Control of Superficial Scald of Apples by Low-oxygen Atmospheres

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OVERVIEW OF THE PROBLEM

Superficial scald is a pervasive physiological disorder of apples and pears (*Pyrus malus* L.) (Ingle and D'Souza, 1989), causing browning of the skin during or after low-temperature storage in air or after controlled-atmosphere (CA) storage, destroying the appearance and fresh-market value of the fruits. The affected cells of the hypodermis die and dehydrate (Bain, 1956; Bain and Mercer, 1963). Affected fruits may be processed as juice or sauce or sliced for bakery products, but product yield is reduced by trimming and costs are increased because of higher labor input. The physiology and control of scald have been reviewed periodically (Blanpied, 1990; Emongor et al., 1994; Ingle and D'Souza, 1989; Meigh, 1970; Smock, 1961), but not recently, and much has been learned from recent, expanded efforts in scald research. This review focuses on the etiology of scald in relation to low-oxygen stress regimens that control scald and the role of volatiles which have been implicated in this physiological disorder.

Apples and pears are major U.S. horticultural crops and are consumed as fresh fruits, minimally processed, sliced fruits, and, after processing, as canned or frozen products, sauce, and bakery and juice items. The domestic and export markets for these fresh fruits are large. Large crops require that more than half of the fruits grown be stored for up to a year in refrigerated air or CA storage to allow orderly marketing for fresh and processed fruit. The scald disorder is induced by storage at the low temperatures required to delay ripening. Most cultivars of apples and pears are susceptible to scald (Ingle and D'Souza, 1989). Scald has the potential to destroy the market value and utility of millions of tons of apples and pears annually unless the fruits are treated with a postharvest drench with diphenylamine (DPA) or ethoxyquin (6-ethoxy-1,2-dihydro-2,2,4-trimethylquinoline). The possible loss of DPA for controlling apple scald has prompted renewed interest among researchers worldwide in developing alternative strategies to control scald.

FACTORS RELATED TO THE SUSCEPTIBILITY OF APPLES TO SCALD

Much is known about the factors that predispose apples to scald, storage conditions that favor or reduce scald, and postharvest treatments that may control it, and some insight has been gained about physical, physiological, and biochemical mechanisms that may help explain the nature and control of the disorder. Here we summarize salient information gained from a vast body of scald-related research spanning the past 60 years about factors and treatments that reduce or control scald, and discuss the characteristics and manifestations of scald and the factors that have been implicated in its development and control.

Characteristics and manifestations of scald

- It affects most, but not all cultivars of apples, which suggests a genetic basis for the disorder.
- It is a dysfunction of the pigment-containing cells of the hypodermis, especially, but not limited to, the non-red portion of the fruit surface.
- It is less prevalent with fruits harvested after exposure to cool temperatures late in the growing season.
- It becomes more prevalent as the fruits senesce or age during storage and upon subsequent warming.
- It is a manifestation of membrane-based chilling injury.
- It is caused by accumulation of a volatile by-product of metabolism in the affected cells.
- It may be a consequence of oxidative metabolism involving reduced species of O₂, e.g., active O₂ species (AOS) such as O₂⁻, H₂O₂, and free radicals derived from them, such as the hydroxyl radical (·OH), peroxy radical (·OOH), and perhaps singlet (¹O₂).
- It is a metabolic dysfunction probably caused by oxidation of α-farnesene to 6-methyl-5-hepten-2-one (MHO) and its subsequent metabolism via free-radical intermediates.
- Cell death may be caused by the oxidation of essential amino acid functional groups of enzymes and of membrane lipids to carbonyl derivatives, preventing them from functioning, or targeting the proteins for proteolysis.

Factors, postharvest treatments, and storage regimens that reduce scald incidence:

- An ample level of naturally occurring antioxidants, such as ascorbic acid, carotenoids, α-tocopherol, and glutathione, which act to

scavenge free-radicals.

