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ScienceDirect
Postharvest Biology and Technology 44 (2007) 101–106
Postharvest Biology and Technology
www.elsevier.com/locate/postharvbio

Effects of 1-MCP and hexanal on decay of d'Anjou pear fruit in long-term cold storage

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Received 27 July 2006; accepted 10 December 2006

Abstract

The objectives of this study were to examine the effect of several rates of 1-MCP from 10 to 100 nL L^{-1} on stem end decay caused by *Botrytis cinerea* and to evaluate the effects of prestorage treatment with 1-MCP, hexanal, and 1-MCP + hexanal on decay of d'Anjou pear (*Pyrus communis* L.) fruit in long-term cold storage. 1-MCP at 300 nL L^{-1} reduced bull's-eye rot and Phacidiopycnis rot. Stem end gray mold also was reduced by 1-MCP at 300 nL L^{-1}, and reduction at rates from 10 to 100 nL L^{-1} was significant in one of two trials. Snow-mold rot was reduced by 1-MCP at 30 nL L^{-1}. Hexanal alone reduced snow mold but increased blue mold caused by *Penicillium expansum*. The combination of 1-MCP and hexanal affected decay similar to 1-MCP. However, hexanal in combination with 1-MCP negated the effect of 30 nL L^{-1} 1-MCP on firmness but did not counteract the effect of 300 nL L^{-1} 1-MCP. Thus, a combination of 1-MCP and hexanal at optimized rates may reduce storage decay, control superficial scald, and allow normal ripening of d'Anjou pear fruit.

Keywords: 1-Methylcyclopropene; Postharvest decay; *Pyrus communis*; *Botrytis cinerea*; *Penicillium expansum*; *Coprinus psychromorbidus*; *Phacidiopycnis piri*; *Neofabraea*

1. Introduction

1-Methylcyclopropene (1-MCP) is a synthetic cyclic olefin that inhibits ethylene by blocking access to the ethylene-binding receptor (Sisler and Serek, 1997). 1-MCP has been used extensively in the apple industry since 2002 to retain fruit firmness in cold storage and extend shelf life. It is marketed as SmartFresh^{SM} by AgroFresh, Inc. (Springhouse, PA).

Pear fruit have been used in studies on the effects of 1-MCP on ethylene biosynthesis, fruit softening, and superficial scald (Ekman et al., 2004; Hiwasa et al., 2003a,b; Kubo et al., 2003; Trinchero et al., 2004). Only one pear study includes the effect of 1-MCP on decay (Argenta et al., 2003). In this research, decay of d'Anjou pear fruit was reduced after 8 months storage at 1 °C by preclimacteric treatment with 100 and 1000 nL L^{-1} 1-MCP but not by 10 nL L^{-1}. The pathogens causing decay in this study were not identified.

When apple fruit were inoculated with *Penicllium expansum* or *Colletotrichum acutatum* then treated with 400–500 nL L^{-1} 1-MCP and placed in controlled atmosphere storage at 0.5 °C for up to 4 months, followed by an additional 2 weeks at ambient temperature, blue mold and bitter rot increased (Janisiewicz et al., 2003). However, decay caused by *P. expansum, C. acutatum*, and *Botrytis cinerea* in apple fruit treated prestorage with 1000 nL L^{-1} 1-MCP decreased when fruit were inoculated after 5 months of storage at 0 °C (Saftner et al., 2003). Poststorage 1-MCP treatment had no effect on decay severity.

