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Keeping quality of cold stored peaches using intermittent warming

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Firm-breaker and firm-mature mid-season peaches (*Prunus persica* L. Batsch cultivar 'Paraguayo') were stored for up to four weeks at 2°C or subjected to intermittent warming cycles of one day at 20°C every six days at 2°C. Several quality parameters were monitored during normal ripening at 20°C and weekly during storage, with and without three days of subsequent ripening at 20°C. After three cycles, intermittent warming avoided or strongly alleviated chilling injuries (particularly woolliness and lack of juiciness) especially in breaker fruit. Low temperature induced abnormal ripening in control fruit, which was detectable when chilling injury was already irreversible. In comparison to sound fruit, injured fruit showed an increased total soluble solids/titratable acidity ratio, a decrease in flesh firmness and in Hue angle flesh color during storage and an excessive loss of acidity in fruit of advanced maturity. Hue angle was a good maturity index only for sound fruit. Intermittent warming appears to maintain the quality of peaches by acclimatizing chilled fruit to subsequent periods of chilling by allowing a gradual ripening of the fruits (softening, enhancement of ground and flesh color, and maintenance of juiciness). © 1998 Canadian Institute of Food Science and Technology. Published by Elsevier Science Ltd. All rights reserved

Keywords: *Prunus persica*, chilling injury, color, flesh firmness, intermittent warming, juiciness, titratable acidity.

INTRODUCTION

Maturity at harvest, ripening and temperature management have been identified as the most critical factors in the postharvest life of peaches, while firmness is the main limiting quality attribute (Shewfelt *et al.*, 1987*a*). Freedom from chilling injuries (CI), firmness, color and aroma define the maturity and quality attributes that consumers use to judge peaches (Bruhn, 1995).

Less mature peach and nectarine fruit are usually more susceptible to woolliness and other chilling injury symptoms (Boyes, 1955; Eksteen, 1984). These disorders appear after periods of more than two weeks of storage at around 0°C (Ben-Arie *et al.*, 1989; Lill *et al.*, 1989; Artés *et al.*, 1996), and are characterized by a dry mealy flesh texture, lack of juiciness and flavor, brown-red discoloration of the flesh, particularly at the pit, and loss of ability to ripen in spite of the normal external appearance of the fruit (Lyons and Breidenbach, 1987; von Mollendorff and de Villiers, 1988; Luza *et al.*, 1992; Wang, 1993). To simulate retail sale and to evaluate CI after cold storage, a period of three days at 20–25°C is commonly applied (Lyons and Breidenbach, 1987; Artés *et al.*, 1996). Normal ripening of peaches comprises softening processes, changes in skin and flesh color (less green with a reduction in Hue angle values), an increase in total soluble solids (TSS), lower titratable acidity (TA) and a higher TSS/TA ratio (Kader *et al.*, 1982; Lill *et al.*, 1989; Meredith *et al.*, 1989; Thai and Shewfelt, 1990; Ravaglia *et al.*, 1996). However, the effect of normal or cyclical warming treatments with or without post-storage ripening on CI and on the keeping quality of peaches has received little attention in the scientific literature. Several intermittent warming (IW) cycles have been proposed to alleviate CI during cold storage

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(Artés *et al.*, 1989, 1996; Lill *et al.*, 1989; Wang, 1993), although an acceleration of softening has always been the main disadvantage of this approach (Kader *et al.*, 1984; Dawson *et al.*, 1995).

In order to deliver top quality produce to the market (especially fruit harvested at immature stages), to avoid the sharp drop in prices that accompanies peak production, and to reduce competition with other cultivars, the shelf-life of mid-season peaches (which are normally very sensitive to CI) must be improved. The present study evaluates the keeping quality of mid-season peaches picked at two maturity stages during conventional and IW storage, with particular attention paid to the onset of CI during storage and after post-storage ripening.

MATERIALS AND METHODS

Plant material and experimental design

According to firmness and skin color at harvest, peaches (*Prunus persica* L. Batsch cultivar 'Paraguayo') were classified as firm-breaker (FB, 95 ± 4 N and Hue angle of 100.4 ± 1.2) and firm-mature (FM, 53 ± 3 N and Hue angle of 94.9 ± 2.5), both kinds of fruit being pre-climacteric (see below). 'Paraguayo' peach is a white fleshed and juicy mid-season cultivar widely cultivated in the Murcia region, on the Mediterranean coast of Spain. Fruits were harvested from a commercial orchard in Cieza (Murcia) and transported by ventilated car 5 Km to a packinghouse, where they were sorted and selected for uniform size, appearance and freedom from defects. Sound fruits were quickly transported by ventilated car to the laboratory at Murcia (35 km from Cieza), where they were immediately forced-air pre-cooled to reach 5°C beside the stone 5 h later, and 2°C 12 h later. The following morning, the peaches were randomly divided into batches of 32 fruit each and placed in clean plastic boxes with the fruit touching. The mean measurements and standard error of the FM fruit were: axial diameter 36.0 ± 0.4 mm; longitudinal diameter 62.4 ± 0.6 mm and weight 82.9 ± 2.6 g. The same measurements for FB fruit were: axial diameter 36.9 ± 0.9 mm; longitudinal diameter 61.5 ± 1.0 mm and weight 83.8 ± 4.5 g.

Peaches intended for continuous cold storage (CS) were placed in a cold room at 2.0 ± 0.5°C, a temperature that generally induces CI (Boyes, 1955; von Mollendorff and de Villiers, 1988) and 90–95% relative humidity (RH). During IW storage, the warming periods consisted of removing the corresponding boxes from the cold room to another room at 20°C and 95% RH. After one day of warming the fruits were returned to 2°C (Artés and Escriche, 1994).