- Exogenously applied antioxidants such as DPA, 6-ethoxy 1,2-dihydro 2,2,4-trimethylquinoline (ethoxyquin), ascorbate-6-palmitate, butylated hydroxy toluene (BHT), butylated hydroxyanisole (BHA), and squalene, which scavenge free-radicals if applied shortly after harvest.
- Hypobaric ventilation during the first month of storage of fruits stored subsequently in air or CA, respectively.
- CA storage at ultra-low O₂ levels, e.g., 0.7% O₂.
- CA storage at 1.5% O₂ with ventilation to scrub carbon dioxide.
- Ethanol vapor treatment of fruits before CA storage.
- Initial low-oxygen stress (ILOS) at 0.5% O₂ for 2 weeks before CA storage at 1.5% O₂.

Cultivars

Some cultivars of apple, e.g., 'Law Rome', 'Granny Smith', 'Delicious', 'McIntosh', and 'Cortland', are particularly susceptible to scald, while others, e.g., 'Empire' and 'Golden Delicious', show some natural resistance (Emongor et al., 1994; Ingle and D'Souza, 1989). The genetic basis for differing susceptibilities to scald among cultivars is not known. Studies under way at Cornell Univ. by Dr. Chris Watkins may provide this needed insight.

Preharvest factors

Environment during the growing season influences scald susceptibility, as does mineral nutrition (Emongor et al., 1994; Fidler, 1957). Apples with low calcium levels often develop more scald than those with high levels (Bramlage et al., 1974). Heavy application of nitrogenous fertilizers increases scald susceptibility in 'McIntosh' apples (Weeks et al., 1958). Apples grown under warm and dry environmental conditions are generally more prone to scald than when grown in cooler climates. This may be related to the nature and amount of the cuticular wax components developed on the fruit and during storage (Emongor et al., 1994).

Maturity

Scald is generally more problematic with fruits of all cultivars when they are harvested while immature. Susceptibility to scald decreases with fruit maturity when fruits are sampled from the same trees in the same season (Anet, 1972b; Christopher, 1941; Ingle

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and D'Souza, 1989). Immature fruits are very susceptible to scald (Huelin and Coggiola, 1968), but apple growers have been compelled to harvest apples relatively immature to extend the CA storage season beyond 6 months. Early harvesting of some cultivars, e.g., 'Granny Smith', is encouraged to ensure high chlorophyll levels needed for successful marketing and this exacerbates its scald problem. But even 'Granny Smith' becomes less prone to scald when allowed to achieve full maturity before harvest. Delayed harvest increases the concentrations of α -tocopherol and carotenoids, but not ascorbic acid, and greatly reduces scald development (Barden and Bramlage, 1994c). Ethephon (2-chloroethylphosphonic acid), an ethylene-generating chemical, hastens ripening and reduces scald (Couey and Williams, 1973; Greene et al., 1977; Hammett, 1976; Lurie et al., 1989b; Windus and Shutak, 1977). Early initiation of ripening by application of ethephon 3 to 5 weeks before harvest reduced superficial scald while increasing the content of lipid-soluble antioxidants in the fruit peel after 8 months in storage (Curry, 1994).

Prediction of superficial scald

Some success has been achieved in predicting scald susceptibility of 'Cortland' and 'Delicious' apples in the northeastern United States (Barden and Bramlage, 1994a), based upon the accumulation of days or hours at temperatures below 10 °C during the late maturation stage of fruit development. For other regions and cultivars this has given promising but mixed results (Watkins and Bramlage, 1994).

Chilling injury

Superficial scald is considered to be a chilling injury-related disorder (Watkins et al., 1995). In support of this premise, Melville and Hardisty (1953) found good control of scald in 'Granny Smith' apples by storing them at $\approx$ 5 °C in air for several weeks followed by storage at 0 °C; apple scald did not occur on fruits stored above 10 °C. However, a disorder similar to scald can be induced at 20 °C by anaerobiosis followed by returning the fruits to air; it, too, was prevented by DPA (Dilley et al., 1963). Bauchot et al. (1999) have confirmed that anoxia can induce this scald-like disorder. Moreover, their studies show that as harvest is delayed, fruits are less susceptible to anoxic treatment; naturally occurring scald exhibits the same relationship with maturity (Huelin and Coggiola, 1968). Transferring tissues from anaerobic to aerobic atmospheres may promote the production of active O_2 species (Crawford and Braendle, 1996), and this may explain anaerobic induction of scald (Bauchot et al., 1999). Storing fruits in air at 0 to 5 °C increases their tendency to scald, although actual symptom development may appear many months later, as demonstrated by studies on the timing of application of a scald inhibitor (Watkins et al., 1995). To be effective in