Several studies have been done on the effects of 1-MCP on decay of nonclimacteric fruit. On strawberry, 1-MCP at 5–15 nL L^{-1} doubled postharvest life at 5 °C but reduced storage life at concentrations of 50–500 nL L^{-1}. Deterioration was primarily related to decay, but pathogens were not specified (Ku et al., 1999). 1-MCP at 150 and 250 nL L^{-1} slowed disease (mainly Rhizopus rot) of strawberry but increased rot at 500 and 1000 nL L^{-1} (Jiang et al., 2001). In another study with strawberry, the rate of rot (pathogen not identified) development increased after exposure to 10, 100 and 1000 nL L^{-1} of 1-MCP (Bower et al., 2003). Both stem-end rot and mold rot (pathogens not identified) of oranges increased after exposure to 100 nL L^{-1}

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doi:10.1016/j.postharvbio.2006.12.003

of 1-MCP (Porat et al., 1999). 1-MCP fumigation of grapefruit infected with *Penicillium digitatum* did not induce any change in disease susceptibility of the fruit (Mullins et al., 2000).

Hexanal is a naturally occurring volatile C-6 aldehyde formed via the lipoxygenase pathway in plants and is a precursor to the formation of alcohols and esters that operate in production of aroma (Hildebrand, 1989). The pathway operates when the plant is wounded and could be important for its defense against natural enemies such as decay-causing fungi. The related volatile, (*E*)-2-hexenal, was first used in postharvest studies for control of *B. cinerea* (Archbold et al., 1999; Fallik et al., 1998; Hamilton-Kemp et al., 1992). However, hexanal was also shown to suppress mold development in early studies conducted on apple slices (Song et al., 1996). Recently Fan et al. (2006) showed that hexanal vapor applied continuously over 48 h reduced decay in apple fruit inoculated with conidia of *P. expansum*. Previously, Sholberg and Randall (2005) had shown that hexanal applied in a manner similar to 1-MCP could also reduce decay in stored apples and pears.

In a preliminary trial with 300 nL L^{-1} 1-MCP, stem end gray mold of d'Anjou pear fruit was significantly reduced from 5.4% in the control to 0.8% (R. Spotts, unpublished). Later, we showed that d'Anjou fruit treated with 50 and 300 nL L^{-1} 1-MCP did not develop superficial scald but also failed to ripen normally. Fruit treated with 10 and 20 nL L^{-1} 1-MCP developed unacceptable scald but ripened normally (Chen and Spotts, 2005). No in-depth studies have been done to examine the effects of the combination of 1-MCP and hexanal on decay of pear fruit.

The objectives of this study were to (1) examine the effect of several rates of 1-MCP from 10 to 100 nL L^{-1} on stem end decay caused by *B. cinerea* and (2) evaluate the effects of prestorage treatment with 1-MCP, hexanal, and 1-MCP + hexanal on decay of d'Anjou pear fruit in long-term cold storage.

2. Materials and methods

2.1. Effect of low rates of 1-MCP on stem end gray mold

d'Anjou pear fruit were surface sterilized with 100 mg of sodium hypochlorite per L and rinsed with tap water. Fruit were stem end inoculated with 2.0×10^6 spores L^{-1} of *B. cinerea* isolate 62 by dipping the stem ends into the inoculum to a depth of about 3 mm. Four replicate boxes containing 19 kg each were treated with 0, 10, 30, 50, 70, and 100 nL L^{-1} 1-MCP. The source of 1-MCP was Smartfresh™ that was formulated as a 0.14% a.i. powder that liberates 1-MCP when added to 40 °C water. Fruit were treated inside a sealed cold storage room or sealed plexiglass chambers inside a controlled temperature storage room. Treatment was at 15 °C for 24 h. The atmosphere inside the room was circulated constantly with a fan. The ability of Smartfresh™ to release the stated amount of 1-MCP was confirmed for higher concentrations by flame ionization gas chromatography as described previously (Chen and Spotts, 2005). However, concentrations below 100 nL L^{-1} could not be verified accurately by this method, and the release rate was assumed to be linear at lower as well as higher concentrations. Treated fruit were stored in wooden boxes with perforated polyliners at −1 °C and evaluated after 3 and 6 months for stem end gray mold. The experiment was repeated with three replicate boxes of fruit per 1-MCP concentration, *B. cinerea* concentration of 4.0×10^6 spores L^{-1}, and fruit evaluated after 3, 6, and 8 months of storage. Disease incidence data were transformed to square root values and analyzed with linear regression analysis using Minitab release 12.1 (Minitab software, Minitab, Inc., State College, PA).