To compare the behavior of fruit stored at room temperatures and that of chilled fruit, the treatments were: N20, normal postharvest ripening for one week at 20°C and 90–95% RH; CS, conventional storage for 1, 2, 3 or 4 weeks at 2°C; IW, storage at 2°C with four cycles of one day at 20°C every six days of storage at 2°C. Each treatment was subjected to three days of post-storage ripening at 20°C and 70–75% RH, to simulate the normal conditions of retail sale and to measure any effect on quality parameters and chilling injury.

Chilling injuries

The degree of woolliness and senescence (shrivelling or overripeness) was assessed by eye in three replicates of 32 fruits each at the end of cold storage plus three days of subsequent ripening at 20°C. In N20 fruit, they were evaluated after seven days at 20°C. Injured fruit were divided into four classes (very slight, slight, moderate and severe injury), according to von Mollendorff *et al.* (1989). As in commercial practice, only moderate and severe levels were considered as losses, representing the intensity of CI.

Respiratory activity and ethylene emission

Measurements of CO_2 and C_2H_4 emissions were made in three replicates of two fruits stored at 20 ± 1°C and 90% RH each hermetically sealed inside 650 ml gas-tight jars prior to gas sampling. Measurements of C_2H_4 were made with a Perkin Elmer Autosystem gas chromatograph, with flame ionization detector (FID) and Porapak QS 80/100 column (1.2 m and 3.18 mm), (Norwalk, Connecticut, USA) calibrated with certified samples of 6 ppm of C_2H_4. Oven, injector and FID temperatures were 50, 115 and 175°C, respectively. Helium flow was $18.4\,\mathrm{ml\,min^{-1}}$, H_2 flow was $80\,\mathrm{ml\,min^{-1}}$, and air flow was $300\,\mathrm{ml\,min^{-1}}$. For CO_2, a Hewlett Packard 5730A gas chromatograph with a metal column (13×50/80 mm i.d.) packed with Porapak Q 80/100 (Avondale, Pennsylvania, USA), calibrated with certified samples of 10% CO_2, was used. Oven temperature was 40°C and injector and thermal conductivity detector were at 200°C. The flow rates of carrier gases were $30\,\mathrm{ml\,min^{-1}}$ for He and $265\,\mathrm{ml\,min^{-1}}$ for air. Hewlett Packard chromatograph was coupled to a 3390a recorder integrator and Perkin Elmer to a Pe1020 integrator. Retention times for C_2H_4 and CO_2, respectively, were 1.1 and 0.8 min. The measurement error was about 0.1% for CO_2 and 1.5% for C_2H_4.

Quality parameter evaluation and preference test

The quality parameters measured in three replicates of five fruits were firmness (Fruit Pressure Tester Effegi 327 penetrometer, Alfonsine, Italy; 7.9 mm probe tip, readings at 20°C), total soluble solids (TSS, Atago N1 hand refractometer, Tokyo, Japan; readings at 20°C), titratable acidity (AOAC, 1995; in meq l^{-1} of malic acid), and ground and flesh color (Minolta CR-300 colorimeter, Osaka, Japan; D-65 standard C.I.E. illumination, 2° observer, expressed as Hue angle (H*) color index [$\tan^{-1}(b^* a^{-1})$]. For a better understanding of changes in the maturity index TSS/TA, was calculated with titratable acidity (TA) expressed as % of malic acid. The three flesh firmness values and color readings were averaged for each peach and the mean of the measurement for five fruits from each replicate was recorded.

Juiciness determination consisted of two steps. First, the amount of extractable juice was determined by separating the juice from 100 g of pulp tissue from four replicates of six fruits each (von Mollendorff and de Villiers, 1988), using an electric liquidizer which separated the juice from the solid phase by fast-rotating sieve. The weight of the juice thus obtained was expressed as a percentage of the weight of the fresh fruit. Thereafter, a known amount of juice was centrifuged at 10 000 xg for 10 min to pellet all solids. The mass of the clear liquid was recorded and expressed as a percentage of the weight of fresh fruit tissue used (juiciness), according to von Mollendorff *et al.* (1989).

Quality parameters and juiciness were measured at harvest and weekly during storage, and after three days of additional ripening at 20°C. For N20 fruit, data after 3 and 7 days of ripening were also included for quality parameters.

For the preference test, a panel test of five trained persons (3 men and 2 women) evaluated the overall quality of each treatment (20 fruit each) after three weeks of storage followed by three days of subsequent ripening. The single criterion followed a 0 to 5 points scale (0 = poor; 1 = fair; 2 = acceptable; 3 = good; 4 = very good; 5 = excellent).

Statistical analysis

The experimental design was completely randomized. Each plastic box constituted a replicate. Given the factorial structure of the two cold storage treatments applied, an analysis of variance (ANOVA) and residual analysis (Little, 1981; Romero and Zúñiga, 1993) was performed for the quality parameters and juiciness of both maturity stages, according to the following statistical model:

$$Y_{(ijk)l} = \mu + t_i + IW_j + PR_k + t_i * IW_j + t_i * PR_k + IW_j * PR_k + t_i * IW_j * PR_k + \varepsilon_{(ijk)l}$$

where $Y_{(ijk)l}$ is the lth replicate or observation of the parameter measured ($l = 1, 2, 3$ or 4 for juiciness) of the ith time or t ($i = 0, 1, 2, 3, 4$, in weeks), jth IW ($j = 0, 1$) and additional post-storage ripening or PR ($k = 0,1$). Parameter μ is the mean effect, whereas ε is the error of the model's estimate. If significant differences were found, Student's least significant difference (LSD) test or orthogonal polynomial contrasts were performed (Little, 1981; Romero and Zúñiga, 1993; Artés and Escriche, 1994). The percentage of losses due to CI were statistically analyzed by converting values to their respective arcsin transformation (Romero and Zúñiga, 1993). For the preference test and CI losses, ANOVA was performed and the LSD test and Duncan's multiple range test, respectively, were calculated to compare means (Romero and Zúñiga, 1993).