controlling scald, DPA must be applied shortly after harvest (Shutak and Christopher, 1960); it is ineffectual once the fruits have been in air storage for more than 3 to 4 weeks. This suggests that low-temperature storage in air potentiates scald development, and is consistent with scald being a manifestation of chilling injury. Intermittent warming treatments are sometimes effective in preventing scald; such treatments commonly reduce chilling injury in other fruits (Lurie, 1998).

Chilling injury is clearly associated with perturbation of membrane functions. Ethanol vapor treatment attenuates scald (Scott et al., 1995a) and also reduces chilling-induced injury of excised cucumber (*Cucumis sativus* L.) cotyledons, apparently by inducing stomatal closure (Saltveit, 1994). Other primary alcohols have a similar effect and their efficacy is related to their lipid solubilities; this was also found for retardation of senescence in oat (*Avena sativus* L.) leaves (Satler and Thimann, 1980). Primary alcohols affect many metabolic processes in a similar manner, as noted by Saltveit (1994); examples include ATPase activity, electron transport, membrane permeability, and photophosphorylation. Thus, alcohols may exert their effects at a fundamental level involving the plasmalemma. Primary alcohols are excellent nucleophilic acceptors for the phosphatidyl moiety of all phospholipids (Heller, 1978). Phospholipase D (PLD), an ubiquitous enzyme requiring Ca^{2+} , catalyzes a transphosphatidyl reaction in which the head group of the phospholipid is removed and a phosphatidyl alcohol is formed; with water as the acceptor, phosphatidic acid is formed. Alcohol utilization is a highly conserved feature of PLD (Ella et al., 1997). This reaction can occur in the plasmalemma in vivo. Inhibition of the normal reaction of PLD in forming phosphatidic acid by alcohols can have profound effects on plant processes by affecting a wide range of signal transduction systems (Ritchie and Gilroy, 1998). Ethanol vapor treatment inhibits α -farnesene production and reduces scald (Grahamani and Scott, 1998a; Wang, 1998). Farnesol may also serve as an alcohol acceptor for phospholipase D, since it is a primary alcohol. Farnesol is not a precursor for α -farnesene (Rupasinghe et al., 1998) in apple tissue, but is produced from farnesyl pyrophosphate at a 100-fold greater rate than is α -farnesene. Thus, sequestering α -farnesol as a phosphatidyl alcohol by the action of PLD may effectively prevent farnesyl pyrophosphate from being converted to α -farnesene and thus explain the correlation between scald and α -farnesene levels. This hypothesis is readily testable.

Storage conditions

High O_2 levels, low carbon dioxide levels, ethylene accumulation, and poor ventilation conditions during storage increase scald incidence and severity (Lau, 1985a, 1985b; Little and Pegg, 1987; Little et al., 1985; Manseka and Vasilakakis, 1993; Porritt, 1966; Roberts et al., 1963).

