Effect of 1-methylcyclopropene on ripening of 'Canino' apricots and 'Royal Ze' plums

Article *in* Postharvest Biology and Technology · March 2002

Impact Factor: 2.22 · DOI: 10.1016/S0925-5214(01)00130-2

3 authors, including:

Susan Lurie
Agricultural Research Organization ARO
233 PUBLICATIONS **6,359** CITATIONS

SEE PROFILE

ELSEVIER

Postharvest Biology and Technology 24 (2002) 135–145

Postharvest Biology and Technology

www.elsevier.com/locate/postharvbio

Effect of 1-methylcyclopropene on ripening of 'Canino' apricots and 'Royal Zee' plums

Li Dong [1], Susan Lurie *, Hong-Wei Zhou

Department of Postharvest Science, The Volcani Center, ARO, P.O. Box 6, Bet Dagan, 50250, Israel

Received 16 November 2000; accepted 11 May 2001

Abstract

'Canino' apricots and 'Royal Zee' plums were treated with 1000 nl l^{-1} 1-methylcyclopropene (1-MCP) at 20 °C for 20 h following harvest before 0 °C storage. After 5 days storage for apricots and 10 days for plums and after 30 days storage for both, fruit were moved to 20 °C for ripening. In addition, apricots were stored for 20 days and then treated with 1-MCP concentrations of 10, 100 and 1000 nl l^{-1} at removal and held for ripening. Ethylene production and respiration rate, as well as fruit quality of apricots varied with treatment. Ethylene production was efficiently inhibited by 1000 nl l^{-1} 1-MCP in fruit treated after storage but not in fruit treated before storage. Fruit softening was associated with ethylene production and affected by 1-MCP in a concentration dependent manner when treated after storage, while 1-MCP did not affect softening in prestorage treated fruit. The color change of fruit was ethylene-independent and not affected by 1-MCP. Internal flesh browning was decreased by 1-MCP regardless of the concentration when treated after storage, while it was enhanced in fruit treated before storage. Decay development in apricots was decreased by 1-MCP in a concentration dependent manner. Ethylene production and respiration in 'Royal Zee' plums was greatly inhibited by 1-MCP during ripening after both short-term (10 day) and long term (30 day) storage. Parameters associated with ripening processes were decreased significantly by 1-MCP, including softening, color change, and loss of titratable acidity. These data demonstrate that 1-MCP has potential to delay ripening of apricots and plums, but the cultivar, maturity of fruit, and time of application must be chosen carefully. It is suggested that 1-MCP is more efficient for extending the shelf life and improving the quality of 'Canino' apricots directly marketed or after storage, whereas it might be a potent compound for extending both storage period and shelf life of 'Royal Zee' plums.

Keywords: Ethylene; 1-Methylcyclopropene; *Prunus armeniaca*; *Prunus salicina*; Ripening; Ethylene

1. Introduction

Apricots and plums are stonefruit, which have a limited postharvest life. Both fruit are climacteric and undergo rapid ripening, including softening. The fruit are picked at a preclimacteric stage in order to be firm enough to withstand packing-

* Corresponding author. Tel.: +972-3-9683606; fax: +972-3-9683622.

E-mail address: zeslov@netvision.net.il (S. Lurie).

[1] Present address: Department of Landscape Architecture, Beijing Forestry University, 35 Qinghua Dong Road, Haidian District, Beijing 100083, PR China.

0925-5214/02/$ - see front matter
PII: S0925-5214(01)00130-2

house handling and marketing. In many cases this fruit does not reach full flavor and aroma after harvest. A treatment to inhibit the rapid softening after harvest would allow harvest to be delayed and for the fruit to be harvested at a tree-ripe stage.

Apricots can be divided into three groups according to low, medium and high levels of ethylene production (Manolopoulou and Mallidis, 1999). 'Canino' apricots fall into the medium ethylene producing category. Ethylene emission in apricots starts relatively early and autocatalytic production may begin before other ripeness parameters are well advanced. Plums can be divided into two groups according to their respiration and ethylene production (Abdi et al., 1997). Some cultivars show ripening patterns typical of climacteric fruit with a distinct rise in ethylene and CO_2 production. 'Royal Zee' falls into this category. Others show a suppressed climacteric wherein ethylene production increases very late in the ripening process (Abdi et al., 1997; Dong et al., 2001a).

Ethylene is known to trigger many, though not all, aspects of fruit ripening. Fruit softening is partially controlled by ethylene, and exogenous ethylene or propylene cause faster softening. In addition, within a fruit species such as plum, high ethylene producers will soften and ripen faster than low ethylene producers (Abdi et al., 1997, 1998). Ethylene inhibitors might be expected to have a greater effect on ripening of medium and high ethylene producing cultivars than on low and suppressed-climacteric cultivars.

Apricots and plums are stored at 0 °C to slow the ripening process, but are limited to a few weeks of storage, because of the appearance of storage disorders. Apricots and plums develop two main types of physiological storage disorders, internal browning and gel breakdown (Taylor et al., 1993a,b, 1994; Jooste and Taylor, 1999). Internal browning manifests itself as a browning of the flesh due to the enzymic oxidation of polyphenols and tannins (Dodd, 1984). Gel breakdown is a gelatinous appearance of the flesh occurring near the fruit pit. It is thought to be due to an unbalanced activity of cell wall hydrolytic enzymes, which leads to the accumulation of unmethylated high molecular weight pectins that have the ability to bind extracellular juice (Ben-Arie and Sonego, 1980; Zhou et al., 2000).

Removing ethylene from storage rooms is generally beneficial in maintaining fruit quality and extending storage. However, peaches and nectarines were found to benefit from the presence of ethylene during storage (Sonego et al., 1999; Zhou et al., 2001). Ethylene did not cause the fruit to soften during storage, but did maintain its ability to ripen normally after storage, thereby preventing gel breakdown. Therefore, inhibitors of ethylene may have detrimental effects on stonefruit during storage.