Flesh firmness was statistically analyzed by converting original values to their respective logarithms (Romero and Zúñiga, 1993), due to lognormal distribution of flesh firmness observed in the normal probability plot. Data in the text are mean ± standard error (SE).

RESULTS

Physiological disorders

CI symptoms (woolliness with an slight browning of the pulp, vitreous texture and scald) did not appear until after two weeks of cold storage after a subsequent ripening period. Less mature peaches were more susceptible to these disorders (Table 1). IW almost totally prevented CI up to the third week of storage.

Senescence appeared as shrivelling after 7 days in N20 fruit (2.9% in FM fruit and 8.9% in FB fruit), and after one week plus three days of post-storage ripening (from 1.0 to 3.9%) in CS fruit. After the second week plus three days of post-storage ripening, moderate to severe symptoms of senescence affected 10 to 15% of CS and IW fruit of both maturity stages. IW exacerbated senescence symptoms (mainly softening, Fig. 1) in fruit stored for up to three weeks, this effect being more noticeable in FM fruit.

Table 1. Mean of chilling injury losses of peaches[a] after cold storage at 2°C and three days of subsequent ripening at 20°C

Maturity stage at harvest	Continuous storage (weeks)			Intermittent warming[b] (weeks)		
	2	3	4	2 cycles	3 cycles	4 cycles
Firm-mature	8.7b	64.5c	63.4c	0a	0a	3.0b
Firm-breaker	31.5c	80.1d	71.8d	1.0a	0.9a	6.3b

[a] Percent (w/w) on a fresh weight basis ($n = 96$ fruits). Mean separation within rows by Duncan's multiple range test ($p = 0.05$).
[b] Cycles of warming: 6 days at 2°C + 1 day at 20°C.

Respiratory activity and ethylene emission

Respiratory activity and C_2H_4 emission at harvest were 136 ± 11 nmol $CO_2\,kg^{-1}\,s^{-1}$ and 0.030 ± 0.003 nmol $C_2H_4\,kg^{-1}\,s^{-1}$ for FM fruit; and 129 ± 15 nmol $CO_2\,kg^{-1}\,s^{-1}$ and 0.027 ± 0.013 nmol $C_2H_4\,kg^{-1}\,s^{-1}$ for FB fruit. In both kinds of fruit, the climacteric peak was attained the 7th day after harvest (178 ± 16 nmol $CO_2\,kg^{-1}\,s^{-1}$ for FM and 204 ± 15 nmol $CO_2\,kg^{-1}\,s^{-1}$ for FB fruit). The maximum C_2H_4 emission occurred five days after the climacteric peak in FM fruit (0.646 ± 0.121 nmol $C_2H_4\,kg^{-1}\,s^{-1}$) but not in FB fruit (0.655 ± 0.134 nmol $C_2H_4\,kg^{-1}\,s^{-1}$ for FB). In spite of this, FM fruit showed 76% of maximum ethylene emission at the climacteric peak. The lack of coincidence between climacteric and maximum ethylene emission may be influenced by senescence.

Quality parameters

The highest percentages of variance explained (more than 95%) were recorded in firmness (also with significant effects) and in H* flesh color, while the lowest were obtained in H* ground color and juiciness in FM fruit (Tables 2 and 3). ANOVA analysis of TA showed a very different behavior for FM and FB fruit, making it difficult to suggest a possible relationship between CI and TA.

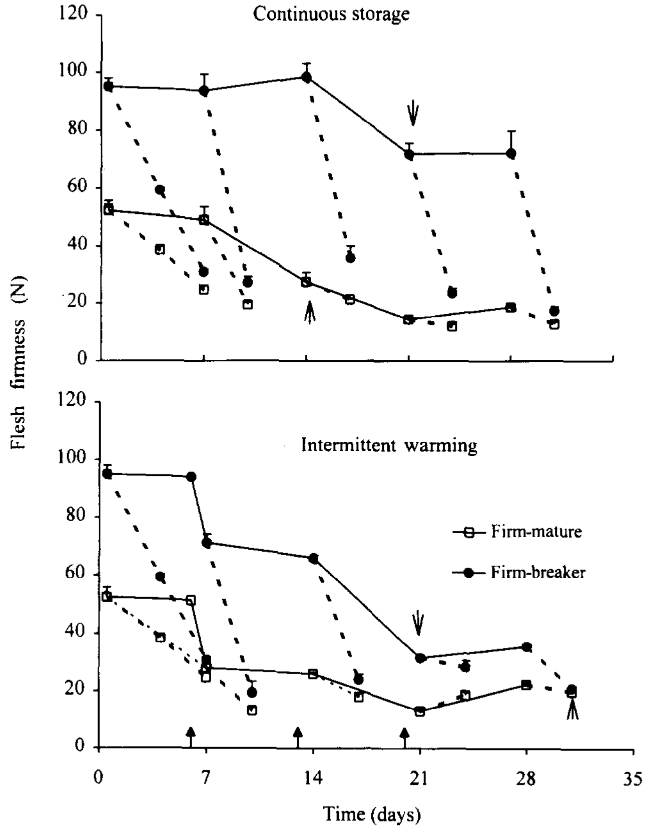

Fig. 1. Flesh firmness at harvest, during postharvest ripening at 20°C, conventional storage at 2°C, and intermittent warming (IW) storage (cycles of one day at 20°C every six days at 2°C) of peaches ($n = 15$). Dashed line represents ripening at 20°C. Error bars are the SE of the mean. Solid arrow represents IW and hollow arrow the onset of chilling injury.