ROLE OF BIOCHEMICAL FACTORS IN SCALD

Volatiles

Early investigations by Brooks et al. (1919) and studies by Fidler (1950) suggested that volatile substances produced by the fruits were the cause of scald. Wrapping fruits with mineral oil-impregnated paper was partially successful in controlling scald, so they hypothesized that some volatile organic substance produced by the fruit was absorbed in the oil and thus prevented its accumulation in the cuticle. Many researchers believe that natural volatiles produced by apple fruits, including α -farnesene (2,6,10-trimethyl-2,6,9,11-dodecatetraene) and its oxidation products, such as conjugated trienes, conjugated trienols, and 6-methyl-5-hepten-2-one (MHO) may be involved in scald development (Du and Bramlage, 1993; Filmer and Meigh, 1971; Huelin and Coggiola, 1970a; Meigh and Filmer, 1969; Murray, 1969; Murray et al., 1964; Song and Beaudry, 1996; Spicer et al., 1993; Wang and Dilley, 1997; Watkins et al., 1993; Whitaker et al., 1997). Fidler (1950) concluded that scald development involves a volatile as well as a nonvolatile substance. α -Farnesene was implicated in scald development more than four decades ago (Meigh, 1969). This compound accumulates in apples soon after harvest (Meigh and Filmer, 1969) and undergoes auto-oxidation by free radicals; the primary monomeric products are conjugated triene hydroperoxides (Anet, 1969) and conjugated trienols (Whitaker et al., 1997), which accumulate during subsequent storage (Anet, 1972a). The concentration and time of appearance of these oxidation products determined the severity of the disorder (Anet, 1972b). Scald development in 'Granny Smith', a cultivar very susceptible to scald, was correlated with the oxidation of α -farnesene to conjugated triene hydroperoxides (Filmer and Meigh, 1971; Huelin and Coggiola, 1970a). Extensive investigations in Australia suggest that scald results from the auto-oxidation of α -farnesene in the fruit skin (Anet, 1972a; Anet and Coggiola, 1974; Huelin and Coggiola, 1968, 1970b, 1970c; Huelin and Murray, 1966; Meigh and Filmer, 1969). The oxidation of α -farnesene yields conjugated triene hydroperoxide free-radicals and conjugated trienols (Whitaker et al., 1997), which may injure the cells and give rise to the symptoms of scald (Rowan et al., 1995). Song and Beaudry (1996) found that application of 6-methyl-5-hepten-2-one (MHO), a product of α -farnesene oxidation, applied to apple fruits caused a scald-like disorder. And, Mir et al., (1999) found that the time course of a poststorage burst of MHO production was associated with development of scald symptoms while DPA-treated fruits had neither such a burst in MHO nor did they develop scald. Ventilation disperses α -farnesene and reduces scald (Anet, 1972b); however, Match et al. (1998) suggested that the effect on scald may not be explained by loss of α -farnesene alone, since the rate of loss from the surface of the fruit depends more on

time of exposure during storage than on its concentration in the wax.

Collectively, research strongly supports the premise that some volatile(s) is closely related to scald development. The pathway of α -farnesene production in apples may have important implications for scald development. Rupasinghe et al. (1998) found that α -farnesene is derived from farnesyl pyrophosphate (FPP) and not from farnesol. The primary volatile produced during early stages of α -farnesene oxidation is MHO (Anet, 1972a). Exogenous application of MHO vapor induced scald symptoms on nine cultivars of apple; scald-susceptible cultivars were more sensitive than scald-resistant ones (Song and Beaudry, 1996). The time course of a poststorage burst of MHO production was associated with development of scald symptoms, while DPA-treated fruits had neither such a burst in MHO nor did they develop scald, suggesting that MHO may be a chemical factor in scald development. MHO, which had partitioned into the epicuticular wax of fruits stored hypobarically, was released upon transfer of fruits to 20 °C; both MHO accumulation and scald development were directly proportional to the duration of the delay in transfer to hypobaric storage (Wang and Dilley, 1999a). However, cultivars that did not develop scald also showed similar MHO levels and release kinetics. Application of ILOS at 0.25% and 0.5% O_2 inhibited α -farnesene and MHO production; the accumulation of MHO was highly related to scald development of apples while accumulation of α -farnesene was not (Wang and Dilley, 1999b).

Extensive analysis of the volatiles produced by apples receiving low O_2 stress or ethanol vapor treatments support the premise that metabolism of α -farnesene in the pigment-bearing cells is closely associated with development of scald. Scald development is highly correlated with accumulation of MHO (Mir et al., 1999; Song and Beaudry, 1996; Wang and Dilley, 1997). Moreover, DPA inhibited production of MHO, but not of α -farnesene from which MHO is derived. Our studies on fruits stored under continuous hypobaric ventilation (including 'GrannySmith') demonstrate that apples do not scald even after a year of such storage nor after subsequent removal to air at ambient temperature (Wang and Dilley, 1999a). Hypobaric storage favors the removal of all volatiles, including ethylene, produced by the fruits, although the fruits produce normal levels of α -farnesene and its oxidation product MHO following hypobaric storage. We suspect that the fruit's capacity to convert α -farnesene to MHO is prevented during hypobaric ventilation. However, hypobaric storage can control scald only if applied during the first month of storage at low temperature. This suggests that some chilling-related and aerobic metabolism-related phenomena occur during this period that is related to scald and these processes potentiate scald development in an irreversible manner. Hypobaric ventilation after these events have been entrained has no effect on scald development. Our studies with ILOS suggest a similar scenario, and, moreover, may explain scald