The ethylene action inhibitor 1-methylcyclopropene (1-MCP) (Sisler and Serek, 1997), has been shown to delay ripening and improve post-storage quality of climacteric fruit (Abdi et al., 1998; Golding et al., 1998; Fan et al., 1999a,b, 2000). The present study was performed to characterize the physiological responses of 'Canino' apricots and 'Royal Zee' plums to 1-MCP treatment and to examine if 1-MCP will enable the extension of the storage period or shelf life of these two fruit, in addition to shedding light on the role of ethylene in the ripening process.

2. Materials and methods

2.1. Plant material and treatment

'Canino' apricots and 'Royal Zee' plums were harvested from a commercial orchard in Israel. Harvest was according to peel color and size. 'Canino' apricots still had some green color at the suture, while 'Royal Zee' plums did not have a full red cover of the peel. Treatments were conducted as follows. (1) Following harvest, fruit were incubated with 1000 nl l^{-1} 1-MCP at 20 °C for 20 h, then stored at 0 °C together with untreated (control) fruit. Apricots and plums were removed after 5 and 10 days operative storage, respectively, and at the end of 30 days storage, kept at 20 °C for ripening. Ethylene production and respiration rates were followed during ripening. Firmness, color change, soluble solids content (SSC) and titratable acidity (TA) were determined

during and/or after ripening. Fruit were halved for quality evaluation at the end of shelf life. (2) Fruit of apricot from the same harvest were stored immediately for 20 days at 0 °C. Then fruit still having a greenish–yellow color at the suture were chosen for 1-MCP treatment with concentrations of 0 (control), 10, 100, 1000 nl l^{-1} at 20 °C for 20 h. Following treatment, fruit were held at 20 °C for ripening. Firmness was determined at 4 days of ripening, and color change and fruit quality were checked after 6 days of ripening.

2.2. Application of 1-MCP

Fruit were enclosed in 15 l glass jars. 1-MCP was obtained from Biotechnologies for Horticulture, Inc. as a commercial powder (EthylBloc) and prepared as a 500 μl l^{-1} concentrated stock in a 1 l sealed bottle. 1-MCP was released from 357 mg of powder (0.14% a.i.) to the vapour phase by adding 10 ml of 1% KOH. The required concentrations of 1-MCP were obtained by injecting 30, 3 or 0.3 ml for 1000, 100 or 10 nl l^{-1}, respectively, of the stock into the jars via a port on the cover.

2.3. Ethylene production and respiration rate determination

Five pairs of fruit (two fruit per jar) from each treatment were enclosed in 600 ml airtight jars for 1 h at 20 °C, then a 5 ml gas sample was taken and injected into gas chromatographs with FID and TDC detectors, respectively, for ethylene and CO_2 detection.

2.4. Firmness, soluble solids content (SSC) and titratable acidity (TA) measurement

Firmness was measured on the opposite pared cheeks of each fruit with a penetrometer (Hunter Spring, Hatfield, PA) incorporating a 8 mm diameter probe. At least 30 fruit were measured for each treatment.

A wedge-shaped slice of flesh was taken from each fruit, ten fruit wedges were pooled and juiced. SSC was determined by a digital refractometer (Atago, Tokyo, Japan), and TA by titration of 2 ml juice with 0.1 N NaOH and expressed as % (W/V) malic acid.

2.5. Color assessment

Thirty fruit from each treatment were used for color measurement. For apricots, the color was measured on the opposite pared cheeks along their equatorial axes, and for plums, on the cheek of the redder side of the fruit, using a Minolta Chromo Meter, model CR-200. The parameters of '*a*' and '*b*' were measured and the final results were expressed as hue angle ($h°$) according to McGuire (1992).

2.6. Internal quality evaluation

At the end of shelf life, fruit were halved and estimated visually for decay and storage disorders. Decay was recorded as percentage of rotten fruit. The severity of storage disorders was evaluated as an index as follows: ((% fruit with slight disorder $\times 1$) + (% fruit with medium disorder $\times 2$) + (% fruit with severe disorder $\times 4$))/4. At least 70 apricot fruit and 40 plum fruit in each treatment were used for quality evaluation.

3. Results

3.1. Ethylene production

In 'Canino' apricots, ethylene production increased rapidly over 7 days ripening, when fruit were removed from storage after 5 days (Fig. 1A). Ethylene production was much lower during ripening following 30 days of storage (Fig. 1B). The effect of 1-MCP was different between the two storage periods. Following 5 days storage, ethylene evolution was not affected by 1-MCP for the first 4 days of ripening, though it began to be inhibited later on, whereas it was slightly enhanced by 1-MCP after 30 days storage. Fruit treated with 1-MCP after 20 days storage and then ripened at 20 °C had a higher initial ethylene production at 1 day of ripening, tenfold higher than in fruit subjected to 5 or 30 days storage after treatment. Ethylene production in 1000 nl

l^{-1} 1-MCP-treated fruit was greatly inhibited during the first 4 days of ripening, while no differences were found between control fruit and the two treatments with lower concentrations of 1-MCP (Fig. 1C).