2.2. Semicommercial trials at Hood River, OR, USA and Summerland, BC, Canada

At Hood River, d'Anjou pears were harvested on 7–9 September 2004 and treated the same day, one trial per day. Conidia of *B. cinerea* isolate 62 were harvested from a 14-day-old culture growing on potato dextrose agar acidified with lactic acid, 1.5 mL L^{-1}. Eight milliliters of spore suspension at 1×10^7 CFU L^{-1} were sprayed on the fruit in each replicate box using an airbrush (Paache Airbrush Company, Harwood Heights, IL). Fruit were sealed in 0.35 m^3 plexiglass chambers at 15 °C and treated with (1) 944 μl L^{-1} of hexanal, (2) 300 nL L^{-1} of 1-MCP, and (3) a combination of hexanal and 1-MCP. 1-MCP was generated from Smartfresh powder as described above. Control fruit were inoculated and placed in a plastic chamber but received no 1-MCP or hexanal. After 18 h, fruit were placed in wooden boxes and stored at −1 °C. Each treatment consisted of 3 replications of 19 kg of fruit. A fourth box per treatment of noninoculated fruit was included for measurement of flesh firmness. Flesh firmness was measured using a fruit texture analyzer (Model GS-14, Guss Manufacturing Ltd., Strand, South Africa). Ten fruit per box were tested with an 8-mm plunger that penetrated 9 mm in 0.9 s. Two measurements were obtained per fruit from opposite sides at the equator, where 20 mm-diameter peel discs had been removed. Visual decay and firmness were evaluated immediately after treatment (firmness only) and after 4, 6, and 8 months of storage. After each evaluation, decayed fruit were removed to prevent secondary spread.

At the Pacific Agri-food Research Centre (PARC), Summerland, BC, d'Anjou pears were harvested on 21–23 September 2004 and treated the same day. Fruit were inoculated and treated similarly to Hood River with a few differences. Fruit were inoculated with *B. cinerea* isolate B-27and treated in a 1 m^3 chamber as previously described (Sholberg et al., 1996). The 1-MCP concentration was 30 nL L^{-1}. After treatment, fruit were placed into polylined cardboard boxes with a top pad and lid, and stored at 1 °C. Each treatment consisted of five replications of 18 kg of fruit. One additional box per replicate was used for analysis of fruit firmness. Flesh firmness was determined with a pressure tester (Lake City Technical Products, Model Ept-1, Kelowna, BC, Canada) equipped with a 7.9 mm tip. Fruit firmness was measured immediately after treatment and after 2, 4, 6, and 8 months of storage. Decay was evaluated visually only once after 8 months of storage.

At both locations, each experiment was done three times. Decay and firmness data were transformed to square root values.

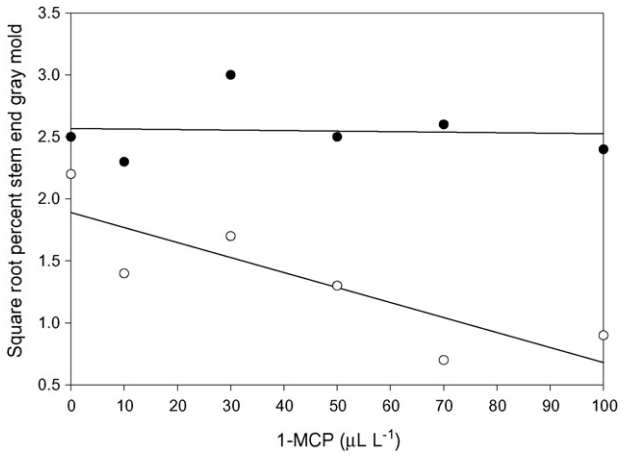

Fig. 1. Linear regression of percent of d'Anjou pear fruit infected with gray mold starting at the stem end (disease incidence) on 1-MCP concentration. Regression equation for trial 1 (filled circles): square root percent gray mold = 2.55 − 0.00045MCP rate; regression equation for trial 2 (open circles): square root percent gray mold = 1.88 − 0.012MCP rate. Equation significant at $P = 0.008$.