Flesh firmness

This parameter linearly decreased in IW treatments at both maturity stages and in CS FM fruit (Fig. 1). However, CS FB fruit kept their firmness at harvest one week more than CS FM fruit. An excessive decrease in firmness (to less than 20 N) in CS and IW FM fruit after two weeks plus post-storage ripening was accompanied by symptoms of senescence.

Total soluble solids (TSS)

At harvest, the TSS of FM and FB peaches were 14.2 ± 0.2 °Brix and 13.3 ± 0.2 °Brix, respectively. In CS fruit, TSS slightly changed during storage to reach maximum values of 16.2 ± 0.2 °Brix and 14 ± 0.2 °Brix in FM and FB fruit during the third and fourth week of storage, respectively. During the post-storage ripening of CS FM fruit, TSS increased 1.6 and 0.9 units only in the first and the second post-storage period, while the values always increased in FB fruit (about 1.2 units). In IW fruit, a maximum of 16.3 ± 0.2 °Brix and 14.0 ± 0.5 °Brix was attained after the second warming (FM fruit) or the third warming (FB fruit). After the second ripening period, only minor changes were detected.

Titratable acidity (TA)

In CS and IW fruit of both maturity stages, TA decreased during storage, the less mature fruit always being more acid. After the first warming, TA was higher than 22.4 meq l^{-1} malic acid, and remained so thereafter (Fig. 2, Table 2). The lower TA in CS FM fruit than in IW fruit could be associated with CI.

TSS/TA ratio (maturity index)

A maximum value of this ratio was detected after the second week of storage in IW FM fruit, but an additional post-storage ripening was required for CS FM peaches to reach a similar level (Fig. 3, Table 2). FB fruit did not attain this level in either IW or CS treatments. The continuous increase of this index in CS fruit with abnormally high values after the third week of storage in both ripening stages, could be related with a strong CI development.

Ground and flesh color

IW enhanced ground and flesh color of both FB and FM peaches (Figs 4 and 5, Table 3). With regards to the decrease in H* ground color, the main effect of IW was evident after the first warming in FM fruit and after the third warming in FB fruit. The main effect of CI on color changes was detected in the flesh color of CS fruit after the second (FM) or the third (FB) week of storage. For H* ground color, the concomitant depletion of H* and the onset of CI was more noticeable in CS FM fruit.

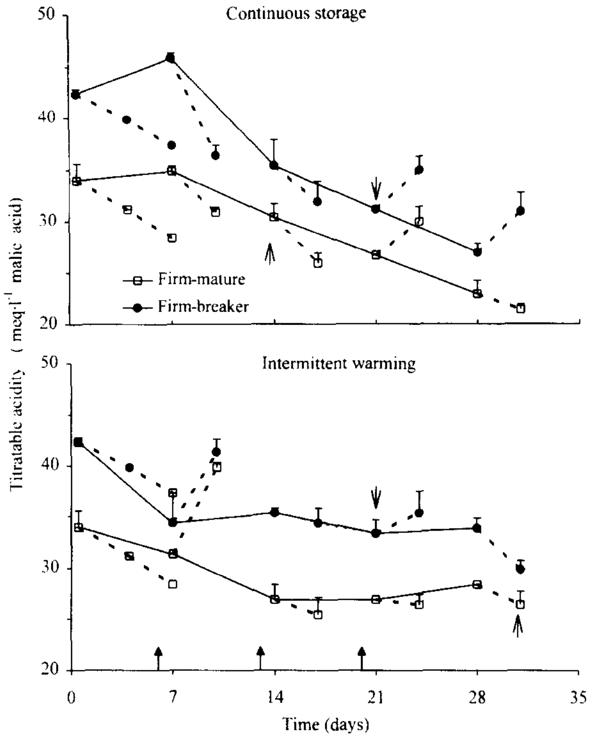

Fig. 2. Titratable acidity at harvest, during postharvest ripening at 20°C, conventional storage at 2°C, and intermittent warming (IW) storage (cycles of one day at 20°C every six days at 2°C) of peaches ($n=3$). Dashed line represents ripening at 20°C. Error bars are the SE of the mean. Solid arrow represents IW and hollow arrow the onset of chilling injury.

