines indicated that larger fruits generally accumulated more acetaldehyde, ethanol, and ethyl acetate when kept in low O_2 and/or high CO_2 atmospheres (Fig. 4).

It appears that a larger fruit size, a more mature stage, a higher respiration rate, and higher accumulation rates of anaerobic volatiles partly contributed to the lower tolerance of 'John Henry' peaches to low O_2 atmosphere.

Tolerances of 'Fairtime' peaches to low O_2 and high CO_2 atmospheres at 0°C vs. 20°C

When 'Fairtime' peaches were kept in air or 0.21% O_2 at 0°C, no significant external or internal injury was observed and these fruits tasted very good for up to 19 days (Fig. 5). For the fruits kept in 0.21% O_2 at 20°C or 0.21% O_2 + 99% CO_2 at 0 or 20°C, visual injury (score of 2 or higher) and/or off-flavor (score of 4 or lower) occurred within a few days. The tolerances of 'Fairtime' peaches to 0.21% O_2 + 99% CO_2 at 20°C, 0.21% O_2 + 99% CO_2 at 0°C, and 0.21% O_2 at 20°C were 3.8, 5.0, and 6.0 days, respectively (Fig. 5).

During exposure to 0.21% O_2 at 0°C, acetaldehyde, ethanol, and ethyl acetate did not accumulate in 'Fairtime' peaches (Fig. 5), which was consistent with the absence of off-flavor in these fruits. In contrast, exposure of the fruits to 0.21% O_2 at 20°C or

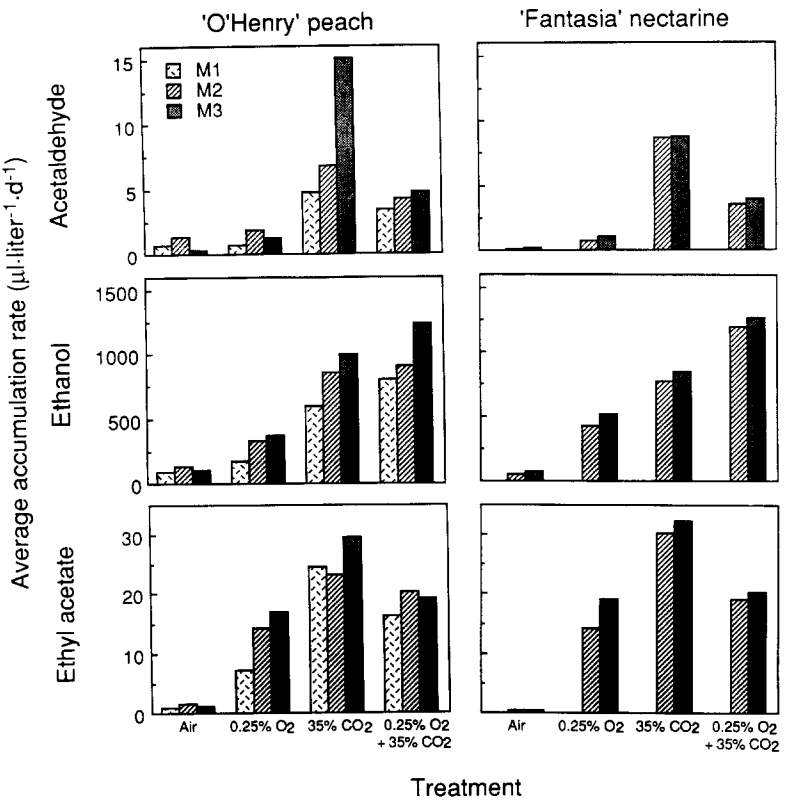

Fig. 3. Accumulation rates of anaerobic volatiles of medium size "O'Henry" peaches (picked at 3 maturity stages) and "Fantasia" nectarines (picked at 2 maturity stages) kept in air, 0.25% O_2, air + 35% CO_2, or 0.25% O_2 + 35% CO_2 at 20°C for 2, 4, or 6 days. See footnote to Table 2 for definition of M1, M2, and M3. Data shown were means of three replicates.

0.21% O_2 + 99% CO_2 at 0°C increased concentrations of anaerobic volatiles. The strongest off-flavor and highest concentrations of acetaldehyde and ethanol were detected in the peaches exposed to 0.21% O_2 + 99% CO_2 at 20°C.

None of the treatments significantly and consistently influenced SSC (7.4% to 9.0%), pH (4.0 to 4.1), titratable acidity (0.4% to 0.5%), and vitamin C content (93% to 112% of initial level), indicating that these constituents of 'Fairtime' peaches were not affected by exposure to the insecticidal low O_2 and/or CO_2 atmospheres.

Potential of CA application for insect control on peaches and nectarines

Peaches and nectarines tolerated 0.25% to 0.21% O_2 at 20°C for 3 to 6 days, 0.21% O_2 at 0°C for up to 19 days, and 0.21% O_2 + 99% CO_2 at 0 or 20°C for 4 to 5 days. Soderstrom et al. (1987, 1990) indicated that adults and eggs of codling moth in stone fruits reached 100% mortality following 2 to 3 days of exposure to 0.5% O_2 + 10% CO_2 at 25°C; but it took 6 to 12 days to completely kill pupa. Therefore, it is questionable if 0.25% O_2 at 20°C could completely kill all the