'Royal Zee' plums showed a typical pattern of ethylene production and a much higher level of ethylene during ripening than apricots (Fig. 2). Ethylene production in control fruit increased rapidly and reached a peak at 5 days of ripening, both after 10 or 30 days storage. With extension

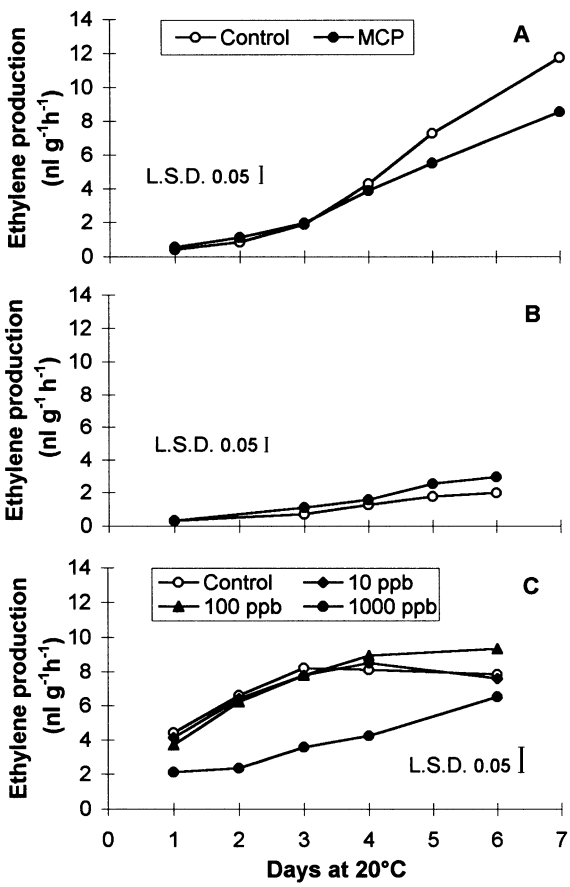

Fig. 1. Ethylene production of 'Canino' apricot during ripening at 20 °C. (A) After 5 days storage at 0 °C following treatment with 1000 nl l^{-1} 1-MCP at harvest; (B) After 30 days storage at 0 °C following treatment with 1000 nl l^{-1} 1-MCP at harvest; (C) Ripened directly after treatment of different concentrations of 1-MCP following 20 days storage at 0 °C. Data were means of five replicates with two fruit each. LSD represents the least significant difference at 5% level of Duncan's multiple range test.

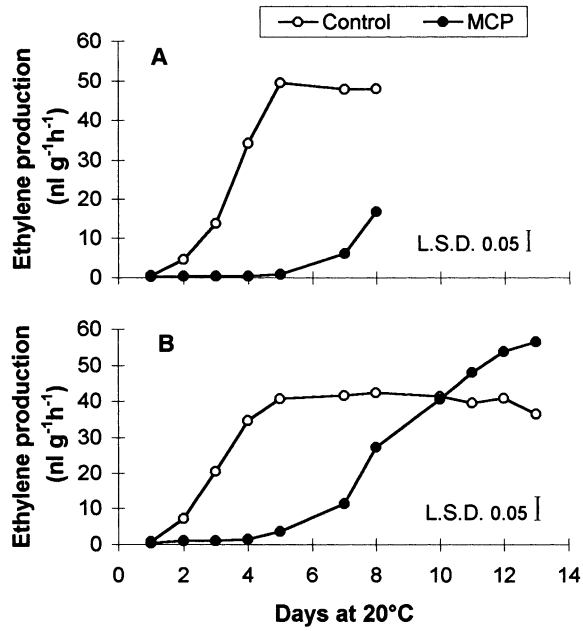

Fig. 2. Ethylene production of 'Royal Zee' plum during ripening at 20 °C. (A) After 10 days storage at 0 °C following treatment with 1000 nl l^{-1} 1-MCP at harvest; (B) After 30 days storage at 0 °C following treatment with 1000 nl l^{-1} 1-MCP at harvest. Data were means of five replicates with two fruit each. LSD represents the least significant difference at 5% level of Duncan's multiple range test.

of storage, the magnitude of the ethylene climacteric was slightly decreased. 1-MCP not only delayed the onset of the ethylene climacteric, but also enhanced its magnitude, which was shown clearly after 30 days storage when observation was prolonged to 13 days (Fig. 2B). The ethylene production was inhibited dramatically by 1-MCP, irrespective of storage duration. At 5 days of ripening, ethylene production in 1-MCP-treated fruit was inhibited to about 2 and 10% of that in control fruit, after 10 and 30 days storage respectively (Fig. 2A and B).

3.2. Respiration rate

Following 5 days storage of apricots, the respiration rate was quite even and not affected by 1-MCP over 7 days ripening. Nor was an appreciable effect of 1-MCP found after 30 days storage (Fig. 3A and B). The respiration rate in

apricots treated after 20 days storage showed a similar pattern with little climacteric rise and with no effect of the 1-MCP on respiration (data not shown).

The respiration rate of 'Royal Zee' plums, which also peaked at 5 days ripening, corresponded very well to their ethylene production, irrespective of storage duration (Fig. 4). With extension of storage, the magnitude of the climacteric was slightly lower in control fruit. 1-MCP delayed the onset of the respiratory climacteric and inhibited considerably the preclimacteric respiration rate, following both storage durations, although it did not affect the magnitude of the respiration rate (Fig. 4A and B).

3.3. Softening

'Canino' apricots soften very quickly during ripening. In fruit stored for 5 days, firmness decreased from 37 to 5 N during 5 days of ripening.