control by continuous ultra-low oxygen levels. The low-temperature aerobic metabolism during the first few weeks of storage, which predispose apples to scald, may involve the consequences of active oxygen species during the scald induction period.

Active oxygen species and enzyme systems

Active oxygen species (AOS) oxidize protein amino acid residues, such as lysine, resulting in formation of carbonyl groups, as measured by carbonyl content, and this is associated with scald development (Wang, 1998). All plant cells produce AOS such as O_2^- and H_2O_2 in aerobic metabolism. These AOS are normally dissipated in the cells by enzymatic reactions and by naturally occurring antioxidants. Failure of these defense systems to keep the titer of AOS at low levels can result in AOS interacting nonenzymatically to produce more highly reactive species (Halliwell and Gutteridge, 1989), such as the hydroxyl radical ($\cdot OH$), peroxy radical ($\cdot OOH$), and singlet oxygen ($^1O_2$). Ubiquitous enzymes, such as catalase, peroxidase, ascorbic acid peroxidase, and glutathione peroxidase, convert H_2O_2 to water. The combined action of these enzymes with naturally occurring antioxidants maintains nondamaging levels of $\cdot OH$ radicals that otherwise may nondiscriminately destroy membrane-bound lipids and proteins and cytosolic enzymes essential for cellular homeostasis (Halliwell and Gutteridge, 1989). In any event, the action of active oxygen species cannot be excluded from being involved at some stage of scald development.

Antioxidants

Anet (1972b) proposed that the high scald susceptibility of immature apples was due to an inefficient antioxidant system in the peel. Eleven antioxidants from apple peel were isolated by using thin-layer chromatography, but only three tocopherols were identified (Anet, 1974). He concluded that scald did not occur if the concentrations of the antioxidants remained adequate to limit α -farnesene oxidation. Lipid-soluble antioxidant activity in apple peel at harvest was negatively correlated with scald development (Meir and Bramlage, 1988). Scalded tissue contained less α -tocopherol than nonscalded tissue in the same fruit (Gallerani et al., 1990). Antioxidant concentrations at harvest were inversely related to maximum conjugated triene concentrations at the end of storage and to scald development. However, no individual antioxidant was associated consistently with conjugated triene accumulation or scald development. As conjugated triene concentrations increased during storage, total lipid-soluble antioxidant activity also increased, but water-soluble antioxidants generally decreased (Barden and Bramlage, 1994b). Abdallah et al. (1997) reported that wounding apples with a hypodermic needle both induced an increase in cinnamic acid derivatives with antioxidant activity and inhibited development of scald.

Several antioxidant chemicals control scald and DPA is particularly effective. Lurie et al. (1989a) concluded that DPA prevents scald by its general antioxidant effect and not specifically by preventing the oxidation of α -farnesene; it affects other metabolic processes as well. Diphenylamine inhibits electron transport in plant mitochondria (Baker (1963). Superficial scald of 'd'Anjou' pears (Chen et al., 1990) and apples (Johnson et al., 1980) is controlled by ethoxyquin, an antioxidant commonly used to control oxidative rancidity in poultry feeds. The antioxidants BHT and BHA (Wills and Scott, 1977) also reduce scald; BHA and BHT are widely used in food packaging to prevent lipid oxidation. Phorone (2,6-dimethyl-2,5-heptadien-4-one) both controls scald and limits the accumulation of α -farnesene and its conjugated triene oxidation products in fruits during storage (Scott et al., 1980), but taints the flavor of the apples; furthermore, no toxicology data are available. Some monoterpenes are effective in controlling scald (Wills et al., 1977), and ascorbate-6-palmitate is somewhat effective (Bauchot and John, 1996).