Data were analyzed with two-way ANOVA with treatment and experiment as main factors and presented as the combination of the three experiments.

3. Results

3.1. Effect of low rates of 1-MCP on stem end gray mold

In the first trial, 1-MCP at the highest rate of 100 nL L^{-1} reduced stem end gray mold by 9.7%, but the regression of decay on 1-MCP rate was not significant (Fig. 1). In the second trial, 100 nL L^{-1} of 1-MCP reduced stem end gray mold by 78.6%. In addition, the regression of decay on 1-MCP concentration was significant ($P = 0.008$) (Fig. 1).

3.2. Semicommercial trials at Hood River and Summerland

In Hood River, control fruit developed 33.4% total decay. Over half of the decay was naturally occurring bull's-eye rot caused by *Neofabraea* spp. (Table 1). Hexanal alone had no effect on incidence of bull's-eye rot, but 1-MCP and 1-MCP + hexanal significantly ($P = 0.003$) reduced disease incidence. Naturally occurring Phacidiopycnis rot caused by *Phacidiopycnis piri* also was reduced by the 1-MCP and 1-MCP + hexanal treatments ($P = 0.013$) but not by hexanal alone (Table 1). None of the treatments affected the incidence of calyx end or puncture gray mold, but stem end gray mold was reduced ($P = 0.001$) by 1-MCP and 1-MCP + hexanal (Table 1). There was no difference between the 1-MCP and 1-MCP + hexanal treatments for any decay.

At PARC, decay was severe and over 95% of control fruit were infected. Because infected fruit were not removed periodically as in Hood River, gray mold was quite advanced, and the type of infection (stem end, calyx end, or puncture) could not be determined. None of the treatments affected total gray mold (Table 2). Naturally occurring snow-mold rot caused by an unidentified basidiomycete infected over 42% of control fruit and was significantly ($P = 0.001$) reduced by all hexanal and 1-MCP treatments (Table 2). Naturally occurring blue mold caused by *P. expansum* increased significantly ($P = 0.001$) in both treatments containing hexanal while 1-MCP alone had no effect (Table 2).

Fruit treated with 1-MCP were significantly more firm than control fruit after 8 months storage at Hood River and Summerland (Table 3). Firmness was determined immediately after removal from storage, and fruit were not ripened in this study. Hexanal alone did not affect firmness. Addition of hexanal to

Table 2
Effect of 1-MCP and hexanal on decay of PARC d'Anjou pear fruit

Treatment[a]	Percent decay[b,c]		
	Gray mold	Blue mold	Snow-mold rot
1-MCP + hexanal	60.4 a	3.8 b	17.5 ab
1-MCP	62.4 a	0.2 a	25.1 b
Hexanal	60.2 a	4.3 b	9.1 a
Control	52.2 a	0.4 a	42.8 c

[a] 1-MCP at 30 μL L^{-1}; hexanal at 944 μL L^{-1}.
[b] Each value is the mean of five replicates per experiment from three combined experiments. Values followed by the same letter within columns are not different at $P = 0.05$ according protected LSD.
[c] Decay evaluated after 8 months cold storage at 1 °C. Decay from all evaluations combined.