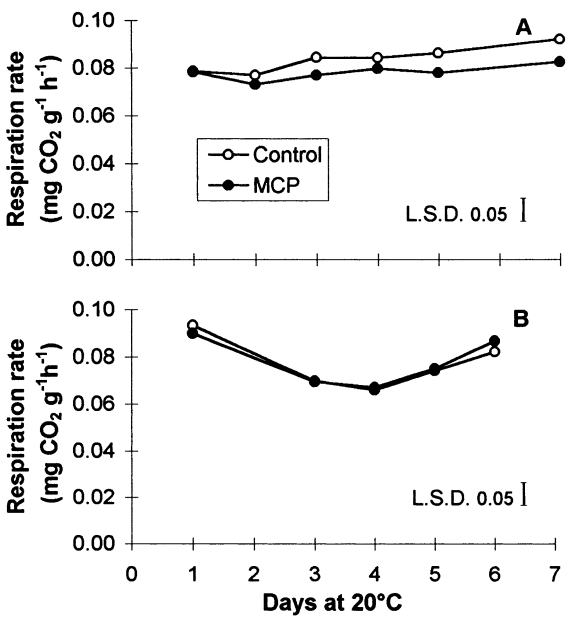

Fig. 3. Respiration rate of 'Canino' apricot during ripening at 20 °C. (A) After 5 days storage at 0 °C following treatment with 1000 nl l^{-1} 1-MCP at harvest; (B) After 30 days storage at 0 °C following treatment with 1000 nl l^{-1} 1-MCP at harvest. Data were means of five replicates with two fruit each. LSD represents the least significant difference at 5% level of Duncan's multiple range test.

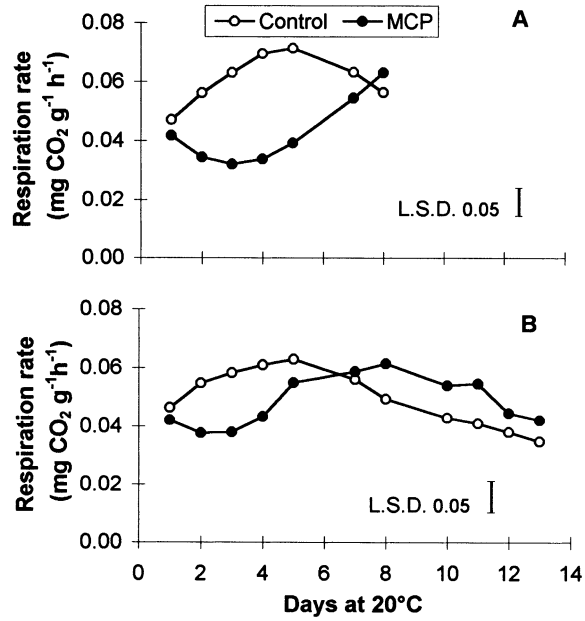

Fig. 4. Respiration rate of 'Royal Zee' plum during ripening at 20 °C. (A) After 10 days storage at 0 °C following treatment with 1000 nl l^{-1} 1-MCP at harvest; (B) After 30 days storage at 0 °C following treatment with 1000 nl l^{-1} 1-MCP at harvest. Data were means of five replicates with two fruit each. LSD represents the least significant difference at 5% level of Duncan's multiple range test.

The loss of firmness was not affected by 1-MCP, regardless of storage duration (Fig. 5A and B). During ripening of fruit treated after storage, 1-MCP affected the softening in a concentration dependent manner. Fruit treated with 1000 nl l^{-1} 1-MCP remained significantly firmer compared to control fruit. Differences in firmness between control and the two lower concentrations of 1-MCP were not significant (Fig. 5C).

'Royal Zee' plums had a longer shelf life than apricot. Within 5 days of ripening following both storage durations, the untreated fruit lost about 40% of their original firmness; from then on, the loss of firmness slowed. Fruit still retained 50% of the initial firmness at 12 days of ripening, the end of our observations following 30 days storage. 1-MCP delayed the softening process strikingly, regardless of storage duration. At 5 days ripening, the time when the biggest difference appeared, 1-MCP-treated fruit only lost 8 and 2% of their

initial firmness, and were 20 and 23 N firmer than the untreated fruit, after 10 and 30 days storage respectively. Later, the difference became smaller and eventually reached the same level at 12 days ripening. There was a 5 day delay in softening with the 1-MCP treatment (Fig. 6A and B).

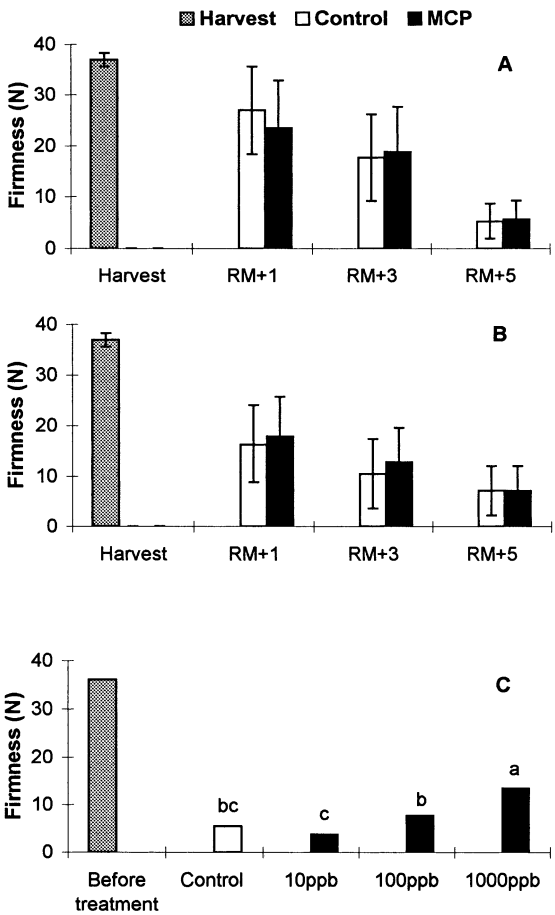

Fig. 5. Firmness of 'Canino' apricot. (A) At harvest and 1, 3, 5 days ripening after 5 days storage at 0 °C following treatment with 1000 nl l^{-1} 1-MCP at harvest; (B) At harvest and 1, 3, 5 days ripening after 30 days storage at 0 °C following treatment with 1000 nl l^{-1} 1-MCP at harvest; (C) Before treatment of 1-MCP when fruit were stored for 20 days at 0 °C, and after 4 days ripening following treatment of 1-MCP with concentrations of 0 (control), 10, 100, 1000 nl l^{-1}. Data are means of at least 30 fruit for each treatment. Bars show the standard error. Letters indicate significant difference at 5% level amongst treatments.