CA STORAGE TECHNOLOGY TO CONTROL SCALD

Low or ultra-low oxygen CA

Ultra-low O_2 (ULO) levels in CA storage reduce scald (Little and Pegg, 1987). Decreasing the O_2 level to $\approx 0.7\%$ during CA storage can effectively control scald of 'Delicious' apples in some growing regions and seasons, but not in others (Lau, 1990; Yearsley et al., 1996). Storage under ultra-low O_2 CA conditions led to markedly lower scald levels on postmature fruit, but did not greatly reduce scald on premature and mature fruit (Truter et al., 1994). CA storage at 0.7% O_2 has effectively controlled scald of 'Delicious' apples in the Northwest (Lau, 1990). For other regions, the results have been less promising and some cultivars show intolerance to the low O_2 levels needed to control scald (Gran and Beaudry, 1993). Low or ultra-low O_2 also showed similar results in reducing or controlling apple scald in other studies (Chen et al., 1985; Little, 1985; Patterson and Workman, 1962; Porritt, 1966; Roberts et al., 1963; Sharples and Johnson, 1981; Truter et al., 1994; Yearsley et al., 1996). Moreover, some cultivars are susceptible to low O_2 injury, and do not achieve optimum dessert quality subsequent to long-term CA storage at O_2 levels below 1% (Gran and Beaudry, 1993; Little, 1985; Truter et al., 1994). This may have a negative effect on consumer acceptance of apples in the United States as was found in Europe following ULO storage. Storage at 1.5% O_2 maintains flesh firmness and flavor for most of the cultivars we have examined over many years and largely controls scald, whereas long-term CA storage at higher O_2 levels does not (Dilley, 1990).

Low ethylene CA

Reducing or removing ethylene in the storage atmosphere reduces scald of apples (Knee

and Hatfield, 1981; Little et al., 1985; Liu, 1985; Skrzynski et al., 1985). Du and Bramlage (1994) suggested that ethylene played a fundamental role in scald development. Inhibition of ethylene production and action may be responsible for control of scald by controlled atmospheres and modified atmospheres created by coatings (Kader, 1986). Studies with ethylene action inhibitors suggest that some aspect of ethylene action is implicated in scald development (Gong and Tian, 1998). Combining low O₂ and low ethylene during storage reduces scald (Fica, 1991; Johnson et al., 1989; Lau, 1983, 1985a, 1985b; 1989, 1990, 1993; Little, 1985).

Hypobaric storage

Hypobaric storage is a system of storing commodities while ventilating with air at less than atmospheric pressure (Dilley, 1982; Wang and Dilley, 1999a). Although refrigerated storage of apples at reduced atmospheric pressures (0.1 to 0.2 atmospheres) prevents scald (Dilley, 1982) it is largely an experimental storage system and not cost-competitive with current CA technologies. Storage at 2% O₂ at atmospheric pressure can delay, but not prevent, scald. At 0.1 atmosphere of air the partial pressure of O₂ is 76 mm-Hg, which is equivalent to ≈2% O₂ at atmospheric pressure. Scald did not develop either during or after transfer to static air at 1 atmosphere for 4 months, provided apples were held in air at 1 °C and placed under hypobaric conditions within 1 month after harvest (Wang and Dilley, 1999a). If hypobaric storage was delayed for 3 months, scald development was similar to that for fruits stored in air. Hypobaric ventilation favors the removal of volatiles, including ethylene, produced by the fruit and this, together with prevention of their synthesis by low oxygen partial pressures, may explain how it prevents scald.

