SmartFresh™ (1-MCP) – The Good and Bad as We Head Into the 2004 Season!

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1-Methylcyclopropene (1-MCP), sold under the commercial name of SmartFresh™, needs little introduction to storage operators in New York. 1-MCP has quickly become a major component of our industry. Its effects on delaying apple ripening, and especially on maintaining the texture quality of fruit, continue to amaze, and 1-MCP is impacting sales both domestically and internationally. We receive telephone calls from retailers wanting to know how 1-MCP works because they cannot believe the quality of Empire apples that they are selling. The UK market has also responded very positively to the beneficial effects of 1-MCP on fruit quality. The advantage that 1-MCP confers on apple fruit is that it helps maintain the fruit's firmness throughout the entire marketing chain, in contrast to air and CA storage alone where fruit can deteriorate and quickly soften after leaving the packing house.

However, there are positives and negatives to the 1-MCP story, some of which can be addressed by research. Others, such as the effects of 1-MCP on consumer expectations for certain varieties, are ultimately ones that the industry must resolve. We are doing as much as we can with the available resources to understand the strengths and weaknesses of 1-MCP, but rapid uptake of the technology by the New York apple industry means that problems are being identified more quickly than solutions are found. In the case of the last major breakthrough in storage technology, controlled atmosphere (CA) storage, implementation took place over many years, and, even today, problems are still common. With 1-MCP, we as an industry are fast-tracking adoption of a new technology that still has many unknowns.

In this article, some of the major issues that are facing users of 1-MCP are outlined as we approach the 2004 harvest season. We do not have all the answers and some of the opinions below must be regarded as speculative.

SmartFresh (1-MCP) has quickly become a major component of the NY apple industry. Its effects on delaying apple ripening, and softening, continue to amaze, and it is positively impacting sales both domestically and internationally. However, there are also some areas of concern. One of these in particular, has been internal browning disorders. We are doing as much as we can with the available resources to understand the strengths and weaknesses of 1-MCP.

Effects of Variety

There are two aspects that are important when considering varietal responses to 1-MCP.

First, what are the inherent qualities that the consumer expects from a particular variety, and will 1-MCP increase or decrease these qualities? In low-aroma apple varieties, such as Empire and Delicious, the most important attributes for consumers appear to be texture and the sugar/acid balance. Consumer responses to such varieties treated with 1-MCP are usually overwhelmingly positive. Exceptions can occur because consumers do expect apples to soften to at least an edible texture, and there have been occasional reports of 1-MCP-treated apples of some varieties being too hard

The situation with high-aroma varieties, such as McIntosh, may be more complex. Inhibition of ethylene production by 1-MCP can inhibit production of aroma volatiles. Therefore, consumer expectations for a soft, aromatic and flavorful fruit may not be met. On the other hand, the market segment for soft apples is declining and it is possible that a less flavorful but firmer McIntosh may create new market opportunities for the industry. Market expectations for a variety must be considered as part of the decision making process regarding 1-MCP use.

The second aspect is the variability among, and within, varieties in responsiveness to 1-MCP. In theory, every apple variety can respond to 1-MCP, but, in practice, this response is affected by fruit ethylene production. Our research shows that there are few examples of absolutely no response to 1-MCP, but rather that there are degrees of response. The effects of 1-MCP can be long- or short-lived depending on many pre- and post-harvest factors that affect ethylene production by the fruit.

To understand the reason for this it is important to remember that apples are natural producers of ethylene, the compound responsible for softening, red color development, and other ripening processes. Ethylene production can occur in fruit while on the tree as well as after harvest, and occurs autocatalytically, i.e.

