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Effects of multiple 1-methylcyclopropene treatments on apple fruit quality and disorders in controlled atmosphere storage

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ABSTRACT

The objective of this study was to investigate the effects of multiple 1-methylcyclopropene (1-MCP) treatments on fruit quality and disorder development in apples, with a second 1-MCP treatment applied after several months of controlled atmosphere (CA) storage. 'McIntosh', 'Empire', and 'Northern Spy' apples were harvested from commercial orchards and cooled overnight to 3 °C. 1-MCP (1 $\mu L L^{-1}$) was applied 2 d after harvest and then again to half of the fruit after 4 months of CA storage. 'Northern Spy' apples also received a single 1-MCP treatment after 4 months of CA storage. Similar fruit from all cultivars were also not treated with 1-MCP. 'McIntosh' and 'Empire' were held at 3 °C and 'Northern Spy' at 0 °C for 9 months in CA storage (2.5 kPa O_2 + 2 kPa CO_2 for 'Empire', 2.5 kPa CO_2 for 'Northern Spy', and 2.5 up to 4.5 kPa CO_2 for 'McIntosh'). Overall, 1-MCP reduced internal ethylene production, and improved firmness and acidity retention in all apple cultivars. The addition of a second 1-MCP treatment after 4 months of CA storage further improved firmness retention in 'McIntosh' and late harvested 'Empire' apples after 7 d at room temperature. 'Northern Spy' apples treated with 1-MCP had lower incidence of external CO_2 injury, regardless of 1-MCP treatment timing. Multiple 1-MCP treatments had varying effects on the incidence of core browning; late-harvested 'McIntosh' treated twice with 1-MCP exhibited the highest incidence of core browning, while late-harvested 'Empire' treated twice had less core browning than those not treated. 'Northern Spy' treated only at harvest time had more core browning compared to those treated only or also after 4 months of CA storage and non-treated fruit. 1-MCP treatment had no significant effect on the incidence of internal browning in 'McIntosh' or 'Empire' apples. These results suggest that a second application of 1-MCP after 4 months of CA storage may improve firmness retention in some cultivars during holding at room temperature, but it can also have variable responses associated with susceptibility to disorders, especially when holding apples in long-term CA storage.

1. Introduction

1-Methylcyclopropene (1-MCP) is a competitive inhibitor of ethylene action that is used to maintain fruit quality by delaying senescence. The postharvest application of 1-MCP (marketed as SmartFresh^{TM}) has been shown to improve quality characteristics of apples, including reduced ethylene production and respiration, improved firmness and acidity retention, and decreased development of senescence-related disorders (Fan et al., 1999a,b; DeEll et al., 2007; Watkins, 2007). Unfortunately, 1-MCP applications may also exacerbate the development of some postharvest disorders in apples. 'McIntosh' and 'Empire' apples treated with 1-MCP tend to have increased susceptibility to external CO_2 injury and flesh browning disorders (DeEll et al., 2003; Fawbush et al., 2008; Jung and Watkins, 2011). The response of apples to 1-MCP treatments can be affected by various factors, including cultivar (Watkins et al., 2000; Bai et al., 2005), harvest maturity (Toivonen and Lu, 2005; DeEll et al., 2008), concentration (DeEll et al., 2008), duration and temperature of exposure (DeEll et al., 2002), and delays in application after harvest (DeEll et al., 2002, 2008; Watkins and Nock, 2005).