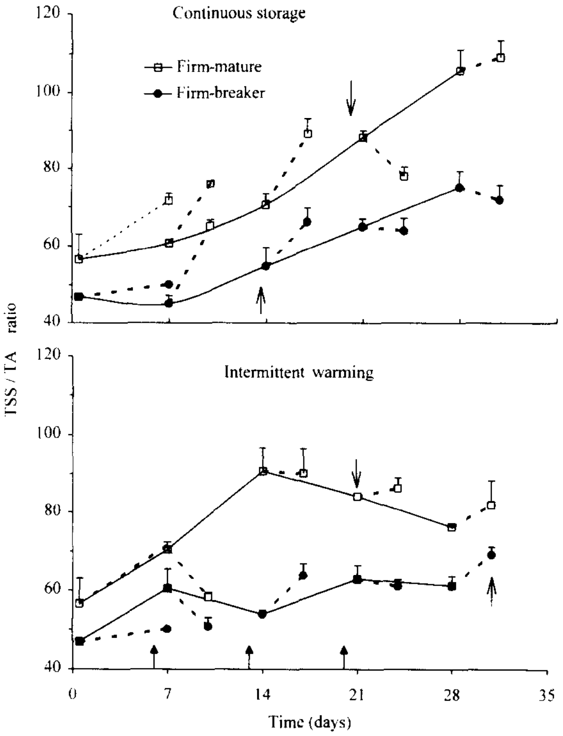

Fig. 3. Soluble solids content/titratable acidity (TSS/TA) at harvest, during postharvest ripening at 20°C, conventional storage at 2°C, and intermittent warming (IW) storage (cycles of one day at 20°C every six days at 2°C) of peaches ($n=3$). Dashed line represents ripening at 20°C. Error bars are the SE of the mean. Solid arrow represents IW and hollow arrow the onset of chilling injury.

Due to the color changes described, a* and b* parameters were separately analyzed. In CS fruit suffering CI, the main effect in the flesh (measured after four weeks at 2°C) was a increase in a* values (about 8.2 ± 0.7 units of increase compared to −7.2 ± 0.5 and −10.5 ± 0.7 at harvest, for FM and FB peaches, respectively) and a decrease in b* values (about 32% compared to b* values at harvest of 21.1 ± 0.8. and 25.7 ± 1.1, for FM and FB peaches, respectively). a* ground parameter also increased as a response to CI, but this effect was more noticeable in FM fruit (from −3.1 ± 1.5 at harvest to 9.4 ± 1.7 after four weeks at 2°C) than in FB fruit (from −6.3 ± 0.9 at harvest to 5.6 ± 0.6 after four weeks at 2°C).

Table 2. Analysis of variance of the significance in chemical quality parameter changes during four weeks of stoage at 2°C of firm-mature (FM) and the firm-breaker (FB) peaches with or without 3 days of post-storage ripening at 20°C

Source	df[a]	Titratable acidity				Maturity index[d]			
		FM		FB		FM		FB	
		SS[b]	*P*[c]	SS	*P*	SS	*P*	SS	*P*
Time *linear (l)*	1	49.4	***	56.6	***	54.5	****	54.9	****
Deviation from l	3	13.3	***	3.3	n.s.	5.4	***	1.0	n.s.
IW[e]	1	0.9	n.s.	0.2	n.s.	1.5	*	1.5	n.s.
PR[f]	1	0.7	n.s.	0.2	n.s.	1.4	*	3.6	**
Time×IW	4	9.4	****	4.0	n.s.	16.9	****	2.6	n.s.
Time×PR	4	5.4	**	3.4	n.s.	2.1	n.s.	4.3	n.s.
IW×PR	1	1.6	*	0.7	n.s.	1.0	n.s.	1.1	n.s.
Time×IW×PR	4	9.2	****	15.2	****	5.2	***	12.2	***
Residual	40	10.1		16.2		11.9		18.8	
% explained	59	89.9		83.8		88.1		81.2	

[a] Degrees of freedom.
[b] Sum of squares in percentage of the total.
[c] Probability: n.s. not significant. *, **, ***, **** significant at $p=0.05$, 0.01, 0.001 or 0.0001, respectively.
[d] Total soluble solids/titratable acidity.
[e] IW: Intermittent warming of 1 day at 20°C every 6 days at 2°C.
[f] PR: Post-storage ripening (3 days at 20°C and 70–75% RH).

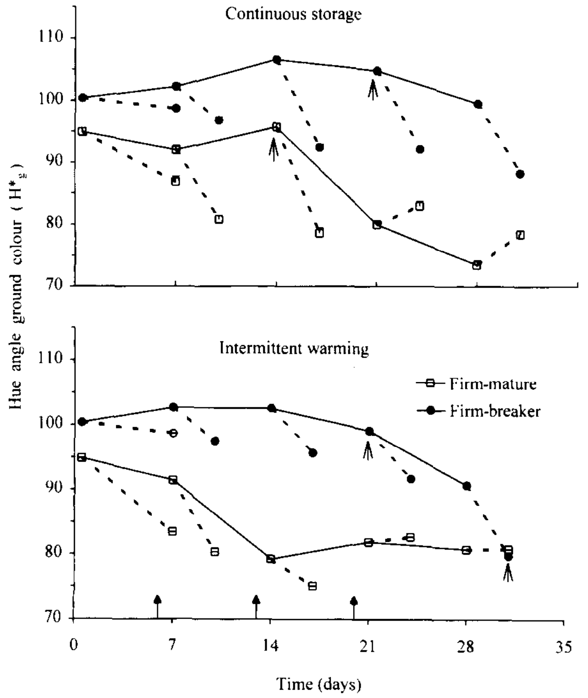

Fig. 4. Ground color (Hue angle $-H^*_g-$) at harvest, during postharvest ripening at 20°C, conventional storage at 2°C, and intermittent warming (IW) storage (cycles of one day at 20°C every six days at 2°C) of firm-mature and firm-breaker peaches ($n = 15$). Dashed line represents ripening at 20°C. Error bars are the SE of the mean. Solid arrow represents IW and hollow arrow the onset of chilling injury.