Table 1
Effect of 1-MCP and hexanal on decay of Hood River d'Anjou pear fruit

Treatment[a]	Percent decay[b,c]						
	Stem gray mold	Puncture gray mold	Calyx gray mold	Blue mold	Bull's-eye rot	Phacidiopycnis rot	Total decay
1-MCP + hexanal	1.4 a	6.4 a	0.7 a	2.3 a	4.4 a	0.2 a	15.8 a
1-MCP	1.3 a	4.4 a	0.9 a	1.1 a	8.0 ab	0.7 ab	17.6 a
Hexanal	5.1 b	5.4 a	0.5 a	0.4 a	14.6 bc	2.1 bc	28.5 b
Control	6.1 b	2.8 a	0.2 a	0.8 a	18.9 c	2.2 c	33.4 b

[a] 1-MCP at 300 μL L^{-1}; hexanal at 944 μL L^{-1}.
[b] Each value is the mean of three replicates per experiment from three combined experiments. Values followed by the same letter within columns are not different at $P = 0.05$ according protected LSD.
[c] Decay evaluated after 4, 6, and 8 months cold storage at −1 °C. Decay from all evaluations combined.

Table 3
Effect of 1-MCP and hexanal on flesh firmness of d'Anjou pear fruit after 8 months cold storage

Treatment	Flesh firmness (N)[a]	
	Hood River	Summerland
1-MCP + hexanal	44 b	39 a
1-MCP	45 b	51 b
Hexanal	33 a	36 a
Control	34 a	35 a

[a] Flesh firmness in Newtons. Means followed by the same letter within columns are not significantly different at $P = 0.10$ (Hood River) or 0.05 (Summerland) according to protected LSD.

1-MCP negated the 1-MCP effect at Summerland but not Hood River (Table 3).

4. Discussion

1-MCP at 300 nL L^{-1} reduced stem end gray mold, bull's-eye rot, and Phacidiopycnis rot. Stem end gray mold also was reduced by 1-MCP at 100 nL L^{-1} and reduction at rates from 10 to 100 nL L^{-1} was significant in one of two trials. Snow-mold rot was reduced by 30 nL L^{-1}. Snow-mold rot (Snowdon, 1990) also known as Coprinus rot is an important disease of d'Anjou pears in the Pacific Northwest (Spotts et al., 1981) and British Columbia (Gaudet and Sholberg, 1990). Previously, only one study of the effects of 1-MCP on pear included data on decay and reported a reduction of decay (pathogens not specified) with 100 and 1000 nL L^{-1} but not 10 nL L^{-1} (Argenta et al., 2003).

The 300 nL L^{-1} 1-MCP rate used in Hood River was the lowest rate recommended by the manufacturer at the time of the study. A 300 nL L^{-1} of 1-MCP reduced gray mold stem end decay in preliminary trials and controlled superficial scald, but fruit did not ripen properly (Chen and Spotts, 2005). Decay was evaluated three times during the storage period at Hood River to prevent secondary spread and give a clear, detailed picture of the effects of 1-MCP on decay. In Summerland, 30 nL L^{-1} 1-MCP was used for potential ease of ripening (Chen and Spotts, 2005). Fruit were evaluated only once after 8 months of storage to more closely simulate commercial conditions. Decay was severe but 1-MCP reduced snow-mold rot. The commercial implication of these results is that 1-MCP should be considered as a component in an integrated decay control strategy but should not be relied on to give adequate decay control alone.

Hiwasa et al. (2003) showed that 1-MCP treatment at the pre-ripe stage of pear fruit markedly retards the initiation of the ripening-related events. They reported that the mRNA accumulation of pear polygalacturonase (PG) genes, PC-PG1 and PC-PG2, was in parallel with the pattern of fruit softening in 1-MCP treatments, and the expression profiles of PG genes paralleled the apparent suppression of softening in 1-MCP-treated pear fruit. It is well known that plant pathogens produce a series of plant cell wall-degrading enzymes involved in pre- and postharvest diseases (Bateman and Basham, 1976). It is commonly accepted that tissue maceration is the result of degradation of the pectic fraction of cell wall polymers by endopectic enzymes (Misaghi, 1982). Among the pectic enzymes, polygalacturonase (PG) (EC 3.2.1.15) has been associated with pathogenesis and disease severity in a variety of host/pathogen interactions (Bateman and Basham, 1976; Misaghi, 1982; Patil and Dimond, 1968). Although the mechanism of action is not understood, it is possible that 1-MCP bound at the ethylene receptors in pear fruit is still capable of inhibiting cell wall-degrading enzymes such as PG secreted by pathogens and thus prevent pathogenesis. Further research is needed in this area.