1-MCP is classified as a plant growth regulator. We have previously outlined how 1-MCP works to prevent ethylene action (Watkins and Nock, 2000), and a summary of our experiences with 1-MCP is available in the proceedings of the 2003 Cornell Storage Workshop (Watkins and Nock, 2003). Further information about the registration of 1-MCP, including safety profiles, is available at: http://www.epa.gov/pesticides/biopesticides/ingredients/fr_notices/frnotices_224459.htm

a small amount of ethylene in the fruit results in increasingly greater amounts over time. Fruit with high rates of ethylene production cannot respond as well to 1-MCP as those fruit with low rates of ethylene production. Typically, varieties that have lower ethylene production rates during the normal harvest window such as Gala, Empire, Delicious and Jonagold respond strongly to 1-MCP. In contrast, varieties with high ethylene production during the normal harvest period respond much less favorably. For example, we find that effects of 1-MCP on Macoun are limited, as is often the case for McIntosh. Use of Ethrel and other pre-harvest factors that induce ethylene production markedly reduce the effectiveness of 1-MCP. (We suspect that NAA used to prevent preharvest drop may also decrease effectiveness of 1-MCP because it can stimulate ethylene production by the fruit, but we have not been successful in obtaining conclusive data). Also, as described below in the section about delays between harvest and 1-MCP treatment, pre- and post-harvest factors are closely linked.

The bottom line is that variety responses to 1-MCP are affected greatly by ethylene production during the harvest period. Different varieties have different ethylene production rates and timing of this production relative to their normal harvest period. Moreover, pre-harvest treatments can affect the timing of autocatalytic ethylene production. The temptation to harvest fruit earlier to improve the response to 1-MCP must be avoided, however, as fruit harvested prematurely will never develop the flavor and quality characteristics desired by the consumer.

A further complication in considering varieties and 1-MCP is that ethylene production varies from region to region, not only in the timing of its autocatalytic increase, but also in actual rates of production. In general, fruit grown in warmer climates have more rapid ethylene production. In varieties such as McIntosh, growers fight a constant battle between obtaining sufficient red coloration and pre-harvest fruit drop, and the relationship between the two factors is affected by region. The best "home" for 1-MCP useage for McIntosh appears to be the Champlain region where good color development usually precedes ethylene production. Therefore, it is possible to harvest high quality fruit and obtain uniform responses to 1-MCP. Elsewhere in the state, the situation is more problematic. Obtaining adequate color development before ethylene increases (often evidenced by preharvest drop) can be difficult, and even worse, affected seasonally. Therefore, 1-MCP is more likely to have inconsistent benefits on texture and other ripening attributes from year to year. A scenario that is not impossible to imagine in Western New York is that for three years in a row we have good coloring weather, allowing for early harvest of fruit and thus good 1-MCP effects. This is then followed by a late coloring year with little response to 1-MCP, and therefore, an inability to provide the market with product that it has come to expect.

The particular variety and when it is harvested provides the base product for 1-MCP treatment. Although maturity guidelines of starch indices and firmness are provided by AgroFresh (the commercial suppliers of 1-MCP), the most reliable guide to responsiveness of fruit to 1-MCP is ethylene production or internal ethylene concentration (IEC). Thus, when one considers the diversity of orchard microclimates and management decisions that exist in the field, the process of determining potential effects of 1-MCP remains relatively crude.

Air Compared with CA Storage

We do not advocate the use of 1-MCP as an alternative to CA storage for medium to long term periods. With increasing storage periods, the two technologies are always more effective when used in combination. Use of CA as a supplement to 1-MCP is also more critical with longer storage times, especially if there are bins of fruit that do not respond to the treatment.

1-MCP can be an excellent replacement for CA storage for short term storage, especially to meet the December/January market when storage quality begins to decline. The potential for 1-MCP usage has already been recognized by New York growers who own retail operations which lack CA facilities. It is important to realize, however, that variety responses to 1-MCP also differ greatly even for shorter term storage periods. Apples such as McIntosh can lose their responses to 1-MCP much more quickly than varieties such as Empire, especially during air storage (Figure 1).

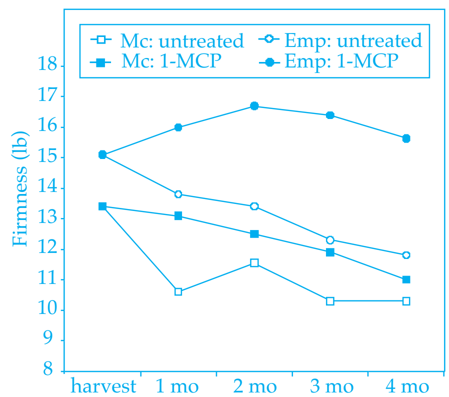

Figure 1. Firmness (lb) of McIntosh and Empire apples treated with 1ppm 1-MCP and stored in air for up to 4 months. Fruit were removed from storage at monthly intervals and firmness measured after 7 days at 68°F.