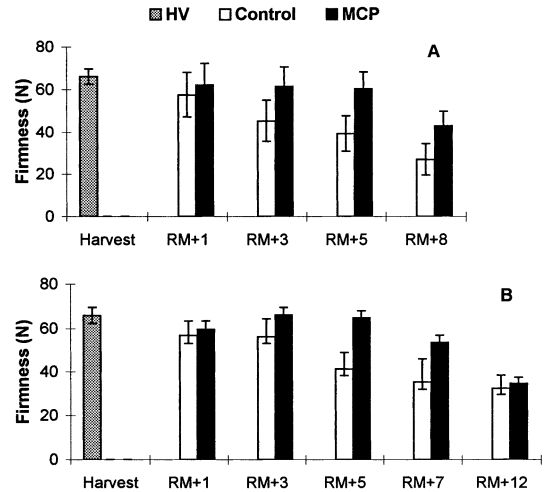

Fig. 6. Firmness of 'Royal Zee' plum. (A) At harvest and 1, 3, 5, 8 days ripening after 10 days storage at 0 °C following treatment with 1000 nl l^{-1} 1-MCP at harvest; (B) At harvest and 1, 3, 5, 7, 12 days ripening after 30 days storage at 0 °C following treatment with 1000 nl l^{-1} 1-MCP at harvest. Data are means of at least 30 fruit for each treatment. Bars show the standard error.

3.4. Color change

Apricots were harvested at a stage when the peel still had some green color and they changed quickly to yellow when fruit were held at 20 °C (Table 1). In prestorage treated fruit, the dramatic change happened after 1 day ripening, during which the hue angle decreased from 88.59 to 82.74°; later on the change slowed and the hue angle was 80.76° at the end of 6 days ripening in control fruit. The color development in fruit treated after storage was similar. 1-MCP did not have any effect on the color change in either of the treatments.

'Royal Zee' plums change to deep purple from a red color during the ripening process. 1-MCP retarded the decrease of hue angle when compared to control. After 8 days ripening following 10 days operative storage, the hue angle decreased from 24.26° (at harvest) to 6.28 and 9.90°, respectively in control and 1-MCP-treated fruit. Following 30 days storage, the hue angle changed in a similar pattern. The inhibition of color change by 1-MCP was maintained until 12 days of ripening (Table 2).

3.5. Fruit quality

During ripening of 'Canino' apricot, there was little change in SSC, but an appreciable decrease in TA (Table 1). However, neither of these parameters were affected by 1-MCP. Extended storage at 0 °C increased internal browning and decay. At the end of shelf life, the internal browning in control fruit increased from 3.3 to 35% when storage was extended from 5 to 30 days. 1-MCP increased internal browning significantly when fruit were treated prior to storage. In contrast, when fruit were treated after storage and ripened directly, 1-MCP decreased the internal browning by almost 50%, regardless of the concentration. Decay development was also decreased by 1-MCP. After ripening following 30 days storage, decay was decreased by 1-MCP from 74 to 47%. Moreover, in the poststorage treated fruit, 1-MCP affected the incidence of decay in a concentration-dependent pattern. While 100 nl l^{-1} of 1-MCP decreased decay considerably, 1000 nl l^{-1} completely prevented decay (Table 1).

In 'Royal Zee' plums, SSC remained relatively stable over the poststorage ripening, both in 1-MCP treated and untreated fruit. TA decreased considerably during ripening in control fruit and 1-MCP inhibited this decrease. This inhibition continued over the whole period of ripening. Fruit treated with 1-MCP ripened normally, although the flesh developed more reddening than the control fruit (Table 2).

Table 1
Quality assessment parameters of 'Canino' apricot

Parameters	Stage	Control	1-MCP
Hue angle ($h°$)[a]	Harvest	88.59 ± 0.86	88.59 ± 0.86
	1 day ripening after 30 day storage	82.74 ± 1.23	84.24 ± 0.74
	6 day ripening after 30 day storage	80.76 ± 1.00	80.11 ± 0.51
SSC (%)[b]	Harvest	13.06 ± 0.67	13.06 ± 0.67
	1 day ripening after 30 day storage	13.05 ± 0.01	12.83 ± 0.35
	6 day ripening after 30 day storage	12.67 ± 0.06	12.57 ± 0.06
TA (%)[b]	Harvest	2.09 ± 0.10	2.09 ± 0.10
	1 day ripening after 30 day storage	1.46 ± 0.10	1.49 ± 0.03
	6 day ripening after 30 day storage	1.00 ± 0.04	1.11 ± 0.02
Internal browning (%)[c]	7 day ripening after 5 day storage	3.33	39.17
	6 day ripening after 30 day storage	35.00	51.00
	6 day ripening after poststorage treatment	39.29	21.67[e]
Percentage of decay (%)[d]	7 day ripening after 5 day storage	0.00	0.00
	6 day ripening after 30 day storage	74.00	47.00
	6 day ripening after poststorage treatment	10.71	0.00[f]
			3.23[g]
			17.24[h]

[a] Average of 30 fruit.
[b] Average of three replicates of ten fruit each.
[c] Determined by the method described in the text.
[d] Determined by percentage of decay fruit in total at least 70 fruit.
[e] Result of 1000 nl l^{-1} 1-MCP treatment. There is no significant difference amongst three concentrations of 1-MCP at 5% level.
[f] Result of 1000 nl l^{-1} 1-MCP treatment.
[g] Result of 100 ppb nl l^{-1} 1-MCP treatment.
[h] Result of 10 nl l^{-1} 1-MCP treatment.