The anomalous behavior of a* values in the flesh could be related with the translucity of the skin and a slight browning caused by the development of scald in the sub-epidermal tissue near the skin. On the other hand, the changes in the color parameters of the flesh could be associated to a slight browning associated to woolliness. To a lesser extent, these pathways could be attributable to the very slow ripening at 2°C as has been reported for other cultivars at 5 and 0°C (Robertson *et al.*, 1990).

Juiciness

IW peaches were more juicy than CS fruit although IW reduced juiciness to values similar to those observed in N20 fruit. However, these levels were always higher than those of CS fruit of the same ripening stage (Fig. 6, Table 3). FB peaches suffer significant loss in their juiciness after two weeks of storage concomitantly with the onset of CI, while this reduction was less remarkable in FM peaches.

Preference tests

In general, IW fruit were preferred by the test panel for flesh and ground color, flavor and juiciness. However, FM IW fruit were preferred to FB IW fruit by all panelists for their flavor in spite of any softening (score of 4.3 and 3.8, LSD = 0.4, $p = 0.05$, respectively). Both CS fruit were rejected mainly due to dryness and, to a lesser extent, due to the slight flesh browning provoked by CI (score of 1 to 2). Flesh softening of FM fruit with or without IW (around 20 N) was associated with juiciness and it should be remembered that 'Paraguayo' peaches are normally consumed when they are very ripe (i.e. nearly senescent).

DISCUSSION

Trends during ripening and maturity indices

The behavior of the quality parameters during normal ripening of 'Paraguayo' peaches agrees with general trends reported in other cultivars (Kader *et al.*, 1982;

Table 3. Analysis of variance of the significance in physical quality parameter changes during four weeks of storage at 2°C of firm-mature (FM) and firm-breaker (FB) peaches with or without 3 days of post-storage ripening at 20°C

Source	df[a]	Flesh firmness				Ground color (H^*_g)[g]				Flesh color (H^*_f)[g]				Juiciness			
		FM		FB		FM		FB		FM		FB		FM		FB	
		SS[b]	P[c]	SS	P	SS	P	SS	P	SS	P	SS	P	SS	P	SS	P
Time *linear (l)*	1	30.4	****	20.6	****	34.2	****	25.1	****	74.2	****	57.5	****	0.2	n.s.	11.7	****
Deviation from l	3	9.4	***	6.8	***	3.1	n.s.	9.8	*	7.1	****	10.7	****	24.7	****	6.4	***
IW[d]	1	2.4	***	5.6	****	0.2	n.s	2.9	**	0.6	**	0.1	n.s	0.9	n.s.	4.7	****
PR[e]	1	22.5	****	50.2	****	7.6	**	32.8	****	9.2	****	22.3	****	9.8	****	31.8	****
Time×IW	4	8.7	****	1.7	***	10.1	*	6.7	***	2.1	****	0.3	n.s.	13.1	****	4.9	***
Time×PR	4	4.1	****	4.6	****	12.7	**	8.6	***	0.4	n.s.	1.9	****	22.6	****	16.9	****
IW×PR	1	4.9	****	3.3	****	0.2	n.s.	1.0	n.s.	0.8	***	1.6	****	0.2	n.s.	6.8	****
Time×IW×PR	4	14.0	****	3.5	****	4.0	n.s.	1.3	n.s.	0.6	n.s.	2.2	****	3.2	n.s.	4.0	**
Residual	40[f]	3.6		3.6		28.0		11.7		4.9		3.4		25.4		12.9	
% explained	59[f]	96.4		96.4		72.0		88.3			95.1		96.6		74.6		87.1

[a] Degrees of freedom.
[b] Sum of sqaures in percentage of the total.
[c] Probability: n.s. not significant. *, **, ***, **** significant at $p = 0.05$, 0.01, 0.001 or 0.0001, respectively.
[d] IW: Intermittent warming of 1 day at 20°C every 6 days at 2°C.
[e] PR: Post-storage ripening (3 days at 20°C and 70–75% RH).
[f] % explained and residual df were: for H^*_f, 99 and 80 respectively; for juiciness, 60 and 79 respectively.
[g] Hue angle.

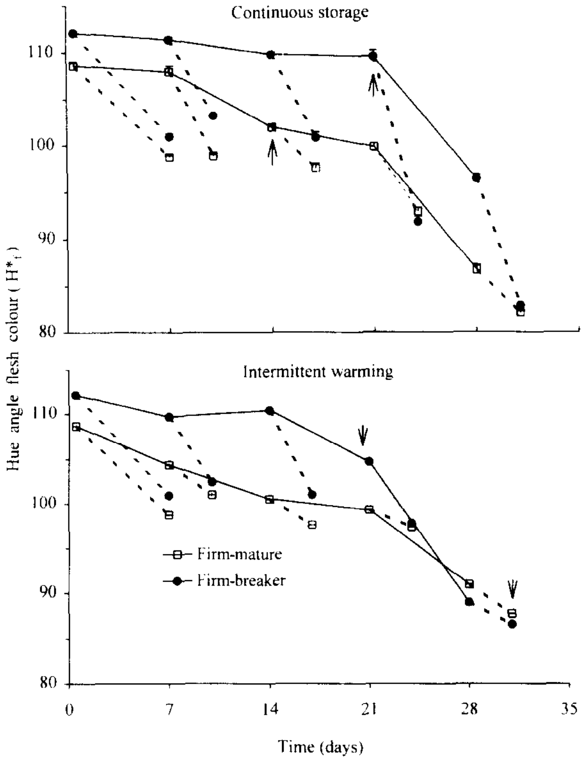

Fig. 5. Flesh color (Hue angle $-H^*_f-$) at harvest, during postharvest ripening at 20°C, conventional storage at 2°C, and intermittent warming (IW) storage (cycles of one day at 20°C every six days at 2°C) of firm-mature and firm-breaker peaches ($n = 15$). Dashed line represents ripening at 20°C. Error bars are the SE of the mean. Solid arrow represents IW and hollow arrow the onset of chilling injury.