OTHER TECHNOLOGIES TO CONTROL SCALD

Chemical control

Partial control of scald was achieved by wrapping fruits in mineral oil-impregnated paper (Brooks et al., 1919). This labor-intensive practice was in common use until the 1960s, when the antioxidant DPA was introduced and commercially developed for postharvest quality control (Smock, 1957). In this procedure, fruits are drenched in an emulsified mixture of DPA (Hall et al., 1961). Early research with DPA as a dip treatment of fruits in bulk bins was conducted in 1963 (Dilley and Dewey, 1963). This was quickly followed by development of overhead drench treatment facilities for treating entire truckloads of apples before they were stored in CA (Dewey and Dilley, 1964); this system is still widely used today throughout the United States and Canada. In Michigan alone at least 5 million bushels (≈100,000 t) of apples are treated each year with a postharvest drench treatment of DPA plus thiabendazole fungicide to control scald and decay during storage. Nationally, more

than half of the apples grown are similarly treated. Diphenylamine prevents the auto-oxidation of α-farnesene in vivo and in vitro (Anet and Coggiola, 1974) and controls scald. It also controls some CO₂-induced disorders (Burmeister and Dilley, 1995) and internal browning in apple (Burmeister and Rowan, 1997). Concern about applying antioxidant chemicals to apples postharvest has been raised by environmentalists, research scientists, growers, and packers, so expanding the use of these chemicals to control other disorders must be questioned.

Food-compatible antioxidant coatings

A sucrose-fatty acid ester coating can improve the storage quality of apples (Smith and Stow, 1994), and, when used with food-compatible antioxidants, can reduce apple scald for a few months (Bauchot et al., 1995b; Little and Barrand, 1989). Bauchot et al. (1995b) concluded that the limited control of scald by ascorbyl palmitate plus a sucrose-fatty acid ester is partially related to modification of the internal atmosphere of the apple, and Dodd and Bester (1993) found that the use of ascorbyl palmitate mixed with oil markedly reduced scald. Ascorbic acid alone reduced scald incidence and severity when apples were stored in CA for 43 weeks, but the effects were not consistent when apples were stored in air (Chellew and Little, 1995). Vegetable oils reduced superficial scald, probably because of a physical effect, and this was not related to chain length of fatty acids or degree of unsaturation (Bauchot et al., 1995a, 1995b; Chellew and Little, 1995; Dodd and Bester, 1993; Little and Barrand, 1989; Scott et al., 1995b; Smith and Stow, 1994).

STRATEGIES TO CONTROL SCALD

Over the past several years, researchers have found several nonchemical treatments that reduce or control scald incidence and severity. These include heat-treatment and intermittent warming, initial ethanol vapor treatment, ILOS, ULO, and initial high carbon dioxide stress. However, most of these treatments have yet to be employed commercially for long-term CA storage.

Heat-treatment

Early studies by Hardenburg and Anderson (1965) showed that prestorage heat-treatment of apples could reduce the incidence of scald. Prestorage heat-treatments of apples for 4 d at 38 °C provided control of scald on 'Granny Smith' apples, but this affected the flavor by reducing the organic acid content (Lurie et al., 1990, 1991). Heat-treatment of a large number of horticultural commodities induces thermotolerance to high and low temperatures and ameliorates chilling injury (Lurie, 1998).

Ethanol vapor treatment

Recent studies (Ghahramani and Scott, 1998a; Scott et al., 1995a; Wang, 1998; Wang

and Dilley, 1996; Wang et al., 1995, 1997a) indicate that ethanol vapor treatments control scald, but the mechanism of action is not known. Ethanol vapor treatment inhibits the ripening of climacteric fruits (Ritenour et al., 1997) and the senescence of oat (*Avena sativa* L.) leaves (Satler and Thimann, 1980) and carnation (*Dianthus caryophyllus* L.) flowers (Heins, 1980). The efficacy of ethanol in reducing scald may result from its effect on reducing ethylene synthesis and by noncompetitively inhibiting ethylene action (Wu et al., 1992).

Initial low oxygen stress

Exposure of fruit to ILOS induces them to produce their own ethanol (Ghahramani and Scott, 1998b; Wang and Dilley, 1996, 1997, 1999b; Wang et al., 1997a), and this may explain the efficacy of ethanol vapor treatments in reducing scald even when the fruits are subsequently stored in air. The biochemical mechanisms responsible for the beneficial effects of low O₂ stress on scald control and the ensuing metabolism of ethanol remain to be elucidated. Extensive analyses of the volatiles produced by apples under low O₂ stress or ethanol vapor treatments support the premise that metabolism of α-farnesene in the pigment-bearing cells is closely associated with development of scald (Dilley and Beaudry, 1998; Ghahramani and Scott, 1998b; Wang and Dilley 1996; 1997; 1999a, 1999b). Truter et al. (1994) reported that storage under ultra-low O₂ conditions led to markedly lower scald levels on postmature fruit, but did not greatly reduce scald on the premature and mature fruit. Storage under the ILOS + low O₂ CA regime, however, induced low levels of superficial scald in premature, mature, and postmature fruit (Little et al., 1982). Recent studies by Van der Merwe et al. (1997) and Wang and Dilley (1999b) indicate good control of scald by ILOS followed by CA storage (1% or 1.5% O₂ with 3% CO₂ at 1 °C).