Table 2
Quality assessment parameters of 'Royal Zee' plum

Parameters	Stage	Control	1-MCP
Hue angle ($h°$)[a]	Harvest	24.26 ± 1.54	24.26 ± 1.54
	8 day ripening after 10 day storage	6.28 ± 0.26	9.9 ± 1.34
	7 day ripening after 30 day storage	10.48 ± 0.44	13.64 ± 1.32
	12 day ripening after 30 day storage	5.30 ± 0.16	7.85 ± 0.13
SSC (%)[b]	Harvest	11.58 ± 0.28	11.58 ± 0.28
	7 day ripening after 30 day storage	11.13 ± 0.06	11.07 ± 0.21
	12 day ripening after 30 day storage	11.13 ± 0.42	11.10 ± 0.10
TA (%)[b]	Harvest	1.49 ± 0.03	1.49 ± 0.03
	7 day ripening after 30 day storage	0.99 ± 0.10	1.24 ± 0.09
	12 day ripening after 30 day storage	0.65 ± 0.10	0.88 ± 0.11
Internal reddening (%)[c]	13 day ripening after 30 day storage	9.00	16.25

[a] Average of 30 fruit.
[b] Average of three replicates of ten fruit each.
[c] Determined by the method described in the text.

4. Discussion

4.1. Effect of 1-MCP on ripening of 'Canino' apricot

4.1.1. Effect of 1-MCP on ethylene production

'Canino' apricots are classified as medium ethylene emitting fruit (Manolopoulou and Mallidis, 1999), and the present study demonstrated that ethylene production of this apricot increased relatively quickly during ripening (Fig. 1A). However, ethylene production was affected by both storage duration and postharvest stage. Fruit treated before storage were harvested at yellow peel color with green along the suture line. Although the initial rates of ethylene production after 5 and 30 days storage were similar (0.40 and 0.30 nl g^{-1} h^{-1}, respectively), the rise in ethylene production was greatly inhibited after extended storage (Fig. 1A and B). The higher initial ethylene found in fruit removed from 20 days of storage for treatment might result from the different physiological stage of the fruit. Although color and firmness were similar to fruit treated before storage, the capacity for initiating ethylene production might be increased during storage without treatment. These ethylene specific characteristics of the apricots might be a critical factor affecting their storability and response to the ethylene inhibitors. The results presented in this study support this hypothesis.

The different relationship between ethylene production and 1-MCP treatment in apricots from different storage durations and stages of treatment might be explained by different ethylene characteristics of fruit as mentioned above. 1-MCP is thought to bind irreversibly to ethylene receptors (Sisler et al., 1996). In fruit stored 5 days after treatment, the ethylene production, unaffected by 1-MCP during the first 4 days of ripening, probably resulted from the inability of these fruit to respond to 1-MCP or a lag of 1-MCP diffusion and binding to the receptors when fruit were held at a chilling temperature immediately after treatment. With extension of storage to 30 days, the enhanced ethylene production by 1-MCP could be a result of the stress caused by low temperature or its combination with 1-MCP treatment. It seems that these fruit were sensitive to cold storage or its combination with 1-MCP treatment, because even control fruit suffered physiological disorders, and 1-MCP treatment made this damage more severe (Table 1). In fruit treated after storage and ripened directly following treatment, the pattern of inhibited ethylene production by 1-MCP was similar to that found in other studies (Fan et al., 1999a, 2000; Feng et al., 2000). The effectiveness of 1000 nl l^{-1}

1-MCP and the failure of the two lower concentrations to inhibit ethylene production indicated that sufficient concentration is necessary in order to competitively bind to enough receptors so as to block the autocatalytic synthesis of ethylene production, since fruit in this treatment had relatively high initial ethylene production. Chahine et al. (1999) reported that 1-MCP efficiently inhibits ethylene production of 'Moniqui' apricot in the preclimacteric stage only. The present results suggest that this might be the situation if treated fruit are not subjected to cold storage. For prestorage treatment in order to inhibit ethylene, the fruit maturity or the physiological stage of ethylene production will be crucial.

4.1.2. Effect of 1-MCP on fruit softening and quality of apricot

In general, the loss of firmness and color change of 'Canino' apricot occurred rapidly, in agreement with the finding of Chahine et al. (1999). Fruit softening is known to be one of the ripening processes that is sensitive to ethylene (Lelievre et al., 1997). Delaying softening of apricot by 1-MCP has been reported previously (Fan et al., 2000). However, in the present study, 1-MCP treatment at different stages of ripeness resulted in different effects on softening. The inhibition of firmness loss in fruit ripened directly following treatment (Fig. 5C), indicated that softening was indeed affected by 1-MCP as shown in other studies (Jiang et al., 1999; Fan et al., 1999a, 2000; Feng et al., 2000) and in a concentration-dependent pattern. The correspondence of the lowest ethylene emission and the highest firmness of fruit further confirmed the role of ethylene on softening of climacteric fruit. The failure of 1-MCP to inhibit softening of fruit treated before storage (Fig. 5A and B), appeared to be related to ethylene production, which was high enough to trigger the softening of treated fruit similarly to that of untreated fruit.

The association between color changes and ethylene varies with the type of pigment, the species and the tissue in which the pigment is being produced (Abdi et al., 1997). Therefore, color development can be either ethylene-dependent or -independent (Lelievre et al., 1997). The lack of difference in color change between 1-MCP treatment and control after ripening in apricot fruit treated either before or after storage (Table 1), indicated that once the ripening began, the color change of apricot was independent of ethylene, and therefore, not affected by 1-MCP. This agrees with the findings of Fan et al. (2000).