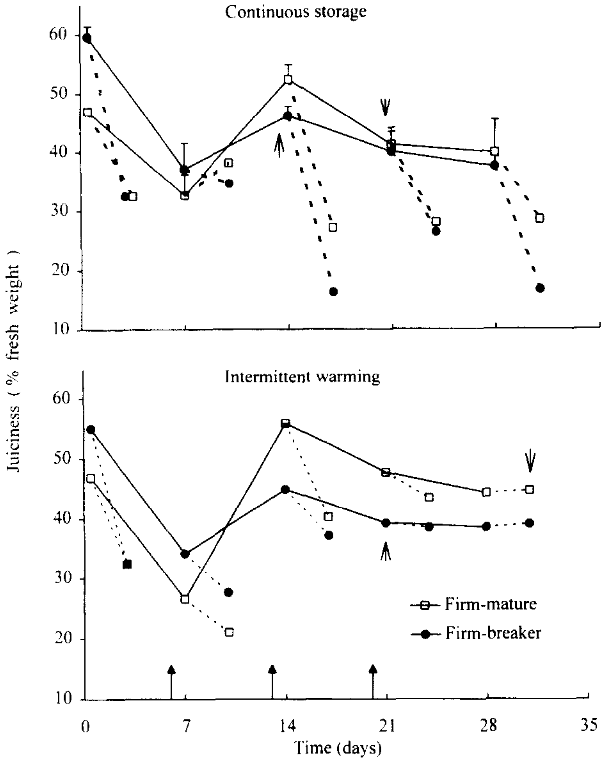

Fig. 6. Juiciness at harvest, during postharvest ripening at 20°C, conventional storage at 2°C, and intermittent warming (IW) storage (cycles of one day at 20°C every six days at 2°C) of firm-mature and firm-breaker peaches ($n = 4$). Dashed line represents ripening at 20°C. Error bars are the SE of the mean. Solid arrow represents IW and hollow arrow the onset of chilling injury.

Artés *et al.*, 1989; Lill *et al.*, 1989; Meredith *et al.*, 1989; Thai and Shewfelt, 1990; Ravaglia *et al.*, 1996).

Flesh firmness alone or in combination with H* ground color was, in general, a satisfactory maturity index. The TSS/TA ratio was found to be more closely related to quality than TA or TSS alone. Hue angle was useful for separating samples of recommended maturity from the immature stages at harvest in agreement with Shewfelt *et al.* (1987*a*). The predominance of a linear trend during storage in H* ground and flesh color (Table 2) agrees with previous results reported during ripening (Thai and Shewfelt, 1990, 1991; Villalobos and Mercado, 1995; Ravaglia *et al.*, 1996).

Trends during cold storage

The reduction of TA induced by the first warming and its maintenance thereafter is well related with the slight reduction in TA observed in ripe peaches subjected to normal handling step (Shewfelt *et al.*, 1987*a*). The significant decreases in TA and H* ground and flesh color, and the increase in the maturity index at 2°C agree in general with Robertson *et al.* (1990) at 0°C, who did not report CI, but suggested a probable deterioration after four weeks of storage.

In addition, the maintenance of higher TA values in IW fruit than in CS fruit after transfer to post-storage ripening after four weeks confirms results showed by Anderson (1979).

CI and quality parameters

The inhibition or alleviation by IW of CI during storage of both kinds of preclimacteric fruit agrees with the general beneficial effects described for this treatment (Anderson, 1979; Lyons and Breidenbach, 1987; Artés *et al.*, 1989, 1996; Lill *et al.*, 1989; Dawson *et al.*, 1995).

In general, the high incidence of CI is associated with an abnormal reduction in H* ground and flesh color (affecting a* and/or b* co-ordinates), high maturity index and very reduced TA. The effect of low temperature storage with or without CI on both maturity stages was studied by trends analysis of the quality parameters studied. The differences obtained for both kinds of fruit depending on whether or not they were subjected to IW and/or a period of post-storage ripening (reflected by statistical analysis, Tables 2 and 3) were well correlated with the differences in the onset of woolliness because IW generally reduced this disorder. In fact, time ×IW×PR interaction and/or time×IW interactions were always significant.

The behavior of the H* ground and flesh color parameters were very similar to firmness and consequently this index could be used as an index of 'early fruit maturity'. However, when symptoms of pulp browning appear, the H* parameter should not be used because of interferences between normal and abnormal ripening. After pulp browning occurs, the mechanism for carotene synthesis could be affected by low temperatures and/or modified by the onset of CI, resulting in an abnormal ripening.

The abnormally higher TSS/TA of CS fruit reached after the second week of storage could be associated with an abnormal ripening of the fruits as a consequence of excessive acid consumption. It has been described in the cultivar 'J. H. Hale' that when the TSS/TA exceeded 50% the values of normal ripening, woolliness appeared (Crivelli, 1963).