Delays Between Harvest and 1-MCP Treatment

The New York apple industry is diverse, ranging from small retail operations to large volume cooperatives. While the latter type of operation is able to organize fast harvest and rapid CA storage, many smaller operations are not able to do so due to limitations of scale. The AgroFresh guidelines call for a seven day maximum between harvest and treatment with 1-MCP for most varieties with a smaller harvest window of three days for McIntosh. We have carried out extensive studies with several varieties, and the results of these trials are available in Watkins and Nock (2003). Here, we have selected a few results that illustrate the importance of the time between harvest and treatment as a factor in 1-MCP success.

Harvest date interacts with the need to treat fruit with 1-MCP quickly after

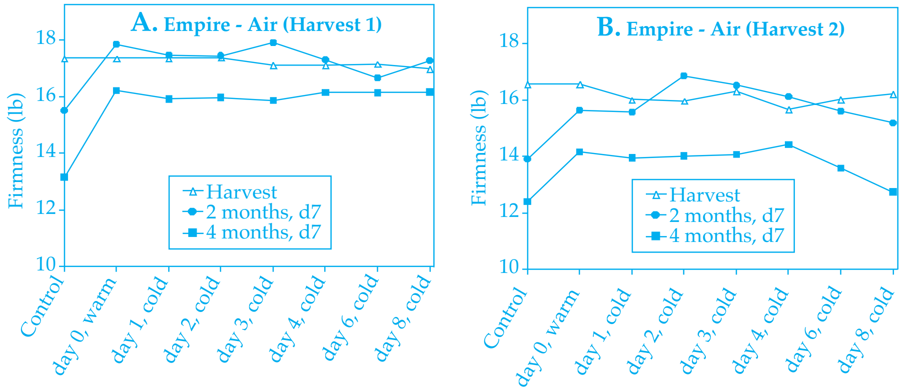

Figure 2. Firmness of Empire apples from two harvest dates (A) Sept. 28, 2000, when the internal ethylene concentrations were 0.39ppm, and (B) October 12, 2000, when the internal ethylene concentrations were 32ppm. Fruit were treated with 1-MCP at harvest (warm) or after 1, 2, 3, 4, 6 or 8 days of cold storage. Fruit were stored in air at 33°F for 2 or 4 months and assessed after 7 days at 68 °F.

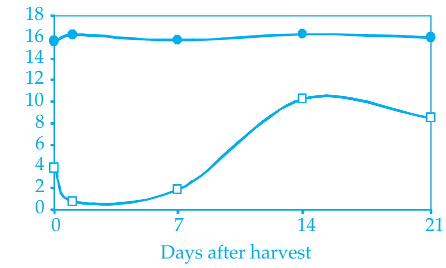

Figure 3. Firmness (lb) and internal ethylene concentration (ppm) changes that occurred in Jonagold apples over a 21 day period in cold storage (33°F) after harvest.

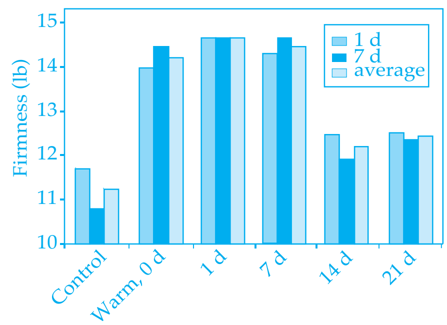

Figure 4. The firmness of Jonagold apples after storage in CA conditions for 5 months, when either untreated, or treated with 1-MCP on the day of harvest (warm), or after 1, 7, 14 or 21 days of cold storage.

harvest. Figure 2 A and B shows the effect of 1-MCP applied on the day of harvest (warm) or after being placed in cold air storage for 1, 2, 3, 4, 6 and 8 days for early and late harvested Empire apples. For fruit harvested at the start of the optimum harvest window for CA storage, negligible softening occurred after two months plus a seven day shelf life (Figure 2 A). There was little difference among 1-MCP treatments, i.e., warm or cold from one to eight days after harvest. After four months of cold storage, fruit had softened about a pound, but there was still no effect of treatment delays. For fruit harvested later, firmness was maintained for two months, and again softening occurred by the four month evaluation, although to a greater extent than for fruit from the first harvest (Figure 2 B). However, fruit had to be treated within a four day time frame to obtain benefits from 1-MCP. For fruit from this late harvest, treatment within three days was necessary to maintain the firmness of CA-stored fruit for eight months (results not shown).