Concerning fruit quality, although there was little difference in SSC and TA, the internal browning and percentage of decay were affected by 1-MCP. The decreased incidence of internal browning in fruit ripened immediately following poststorage treatments of all three concentrations of 1-MCP, indicated that 1-MCP is capable of alleviating the flesh browning of apricot even at low concentrations. However, the increased internal browning by 1-MCP in fruit treated prior to storage highlighted the decisive effect of interaction between the physiological stage of the fruit and the storage environment. It is suggested that the fruit might suffer severe disorder when treated at an improper maturity and held at low temperature, and the longer the storage duration, the more severe the damage. The decreased incidence of decay in both treatments of 1-MCP, and the complete control of decay by 1000 nl l^{-1} 1-MCP, when treated after storage, showed that decay was affected by 1-MCP in a concentration-dependent manner. The level of ethylene emission seems not to be related to the occurrence of decay.

Collectively, it is concluded that although 'Canino' apricot did not favorably respond to 1-MCP when treated prior to storage, 1-MCP did delay the ripening and improved the quality of fruit when ripened directly after poststorage treatment. The results suggest that the proper fruit maturity or physiological stage must be carefully chosen for 1-MCP treatment. 1-MCP therefore is considered more efficient for extending the shelf life of fruit directly marketed or after storage, instead of extending the storage period, which will challenge further studies attempting to find the proper stage of fruit maturity, the optimum concentration of the compound and duration of treatment, as well as combination with the optimum temperature.

4.2. Effect of 1-MCP on ripening of 'Royal Zee' plums

4.2.1. Effect of 1-MCP on ethylene production and respiration rate of 'Royal Zee' plums

'Royal Zee' plums are characterized by a typical climacteric ethylene and respiration pattern (Figs. 2 and 4), which is different from our previous finding in 'Red Rosa' plums (Dong et al., 2001a). The rapid rise and relatively short period to reach the climacteric no doubt contributed to the rapid ripening of the fruit. The greatly inhibited ethylene production by 1-MCP, no matter how long the fruit were stored, indicated that 1-MCP efficiently bound to the receptors and blocked the autocatalytic synthesis of ethylene, thereby suppressing the positive feedback regulation of ethylene production. This suppression might occur at the enzymic level, since it has been reported that 1-MCP inhibited ethylene production in ripening tomatoes by strongly inhibiting the normal increase in activity of ACS and ACO during ripening (Nakatsuka et al., 1997). Our previous study of nectarine has shown that 1-MCP inhibited the transcription of the ACO gene during poststorage ripening (Dong et al., 2001b), indicating that 1-MCP might regulate ethylene synthesis at the gene level. The advent of the ethylene climacteric in 1-MCP-treated fruit, although delayed, indicated that the fruit eventually overcame the inhibition of 1-MCP by making new receptors (Golding et al., 1998).

The increase in respiration rate and ethylene emission of 'Royal Zee' plums, as well as the similar pattern of inhibition by 1-MCP confirmed the effect of 1-MCP on respiration rate which has been found in other studies (Golding et al., 1998; Fan et al., 1999a; Jiang et al., 1999).

4.2.2. Effect of 1-MCP on ripening and quality of 'Royal Zee' plums

The softening of 'Royal Zee' plums correlated well with the ethylene emission. Control fruit lost most of their firmness within 5 days of ripening, during which period the ethylene production rose rapidly. 1-MCP-treated fruit lost most of their firmness at 7–8 days of ripening, when the ethylene production increased dramatically. The effectiveness of 1-MCP on delaying softening of plums agrees with other reports (Fan et al., 1999a; Jiang et al., 1999; Feng et al., 2000).

The color change in 'Royal Zee' plums during ripening was not as dramatic as that of apricot, although it was retarded by 1-MCP treatment. Nevertheless, the relationship of ethylene with color change is not clear, because the hue angle was still higher in treated fruit until 12 days of ripening, which was 2 days after ethylene production in treated fruit exceeded that in control fruit. Studies of climacteric and suppressed-climacteric plums showed that skin color changes in both types of cultivars started before ethylene production could be detected and it was suggested that in plums, the role of ethylene seems to be that of a catalyst hastening and coordinating pigment production and chlorophyll loss (Abdi et al., 1997). The present data agree with this. The inhibition of color development by 1-MCP, might be achieved either by strongly inhibited ethylene or by means other than regulation by ethylene.

The pattern of TA reduction and the effect of 1-MCP was similar to that of color change. Enhanced flesh reddening in 1-MCP-treated fruit might be ascribed to the prolonged storage and shelf life, and possibly contribute to the enhanced ethylene production during the latter period of fruit ripening. It has been reported that some fruit develop disorders after treatment with 1-MCP (Golding et al., 1998; Porat et al., 1999). However, the flesh reddening here was not a disorder, but is what occurs naturally in this cultivar when ripened after storage. The reason for the reddening and the relationship between the inhibited and enhanced development, respectively, in skin and flesh color needs to be studied further.

It is concluded that ripening of 'Royal Zee' plums is coupled with climacteric ethylene production and respiration. 1-MCP inhibited the ripening process manifested as greatly delayed softening, color change and reduction of TA, via delaying the onset of climacteric and blocking ethylene production, without any unfavourable effect on fruit quality under the applied concentrations. This suggests the potential of 1-MCP for extending both storage and shelf life of this plum.

References

Abdi, N., Holford, P., McGlasson, W.B., Mizrahi, Y., 1997. Ripening behavior and responses to propylene in four cultivars of Japanese type plums. Postharvest Biol. Technol. 12, 21–34.