Traditional application of 1-MCP on apples involves a single treatment shortly after harvest at a concentration of 1 $\mu L L^{-1}$ for 24 h, within 7 d of harvest to achieve maximum benefit in most apple cultivars (AgroFresh, 2014). 'McIntosh' is a high ethylene producing cultivar, and thus it is recommended a single 1-MCP treatment within 3 d after harvest for the most beneficial effects (DeEll et al., 2008; AgroFresh, 2014). In recent years, several studies pertaining to the storage of 'Empire' apples have emerged, but recommendations for its 1-MCP treatment remain to be fully determined (Fawbush et al., 2008; James et al., 2010; Jung and Watkins, 2011; DeEll and Ehsani-Moghaddam, 2012a; Deyman

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et al., 2014). Most of the current scientific literature regarding 1-MCP treatment of apples and its effect on fruit quality involve the application of 1-MCP within the first few days after harvest, including a warm or overnight cooling period before treatment (Watkins and Nock, 2005). However, this has been proven difficult to achieve for growers with smaller operations, where it takes more than a week to fill their storage facilities.

The current Canadian label registration for SmartFresh™ of apples allows multiple applications of 1-MCP, up to a maximum of four 1-MCP treatments at a concentration of 1 $\mu L\,L^{-1}$ within 240 d of harvest. As a result, storage facilities can apply multiple 1-MCP treatments when storage rooms are being filled, or after a few months in storage. This has stimulated interest about the timing and application of multiple 1-MCP treatments with the possibility of enhancing fruit quality, as well as reducing the potential risk of storage-related disorders that are exacerbated by 1-MCP. Little information exists regarding the effect of multiple 1-MCP treatments on apple quality and disorder development, especially when treatments are applied to apples already stored in CA.

Preliminary evidence has suggested some benefits and drawbacks associated with more than one treatment of 1-MCP on apples. Research using 'McIntosh' and 'Empire' apples found that the application of early and consecutive 1-MCP treatments prior to CA storage had improved firmness retention and decreased storage-related disorders (Nock and Watkins, 2013). A similar study demonstrated multiple 1-MCP treatments within a week after harvest was the most effective at maintaining fruit quality and limiting disorders in 'Cortland' and 'Delicious' apples (Lu et al., 2013). Furthermore, 'McIntosh' and 'Spartan' apples subjected to consecutive 1-MCP (1 $\mu L\,L^{-1}$) treatments or a single 1-MCP treatment at double the concentration (2 $\mu L\,L^{-1}$) demonstrated risks associated with applications greater than the commercial standard; incidence of external CO_2 injury and internal browning increased during long-term air or CA storage (DeEll and Ehsani-Moghaddam, 2013). For most apple cultivars, there continues to be no clear understanding of the optimal combination of 1-MCP treatment timing, conditions and number of applications to effectively maintain fruit firmness and limit the development of disorders during long-term storage.

There is little scientific literature pertaining to using multiple 1-MCP treatments on apples that have been stored in CA storage. DeLong et al. (2004) showed that a second 1-MCP treatment had no significant effect on 'Cortland' and 'McIntosh' apples after 4.5 months of CA or ambient air storage, but the concentration of 1-MCP utilized was less than that used commercially. The objective of this study was to investigate the effects of multiple 1-MCP treatments, once 2 d after harvest and again after 4 months of CA storage, on fruit quality and the development of storage disorders in 'McIntosh', 'Empire' and 'Northern Spy' apples during long-term storage. 'Northern Spy' apples were also used to determine if a single 1-MCP treatment after 4 months of CA storage is similar to a single 1-MCP treatment prior to CA storage at 2 d postharvest. To date, there are no scientific reports of 1-MCP treatments in combination with CA storage of 'Northern Spy' apples.

2. Material and methods

2.1. Plant material

Storage trials were conducted with 'McIntosh' and 'Empire' apples in 2011, and 'Northern Spy' apples in 2012. All apple harvests were from commercial orchards located in Simcoe (Norfolk County), Ontario, Canada. 'McIntosh' apples were harvested on September 12 (Harvest 1) and September 19 (Harvest 2), while 'Empire' apples were harvested on September 28 (Harvest 1) and October 5 (Harvest 2) in 2011. 'Northern Spy' apples were harvested on September 24 in 2012. There were 9 boxes of apples (>100 fruit in each) for each of 'Empire' and 'McIntosh' per harvest time, and 12 boxes of 'Northern Spy'. Each box contained fruit that were sampled from several trees and various locations within the trees. Apples were transported immediately after harvest to the nearby storage research facility and cooled overnight at 3 °C.