Because it is common for smaller New York storages to have fewer CA rooms and longer periods of accumulations of fruit, and often different varieties, we also tested the effect of delays of up to 21 days before application of 1-MCP. Jonagold fruit are used as an example of why the response to 1-MCP is affected by time. After harvest, the IEC of fruit initially declined but started to increase by day seven (Figure 3). Our expectation was that this increase would coincide with the declining effectiveness of 1-MCP, and this was illustrated by fruit firmness after five months of CA storage (Figure 4). Fruit treated with 1-MCP either warm, or cold after one or seven days were markedly firmer than fruit that were untreated. However, the effectiveness of 1-MCP declined markedly in fruit that were treated after 14 or 21 days.

These types of data form the basis of current recommendations for maximum delays between harvest and 1-MCP application. It is important to recognize, however, that there are degrees of response to 1-MCP that are affected by both pre- and post-harvest handling interactions. The times between harvest and 1-MCP treatment to obtain optimum responses may be shorter than the industry recommendations, and a good rule of thumb is that the longer the storage period, the more important is rapid 1-MCP application.

Physiological Disorders

1. Carbon dioxide injury. An early concern about 1-MCP was that it appeared to increase fruit susceptibility to external carbon dioxide injury (Figure 5). The varieties that we were most concerned about were McIntosh, Cortland and Empire. (We have not examined the effects of 1-MCP on internal carbon dioxide injury). The mechanism of carbon dioxide injury is not well known, but greener, less mature tissues appear to be more susceptible. 1-MCP may increase susceptibility to injury by maintaining fruit in a younger physiological state during storage. Some of our previous research determined that delays between harvest and exposure to high carbon dioxide concentrations, or application of diphenylamine (DPA) used for control of superficial scald, decreased or eliminated external carbon dioxide injury. Also, the critical time for exposure of fruit to carbon dioxide was in the first month or so of storage.

We have suggested three possible solutions to avoid carbon dioxide injury (Watkins and Nock, 2003):

1a. Treat all carbon dioxide injury susceptible varieties with DPA. No external carbon dioxide injury has been observed in DPA-treated fruit. Therefore, DPA drenching remains the most straightforward solution to the problem of carbon dioxide injury when used according to the label to prevent scald. However,

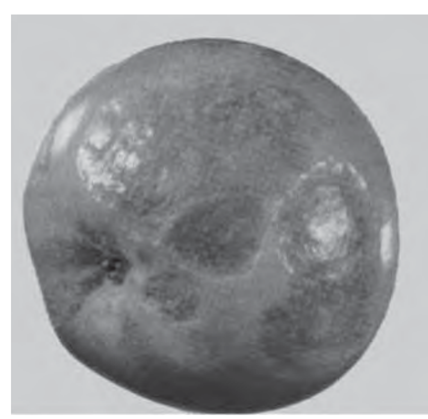

Figure 5. Severe carbon dioxide injury. In some instances, injury is barely perceptible, especially on Empire apples.

many storage operators are reluctant to use DPA because of the chemical and handling costs necessary for treatment. Handling costs are much greater, especially for smaller operations that are not able to utilize truck drenching operations that are typically practiced in Western New York. Also, some operators have found that decay of fruit in bins is higher when fruit are drenched. Finally, regions such as the Champlain that do not use DPA for McIntosh because of a lower scald risk than elsewhere in the state, are understandably reluctant to incorporate its use into their handling operations.

1b. Maintain carbon dioxide levels lower than 1 percent for the first 4 to 6 weeks of CA storage. Several storage operators have used this method during the last two years. Anecdotal evidence has shown that carbon dioxide injury has usually not been eliminated but was reduced to minimal levels, certainly lower than those due to decay where DPA has been used. However, major losses have been suffered by some storage operators even when carbon dioxide levels have been less than 1%. The reasons why some storages were affected more than others are not known. In addition there are many unknowns related to loading and cooling time and effects of elevated carbon dioxide during this time in relation to injury.