The current model describing the regulation of tomato fruit ripening is based on the action of at least two signal transduction pathways: one that is ethylene independent and developmentally regulated and another that is ethylene dependent (Theologis et al., 1993). According to this model, it has been suggested that PG expression is developmentally regulated through the ethylene-independent signal transduction pathway but that translatability of PG mRNA or the stability of the PG protein may be ethylene dependent. However, Sitrit and Bennett (1998) have demonstrated that PG mRNA accumulation is ethylene regulated. They also show that two criteria have been used to establish the role of ethylene in regulating specific gene expression: (a) mRNA accumulation should be induced at physiologically active concentrations of ethylene and (b) the response to ethylene should be fast (Lincoln et al., 1987; Harpham et al., 1996). The 1-MCP treatment of 'd'Anjou' pear fruit effectively inhibited ethylene production after cold storage followed by ripening at 20 °C (Chen and Spotts, 2005). It is not yet known if pathogen PG mRNA accumulation is ethylene regulated and thus affected by 1-MCP.

Light microscopy examination of fungal hyphae treated with (*E*)-2-hexenal ($C_6H_{10}O$) showed that a high concentration of this volatile compound dehydrated the hyphae and disrupted their cell walls and membranes (Fallik et al., 1998). However, lower concentrations of this material stimulated the growth of *B. cinerea* mycelium when applied 2 days after the fungus had germinated. Hexanal ($C_6H_{12}O$) differs from (E)-2-hexenal by the absence of a double bond but still appears to have a similar effect on fungi. Archbold et al. (1997) found that both of these volatile compounds reduced growth of *Botrytis* spp. on strawberries to less than 10% when directly compared at the same concentration and stored under exactly the same conditions. Gardini et al. (1997) showed that the antifungal activity of hexanal is dependent on its vapor pressure increasing as temperature rises. It appears that the snow-mold fungus was more sensitive to the vapor pressure of hexanal in cold storage than the other decay-causing fungi found in this study. On the other hand, *P. expansum* appeared to be stimulated by the application of hexanal both alone and in combination with 1-MCP. *Trans*-2-hexenal is known to stimulate conidial germination of *P. expansum* at low rates or when applied for short periods of time. (Neri et al., 2006a). When *trans*-2-hexenal was applied to apple and pear fruit 2 h after inoculation, blue mold was unaffected or increased. However, application 24 h after inoculation reduced blue mold 50–98% (Neri et al., 2006b,c). Further research is needed to determine the best concentration and timing of hexanal to use for control of blue mold when it is combined with 1-MCP.

Hexanal may affect pear firmness, reducing the effect of 1-MCP in producing overly firm fruit. Fallik et al. (1998) reported that (*E*)-2-hexenal reduced firmness in strawberry fruit during storage at 22 °C, but fruit total soluble solids, pH, titratable acidity, and color were not affected. We found in the present study that hexanal negated the effect of 30 nL L^{-1} 1-MCP on firmness but did not counteract the effect of 300 nL L^{-1} 1-MCP. Hexanal also has improved aroma in pome fruit (Sholberg and Randall, 2005; Song et al., 1996).

Thus, the combination of 1-MCP and hexanal reduced several decays and appeared to enable proper ripening of pear fruit treated with 1-MCP. Additional research is needed on the mode of action of the 1-MCP/hexanal combination and use of this combination on pear fruit in commercial storage and ripening regimes.

Acknowledgements

We thank the Fresh and Processed Pear Subcommittee, Washington Tree Fruit Research Commission Winter Pear Control Committee, and the Matching Investment Initiative program of Agriculture and Agri-Food Canada for partial funding of the research. Use of trade names in this article does not imply endorsement by Oregon State University of the products named or criticism of similar products not mentioned.

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