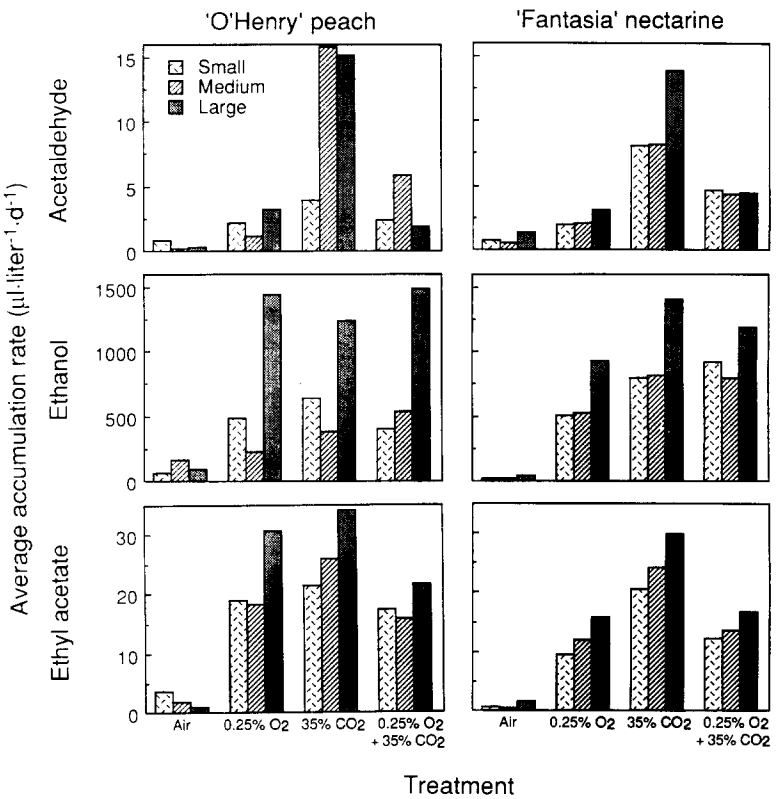

Fig. 4. Accumulation rates of anaerobic volatiles of "O'Henry" peaches and "Fantasia" nectarines (three sizes) kept in air, 0.25% O_2, air + 35% CO_2, or 0.25% O_2 + 35% CO_2 at 20°C for 2, 4, or 6 days. See footnote to Table 3 for definition of small, medium, and large. Data shown were means of three replicates.

developmental stages of codling moth before detrimental effects occur in peaches and nectarines. Smilanick and Fouse (1989) concluded that 0.5% O_2 at 5 or 15°C would damage nectarines before completely killing insects. We found that 'Fairtime' peaches tolerated 0.21% O_2 at 0°C for up to 19 days (Fig. 5) and 0.25% O_2 at 0°C for up to 40 days (Ke et al., 1991b). The insecticidal effects of these low O_2 atmospheres at 0°C merit further investigation.

In apples, all developmental stages of codling moth were completely killed in 2 days by exposure to 1% O_2 + 95% CO_2 at 27°C (Gaunce et al., 1982). San Jose scale reached 100% mortality in 2 days when treated with 1% O_2 + 90% CO_2 at 12°C (Morgan and Gaunce, 1975). Western flower thrips were completely killed in 1 to 2 days by exposure to 1% O_2 + 90% CO_2 at 2.5°C (Aharoni et al., 1979, 1981). Although the efficacy of such extremely high CO_2 concentrations to control insects in stone fruits has not been determined, it seems possible that the 0.21% O_2 + 99% CO_2 atmosphere at 0 or 20°C may completely kill some insects in 1 to 2 days and therefore has a potential as quarantine treatment for insect control on peaches and nectarines.

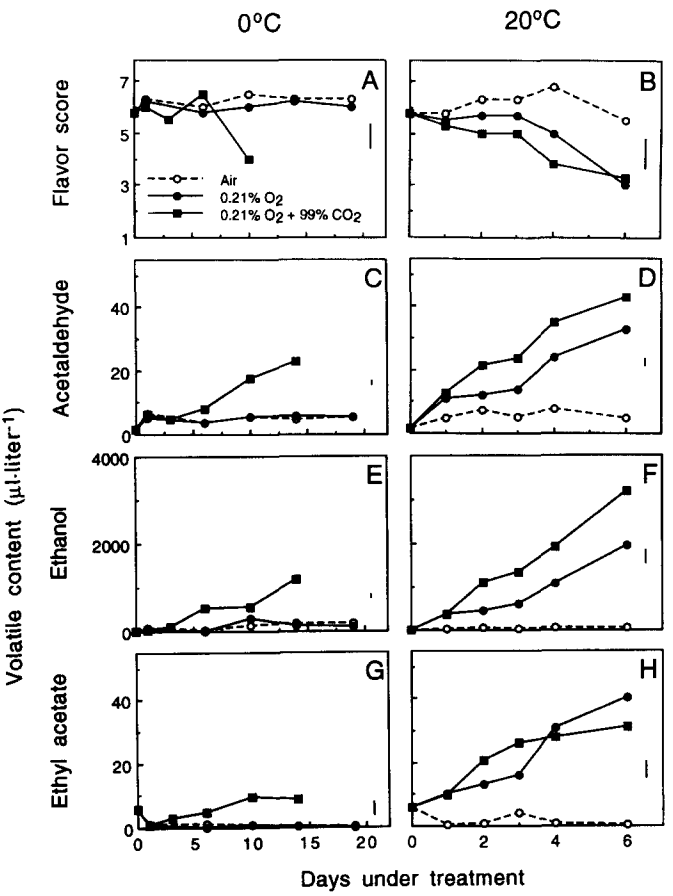

Fig. 5. Flavor score and concentrations of acetaldehyde, ethanol, and ethyl acetate of "Fairtime" peaches kept in air, 0.21% O_2, or 0.21% O_2 + 99% CO_2 at 0°C for up to 19 days or 20°C for up to 6 days. See footnote to Fig. 1 for description of the flavor scoring methods used. Vertical bars represent pooled LSD at $P = 0.05$.

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