For this season we are altering this recommendation for Empire to "maintain carbon dioxide levels less than 0.5 percent for the first 4 to 6 weeks of CA storage." McIntosh appears less sensitive to carbon dioxide injury but we don't have a recommendation for carbon dioxide levels at this time. Lack of a recommendation for McIntosh only affects the Champlain region as DPA is used in all other New York growing regions.

The other consideration about maintaining low carbon dioxide levels in storage is that Empire and McIntosh require high carbon dioxide levels in the storage atmosphere to maintain fruit firmness. Figure 6 shows that carbon dioxide levels close to 2.5 percent are better for maintaining firmness in fruit that have not been treated with 1-MCP. This requirement is reduced in 1-MCP-treated fruit, but Drs. DeEll and Murr in Ontario have found that the absence of carbon dioxide can result in greater losses of firmness than we have observed. Therefore, we recommend allowing carbon dioxide levels to increase after the initial low period.

1c. Delayed application of CA storage after treatment of fruit with 1-MCP. If fruit respond to 1-MCP, their metabolism is slowed down. Therefore, it should be possible to treat with 1-MCP, but not apply CA storage regimes for a week or two. No commercial testing of this recommendation has been carried out to our knowledge for control of carbon dioxide injury, although treatment of smaller fruit volumes on a daily basis and later closing of rooms is becoming more common. In the 2003 harvest season we tested delays of 7 and 14 days on fruit treated with 1-MCP at harvest. McIntosh from the Champlain (Rogers) and Western New York (Marshall), and Empire from the Hudson Valley and Western New York, were harvested from three orchard blocks in each region.

Both McIntosh and Empire fruit responded to 1-MCP in typical fashion (Tables 1 and 2); fruit were firmer than untreated fruit and the softening during the shelf life period at 68°F was reduced or prevented. Treating fruit at the time of harvest, but not applying CA for up to 14 days did not result in softer fruit.

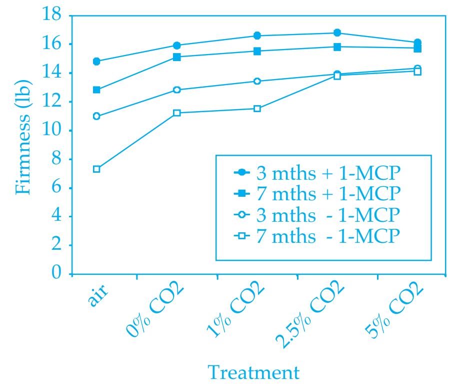

Figure 6. Firmness (lb) of Empire apples either untreated or 1-MCP treated at harvest and stored in air or in 0, 1, 2.5 or 5% carbon dioxide (in 2% oxygen) for 3 and 7 months. The 1-MCP-treated fruit (closed symbols) maintained firmness irrespective of carbon dioxide concentration, whereas the firmness of untreated fruit declined with carbon dioxide of less than 2.5%.

However, the objective of this method was to reduce carbon dioxide injury. For McIntosh, injury was found only on Champlain fruit and for Empire only from Western New York grown fruit. Injury was detected only on 1-MCP-treated fruit

TABLE 1

Firmness (lb) of McIntosh apples from Champlain and Western New York orchards harvested on 24 and 22 September, 2003, (internal ethylene concentrations averaged 15 and 42 ppm) respectively. Fruit were treated with 1ppm 1-MCP after overnight cooling and placed under CA (2% carbon dioxide. 2% oxygen) conditions 2, 7 or 14 days after harvest. Firmness was measured after 6 months of storage plus 1 or 7 days at 68°F.

	Champlain				Western New York			
	No 1-MCP		1-MCP		No 1-MCP		1-MCP	
Delay	1 d	7 d	1 d	7 d	1 d	7 d	1 d	7 d
2 d	14.2	11.7	14.5	14.2	12.6	11.8	13.4	13.1
7 d	12.1	10.3	14.5	13.6	12.2	11.6	13.8	13.9
14 d	11.6	10.5	14.7	13.8	11.7	11.3	13.2	12.9

TABLE 2

Firmness (lb) of Empire fruit from the Hudson Valley and Western New York orchards harvested on 6 and 7 October, 2003, (internal ethylene concentrations averaged less than 1 ppm) respectively. Fruit were treated with 1ppm 1-MCP after overnight cooling and placed under CA (2% carbon dioxide. 2% oxygen) conditions 2, 7 or 14 days after harvest. Firmness was measured after 6 months of storage plus 1 or 7 days at 68°F.