2.2. Postharvest treatments

The following 1-MCP treatments were applied to 3 boxes of apples for each cultivar from each harvest: (1) 1 $\mu L\,L^{-1}$ applied 2 d after harvest; (2) 1 $\mu L\,L^{-1}$ applied 2 d after harvest and again after 4 months of CA storage; and (3) no 1-MCP. In addition, 3 boxes of 'Northern Spy' apples received a single treatment of 1 $\mu L\,L^{-1}$ applied after 4 months of CA storage, to determine if a single 1-MCP application at 4 months differed from treatment at 2 d postharvest. All 1-MCP applications at 2 d after harvest were made using SmartFresh™ tablets (AgroFresh Inc., Spring House, PA) within an air-tight treatment tent (Storage Control Systems Inc., Sparta, MI) and lasted for 24 h at 3 °C. Similar 1-MCP applications were made after 4 months of storage within the CA storage chambers (Storage Control System Inc.).

'McIntosh' and 'Empire' were maintained at 3 °C, and 'Northern spy' at 0 °C, under CA storage for 9 months. The CA storage regime for 'McIntosh' apples consisted of 2.5 kPa O_2 + 2.5 kPa CO_2 for one month, 3.5 kPa CO_2 for the next month and then 4.5 kPa CO_2 thereafter. 'Empire' and 'Northern Spy' apples were maintained in CA conditions of 2.5 kPa O_2 + 2 kPa CO_2 and 2.5 kPa O_2 + 2.5 kPa CO_2, respectively.

The CA system consisted of small aluminum storage chambers (0.9 m^3 volume) fitted with a circulating fan system (Storage Control System Inc.). The atmospheric composition was checked automatically every hour and maintained within 0.2 kPa of the target values using an ICA61/CGS610 CA Control System (International Controlled Atmosphere Ltd., Kent, U.K.), which was modified with flow controllers for the experimental chambers (Storage Control Systems Inc.).

2.3. Fruit quality evaluations

For each apple cultivar, initial fruit maturity was evaluated on a 10-apple sample at the time of harvest. Internal ethylene concentration (IEC) was determined by withdrawing a 3-mL gas sample from the core of each fruit using a syringe and injecting the gas sample into a Varian CP-3800 gas chromatograph (Varian Canada Inc., Mississauga, Ontario, Canada) equipped with a 0.5 mL sample loop, flame ionization detector, and 15 m × 0.32 mm Restek Rt-SPLOT™ capillary column (Chromatographic Specialties Inc., Brockville, Ontario, Canada). The injector, column and detector temperatures were 120, 35 and 225 °C, respectively. High-grade helium was used as the carrier gas at a flow rate of 0.37 $mL\,s^{-1}$ with a typical run time of 1.5 min.

Fruit firmness was determined on opposite sides of each apple after peel removal, using an electronic texture analyzer fitted with an 11-mm tip (GÜSS, South Africa). Titratable acidity (expressed as mg equivalents of malic acid per 100 mL of juice) was determined by titrating a 2-mL juice sample with 0.1 N NaOH to an end point of pH 8.1 (indicated using phenolphthalein). Soluble solids concentration (SSC) was determined on a juice sample using a digital refractometer (BRX-242; Erma Inc., Tokyo, Japan). Starch index was determined using the Cornell Starch Chart (Blanpied and Silsby, 1992). Apples were cut in half at the equator, dipped in potassium-iodine solution and rated on a scale of 1–8, where 1 = 100 % starch staining, and 8 = 0 % starch staining.

After the storage period plus 1 and 7 d at room temperature (RT, 18–22 °C), 10 fruit per box replicate of each treatment were also