Abdi, N., McGlasson, W.B., Hoford, P., Willians, M., Mizrahi, Y., 1998. Responses of climacteric and suppressed-climacteric plums to treatment with propylene and 1-methylcyclopropene. Postharvest Biol. Technol. 14, 29–39.

Ben-Arie, R., Sonego, L., 1980. Pectolytic enzyme activity involved in woolly breakdown of stored peaches. Phytochem. 19, 2553–2555.

Chahine, H., Gouble, B., Audergon, J.M., Souty, M., Albagnac, G., 1999. Effect of ethylene on certain quality parameters of apricot fruit (*Prunus armeniaca*, L.) during maturation and postharvest evolution. Acta Hort. 488, 577–584.

Dodd, M.C., 1984. Internal breakdown in plums. Decid. Fruit Grower 34, 255–256.

Dong, L., Zhou, H.W., Sonego, L., Lers, A., Lurie, S., 2001a. Ripening of 'Red Rosa' plums: effect of ethylene and 1-methylcyclopropene. Aust. J. Plant Physiol.

Dong, L., Zhou, H.W., Lers, A., Lurie, S., 2001b. Ethylene involvement in the cold storage disorder of 'Flavortop' nectarine. Postharvest Biol. Technol.

Fan, X., Blankenship, S., Mattheis, J.P., 1999a. 1-methylcyclopropene inhibits apple ripening. J. Am. Soc. Hort. Sci. 124, 690–695.

Fan, X., Mattheis, J.P., Blankenship, S., 1999b. Development of superficial scald, core flush, and peel greasiness is reduced by MCP. J. Agric. Food Chem. 47, 3063–3068.

Fan, X., Argenta, L., Mattheis, J.P., 2000. Inhibition of ethylene action by 1-methylcyclopropene prolongs storage life of apricots. Postharvest Biol. Technol. 20, 135–142.

Feng, X., Apelbaum, A., Sisler, E.C., Goren, R., 2000. Control of ethylene responses in avocado fruit with 1-methycyclopropene. Postharvest Biol. Technol. 20, 143–150.

Golding, J.B., Shearer, D., Wyllie, S.G., McGlasson, W.B., 1998. Application of 1-MCP and propylene to identify ethylene-dependent ripening processes in mature banana fruit. Postharvest Biol. Technol. 14, 87–98.

Jiang, Y., Joyce, D.C., Macnish, A.J., 1999. Extension of the shelf life of banana fruit by 1-methylcyclopropene in combination with polyethylene bags. Postharvest Biol. Technol. 16, 187–193.

Jooste, M.M., Taylor, M.A., 1999. Effect of harvest maturity and cold storage period on the overall quality of 'Bebeco' apricots, with special reference to gel breakdown and variates used to accurately establish harvest maturity. Decid. Fruit Grower 49, S1–S10.

Lelievre, J.M., Latche, A., Jones, B., Bouzayen, M., Pech, J.C., 1997. Ethylene and fruit ripening. Physiol. Plant. 101, 727–739.

Manolopoulou, H., Mallidis, C., 1999. Storage and processing of apricots. Acta Hort. 488, 567–576.

McGuire, R.G., 1992. Reporting of objective color measurements. HortScience 27, 1254–1255.

Nakatsuka, A., Shiomi, S., Kubo, Y., Inaba, A., 1997. Expression and internal feedback regulation of ACC synthase and ACC oxidase genes in ripening tomato fruit. Plant Cell Physiol. 38, 1103–1110.

Porat, R., Weiss, B., Cohen, L., Daus, A., Goren, R., Droby, S., 1999. Effects of ethylene and 1-methylcyclopropene on the postharvest qualities of 'Shamouti' oranges. Postharvest Biol. Technol. 15, 155–163.

Sisler, E.C., Serek, M., 1997. Inhibitors of ethylene responses in plants at the receptor level: recent developments. Physiol. Plant 100, 577–582.

Sisler, E.C., Jupille, E., Serek, M., 1996. Effects of 1-methylcyclopropene and methylenecyclopropane on ethylene binding and ethylene action on cut carnations. Plant Growth Regul. 18, 79–86.

Sonego, L., Lers, A., Khalchitsky, A., Zutkhi, Y., Zhou, H., Lurie, S., Ben-Arie, R., 1999. Ethylene delays onset of woolly breakdown in cold-stored peaches. In: Kanellis, A., Chang, C., Klee, H., Bennett, A., Pech, J., Grierson, D. (Eds.), Biology and Biotechnology of the Plant Hormone Ethylene II. Kluwer Academic Publishers, Dordrecht, The Netherlands, pp. 405–410.

Taylor, M.A., Jacobs, G., Rabe, E., Dodd, M.C., 1993a. Physiological factors associated with overripeness, internal breakdown and gel breakdown in plums stored at two temperatures. J. Hort. Sci. 68, 825–830.

Taylor, M.A., Rabe, E., Jacobs, G., Dodd, M.C., 1993b. Physiological and anatomical changes associated with ripening in the inner and outer mesocarp of cold stored 'Songold' plums and concomitant development of internal disorders. J. Hort. Sci. 68, 911–918.

Taylor, M.A., Rabe, E., Dodd, M.C., Jacobs, G., 1994. Effect of storage regimes on pectolytic enzymes, pectic substances, internal conductivity and gel breakdown in cold stored 'Songold' plums. J. Hort. Sci. 69, 527–534.

Zhou, H.W., Ben-Arie, R., Lurie, S., 2000. Pectin esterase, polygalacturonase and gel formation in peach pectin fraction. Phytochem. 55, 191–195.

Zhou, H.W., Dong, L., Ben-Arie, R., Lurie, S., 2001. The role of ethylene in the prevention of chilling injury in nectarines. J. Plant Physiol. 158, 55–61.