	Hudson Valley				Western New York			
	No 1-MCP		1-MCP		No 1-MCP		1-MCP	
Delay	1 d	7 d	1 d	7 d	1 d	7 d	1 d	7 d
2 d	15.3	14.4	15.5	15.5	16.6	16.4	17.1	16.9
7 d	14.6	13.7	15.7	15.7	16.2	15.0	17.3	17.0
14 d	15.1	13.8	15.9	15.5	16.1	14.9	17.1	17.1

from two of three growers, the maximum being 5 percent for one grower. A delay of seven days did not reduce injury, but less than 1 percent was detected after a 14 day delay. However, in Empire, injury was increased by 1-MCP, but not affected by the 14 day delay.

Other disorders were found in these experiments. In Champlain McIntosh, senescent breakdown in untreated fruit increased with delays before CA storage. Depending on the grower lot, 1-MCP decreased but did not prevent development of breakdown. In Marshall McIntosh, the incidence of breakdown was affected by grower but not by 1-MCP or delays.

For Empire, flesh browning was not affected by 1-MCP in fruit from either region. Core browning and decay in fruit from the Hudson Valley was low and not affected by 1-MCP. However, in the Western New York fruit, core browning was usually reduced by 1-MCP. Decay incidence increased with delays between 1-MCP treatment and CA storage, but was affected by grower, and was usually reduced by 1-MCP. The greatest concern about this technique is that if fruit in the room are not responsive to 1-MCP, then their quality will be worse than if the room was sealed more rapidly after harvest. Therefore, we do not recommend this method to reduce carbon dioxide injury, especially as susceptibility to other disorders may be enhanced.

2. Superficial scald. Development of superficial scald has not been a problem for storage operators who have relied on 1-MCP instead of DPA. More information about scald control and 1-MCP is available in Watkins and Nock (2003). We continue to believe that if applied appropriately, 1-MCP will control superficial scald for many varieties, especially Delicious, but that under New York conditions control is often incomplete for Cortland. In general, if the effects of 1-MCP are beginning to wear off as indicated by fruit softening, then the risk of scald developing in susceptible varieties will increase dramatically.

3. Chilling injury and internal browning disorders. The 2003 storage season has been a difficult one for the industry, with the appearance of browning type disorders. These have fallen into two types – chilling injury and internal breakdown.

TABLE 3

Storage disorders of Empire apples harvested from the Hudson Valley (Oct.3, 2002) and Western New York (Oct. 4, 2002), treated with 1ppm 1-MCP and stored at 33 or 38°F in CA (2% carbon dioxide/2% oxygen) for 9 months and assessed after 7 days at 68 °F. Means are the average of fruit from three orchard blocks.

Growing region	Temperature (°F)	1-MCP	Decay (%)	Senescent breakdown (%)	Flesh browning (%)	Core browning (%)	Ext. carbon Dioxide injury (%)
Hudson Valley	33	-	10	0	6	4	0
		+	10	0	2	14	0
	38	-	38	30	0	26	0
		+	38	0	54	21	0
Western NY	33	-	5	0	12	12	1
		+	6	0	14	16	0
	38	-	20	0	21	29	6
		+	21	0	41	35	4

The most common disorder that was noticed by the industry this year is chilling injury as shown in Figure 7. This injury first appears as a very slight browning discoloration of the flesh, sometimes, but not always accompanied by core browning. To the untrained eye this discoloration can be barely visible and the fruit marketable as no off-flavors are detectable. However, the disorder progresses quickly to the point where fruit become unmarketable. Chilling injury susceptibility is a feature of Empire in particular, and the reason why storage temperature recommendations for this variety are 35-36°F, especially if fruit are stored beyond May when the risk increases substantially. Risk is typically higher in years when July and August temperatures are below the 30 year average. Last season, temperatures were not particularly low, but the weather was cloudier and fruit generally had lower soluble solids contents than normal. Thus the risk was higher than normal and many storage operators responded by increasing storage temperatures. It is uncertain if 1-MCP increased the risk of chilling injury development, especially as there are few examples of the same fruit not being treated with the chemical and being stored under identical conditions.