Low oxygen CA

Our laboratory studies with CA atmosphere purging at 1.5% O₂ have continued to show good control of apple scald. This has been demonstrated at the commercial level at the Michigan State Univ. Clarksville Horticulture Experiment Station (MSU CHES) CA facility since 1987 using 1.5% O₂ with purging to scrub CO₂ (Dilley, 1990). Numerous Michigan CA operators have verified this procedure with good results for at least 6 months of CA storage. Success using this procedure is predicated on harvesting apples at the onset of the ethylene climacteric, having the fruit under CA within a week after harvest and employing a hollow fiber membrane air separator such as the Permea® (Permea, Inc., St. Louis) system for CO₂ scrubbing. These parameters are not always readily achieved. For CA storage beyond 6 months, fruit generally must be harvested at preclimacteric ethylene levels in order to slow ripening and maintain fruit quality. Since 1960, our laboratory studies have

indicated that continuous purging with low O₂ atmospheres controlled scald for at least 9 months, while nonpurged storage has not. This suggests that purging may remove a fruit-produced scald-related volatile substance that would otherwise accumulate. There is much precedence for this scenario dating back to the seminal studies of Brooks et al. (1919) more than 70 years ago showing that using mineral oil-coated wraps can sometimes be effective in controlling scald. Moreover, ventilation and the use of activated carbon has also reduced scald, but not consistently.

CONCLUSIONS

For U.S.-produced apples to be available year-round for fresh and processing markets, nearly half of them stored under refrigeration must be treated with a postharvest DPA drench to control scald. Without DPA or an alternative treatment, scald could destroy the market value and utility of millions of tons of apples annually. Alternative strategies are needed to control scald of apples to avoid using any postharvest-applied chemicals. Improved fruit storage technologies should be developed and extended to provide high quality and wholesome apples for the consumer at an affordable price, while at the same time assuring the producers and handlers a sufficient profit margin to encourage them to adopt these technologies. Some recent studies suggest that this goal may be achieved in the not-too-distant future. This research has confirmed the involvement of α -farnesene in scald development and its oxidation products MHO, conjugated triene hydroperoxide free-radicals, and conjugated trienols. Ethylene is also a scald-related factor, based on recent studies with inhibitors of ethylene action. Many factors, including cultivar, fruit maturity, natural antioxidant levels of fruits, and storage conditions affect scald development. Postharvest-drench treatment with DPA is used commercially to control scald, but use of DPA has raised concerns of food safety and environmental problems. To control scald and ensure food safety, alternative strategies must be considered; some that have evolved include ultra-low O₂ storage, ethanol vapor pretreatment, and initial low O₂ stress prior to low O₂ CA storage. Continuous, ultra-low O₂ CA storage can prevent apple scald, but may cause off-flavor or fruit fermentation in some cultivars or growing locations. Ethanol vapor pretreatment can attenuate scald but its effectiveness may be lost after long-term storage. Initial low O₂ stress (0.25% to 0.5% O₂ for 2 weeks), followed by CA storage at 1.5% O₂ and 3% CO₂, can significantly control or prevent scald; this treatment strongly inhibits the conversion of α -farnesene to its oxidation product MHO. Volatiles produced by fruits during the first month in storage appear to be important in development of scald later during storage. This conclusion is based on the observation that hypobaric storage prevents scald only if fruits are placed under hypobaric conditions within 1 month after harvest. Ethanol and ILOS treatment effects on attenuating scald may have a common basis by inhibiting

the formation of α -farnesene and its subsequent conversion to MHO.

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