In N20 fruit, flesh firmness decreased linearly, in agreement with the exclusively linear decrease obtained in other cultivars (Thai and Shewfelt, 1990; Ravaglia *et al.*, 1996). In CS fruit, depending on maturity at harvest, softening associated with ripening was inhibited for 1 or 2 weeks at 2°C, while in other cultivars stored at 5°C this was not the case (Shewfelt *et al.*, 1987*b*). The coincidence between the onset of CI and a sudden decrease in flesh firmness in CS fruit and even in FB IW fruit (although masked by the warming effect), agrees with that reported in other cultivars by von Mollendorff and De Villiers (1988). These changes, which are first related to ripening and later to CI, confirm results from Luza *et al.* (1992), who indicate that the changes are related to the loosening of cell walls, loss of wall cohesion, development of an intercellular matrix with soluble carbohydrates and pectins, and apparent cell wall synthesis.

In fact, the slight browning of the pulp (roughly reflected by H* flesh color of CS fruit) could be associated with substrate and enzyme being mutually accessible due to cell wall deterioration caused by CI. In particular polyphenol oxidase activity is active in peaches even at 3°C (Jen and Kahler, 1974).

Although the find levels of peach firmness after storage are strongly dependent on maturity at harvest and other factors (Shewfelt *et al.*, 1987*a*,*b*), the effect of CI during storage on chilling-sensitive peaches should be carefully considered in postharvest studies.

The mechanism involving CI development in 'Paraguayo' could be related to an imbalance between polygalacturonase (PG) and pectinmethylesterase (PME) activities during storage (Ben-Arie and Sonego, 1980; Artés *et al.*, 1996), that would provoke a decrease in firmness concomitantly with CI. The PG in FB and FM fruit was composed of two isoenzymes (endo and exo PG) which was detected during ripening 'Paraguayo' peach (A. Cano, pers. comm.). Softening in ripening peaches is attributed to solubilization of protopectin resulting from PG activity (Pressey and Avants, 1978; Shewfelt *et al.*, 1987*b*). On the contrary, mealy nectarines ripened after cold storage show limited solubilization of pectins and depolymerization, and predominance of high relative molecular weight polymers (Dawson *et al.*, 1995). After transfer to room temperature, PG probably increase sharply to similar levels to those shown by sound fruit (von Mollendorff *et al.*, 1988), because after 3 or 4 weeks at 2°C plus three days of post-storage ripening the firmness of our CS fruit was about 7 N and 4 N less than in IW FM and FB fruit, respectively. In other peach cultivars of hard mesocarp texture, the softening of the fruit is delayed during ripening as a result of the deterioration of PG and high PME enzyme activities after two weeks at 0°C (Ben-Arie *et al.*, 1989; Artés *et al.*, 1996). During ripening nectarine fruits, after storage, pectic polymer solubilization is not as extensive in intermittently warmed fruits as in those undergoing normal ripening (Dawson *et al.*, 1995).

On the other hand, strong evidence has been found involving PME in peach and tomato softening related to CI during storage (Marangoni *et al.*, 1995; Artés *et al.*, 1996). Differences in the textural characteristics of freestone and clingstone peaches, due to differences in the enzymes involved in the transformation of insoluble pectins into soluble pectins (Pressey and Avants, 1978), could explain the differences between 'Paraguayo' and the results with other cultivars. Preliminary genetic evidence suggests that the structure of the endoPG gene differed between melting flesh and non-melting flesh cultivars (Lester *et al.*, 1994). Moreover, further correlation between the absence of endoPG activity and the NMF phenotype has been found (Lester *et al.* 1996). The fact that endo-PG activity is damaged during storage as CI develops in a clingstone cultivar (Artés *et al.*, 1996), the gradient of internal flesh firmness and ethylene biosynthesis in some freestone cultivars (Tonutti *et al.*, 1996), the different ethylene emission rates between cultivars and particularly between melting and non-melting type peaches (Biggs *et al.* 1982; Klozenbucher *et al.* 1994), suggest that other biochemical pathways and a possible gradient of PG or other enzyme activities might play a role in the onset of CI in peaches.

Technological aspects of IW

In spite of the benefits to be gained from using IW with FM fruit, a low temperature storage for more than about two weeks cannot be recommended because of the development of softening (to around 20 N) and senescence after post-storage ripening. From a technological point of view, this reduced flesh firmness, which is normally associated to juicy and mature peaches, is not a serious inconvenience for consumers providing the fruit is free from fungal attack and senescence. According to our results, the best quality for 'Paraguayo' peaches is at a flesh firmness of no more than 45 N after storage, a background color with positive a* values (yellow to yellow-orange), and fruit free from woolliness and other CI symptoms. The H* ground color of this cultivar picked in FM stage should be about 70 to 85 for optimum quality, while FB peaches only reach their maximum potential H* ground color (around 90 to 95) if they are subjected to post-storage ripening after 3 or 4 weeks of IW storage.

IW could be optimized to extend shelf-life of FM or FB fruit. IW storage of FB fruit was adequate to enhance ripening (a commercial flesh firmness of around 20 to 30 N and a change in color from green to yellow), and to extend its shelf-life without excessive CI. The improvement in peach quality by IW can be achieved within the existing handling system by a convenient control of harvest maturity. In order to extend the shelf life of peaches in the consumer's own home, the subsequent ripening step after storage is not advisable.

CONCLUSIONS

In summary, intermittent warming appears to allow chilled fruit to acclimatize to subsequent periods of chilling by allowing a controlled and gradual ripening of the fruits. Although several quality and/or maturity index parameters are affected by the onset of CI, they were not able to predict early or reversible symptoms of CI.

Due to softening, IW 'Paraguayo' peaches did not need a post-storage ripening period. IW fruit were preferred by panelists for their freedom from CI and overall quality. Although additional technological and physiological studies should emphasize quality and maturity indices based on consumer acceptance, the specific problem of CI (woolliness) in melting mid-season peaches must be considered.

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