The second problem has been fruit breakdown and attendant softening that has been associated with use of 1-MCP. This has tended to show up in later harvested fruit, but we do not know what the exact causes are. In some cases, as described below, the browning is diffuse and similar in appearance to chilling injury, but in others, the breakdown is much more extensive.

Our results from previous trials are confusing. In 2002 we harvested fruit from three orchard blocks in the Hudson Valley and Western New York and stored untreated and 1-MCP treated fruit under CA conditions at 33 °F and 38 °F for 9 months. The disorder results (Table 3) show that:

Figure 7. Chilling injury symptoms on Empire apples.

3a. Decay was greater in fruit stored at 38 °F than at 33 °F, regardless of region, and there was no effect of 1-MCP on decay.

3b. Senescent breakdown occurred only in untreated fruit from the Hudson Valley that were stored at 38 °F. As we have found elsewhere, senescent disorders were markedly reduced by 1-MCP application.

3c. Flesh browning, which was diffuse, and easily confused with chilling injury, was more prevalent in fruit stored at 38 °F compared with 33 °F, and was much more so in fruit that were treated with 1-MCP.

3d. Core browning was more common at higher storage temperatures but not affected greatly by 1-MCP application.

3e. External carbon dioxide injury was not detected in fruit from the Hudson

Valley, while in Western New York it was worse at 38 °F than at 33 °F, but was not affected by 1-MCP application.

We are also re-examining disorder results from other trials. One for example, was described above where we treated Empire fruit with 1-MCP at harvest or after delays of up to eight days. In the experiment where we stored fruit for four and eight months under CA conditions there was 27 percent flesh browning in fruit from the first harvest, but 83 percent in fruit from the second harvest. The fruit from the second harvest also had high incidences of core browning and water-soaked areas. However, 1-MCP did not affect the amounts of these disorders relative to the untreated controls.

These results are confusing. We have suggested previously that a response to chilling-type disorders could be to use higher storage temperatures, especially since 1-MCP should control ripening and therefore reduce the requirement to use as low as storage temperatures as possible. This recommendation is tempered by the observations that other problems may be much more severe at the higher temperature of 38 °F. Understanding how this problem can be solved is a priority for research during the 2004 harvest season. In the meantime, the industry should assume that there are limits to the use of 1-MCP-treated Empire to extend CA storage periods. Anecdotal evidence is that the problems are associated most with extended storage beyond May/June.

Conclusions

1. The vast majority of apple varieties respond well to 1-MCP, but some, e.g. Macoun, have poor responses probably because of high ethylene production at harvest.
2. 1-MCP can maintain quality of fruit in air for several months, but its effectiveness is affected by variety. Best responses of fruit to 1-MCP occur in combination with CA and we believe that it is unlikely to be a substitute for CA storage. For some varieties, 1-MCP has the potential to greatly improve quality of air-stored fruit marketed during December and January, especially where it is not feasible to hold that fruit in short-term CA storage.
3. Even for responsive varieties, degrees of response to 1-MCP occur. Response to 1-MCP depends on harvest maturity, storage type, length of storage, handling protocols prior to 1-MCP application, and interactions among all of these factors. These interactions are most likely associated with ethylene production of the fruit at harvest and the effectiveness of postharvest handling treatments on slowing down ethylene production by the fruit.
4. Fruit must not be harvested too early to get better responses to 1-MCP however, as these fruit may never develop marketable quality characteristics.
5. Minimizing the time between harvest and 1-MCP treatment becomes increasingly important as the desired storage period increases.
6. 1-MCP can increase risk of carbon dioxide injuries but strategies that can reduce this risk have been identified.
7. 1-MCP can reduce the risk of superficial scald developing, and for many, but not all varieties, can eliminate the requirement for DPA drenching.
8. 1-MCP may increase the risk of chilling injury development, but solutions to the problem have not been identified.

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