Instrumental and Sensory Quality Characteristics of ‘Gala’ Apples in Response to Prestorage Heat, Controlled Atmosphere, and Air Storage

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ABSTRACT. Fruit quality, sensory characteristics, and volatiles produced by ‘Gala’ apples (*Malus × domestica* Borkh.) were characterized following regular atmosphere (RA) storage without and with a prestorage heat treatment (38 °C for 4 days) or controlled atmosphere (CA) storage at 0 and 2 °C for 0 to 6 months plus 7-day shelf life at 20 °C. Static CA conditions were 0.7 kPa O₂ plus 1.0 kPa CO₂, 1.0 kPa O₂ plus 1.0 kPa CO₂, and 1.5 kPa O₂ plus 2.5 kPa CO₂. Most of the more abundant volatiles were esters; the rest were alcohols, an aldehyde, a ketone, and an aryl ether. Respiration and ethylene production rates, internal atmospheres of CO₂ and ethylene, and volatile levels were reduced following CA storage compared with RA storage without and with a prestorage heat treatment. Magness-Taylor and compression firmness, titratable acidity, and sensory scores for firmness, sourness, apple-fruity flavor, and overall acceptability were higher for CA- than for RA-stored fruit. Soluble solids content and sensory scores for sweetness were similar among all treatments. Quality and sensory characteristics were generally similar in heated and nonheated RA-stored fruit, and between 0 and 2 °C in CA- and RA-stored fruit. While one CA regime had a higher CO₂ concentration than the others tested, CA effects on quality and sensory characteristics were generally more pronounced at the lower O₂ levels. Quality characteristics declined between 2 and 4 months storage. The results indicate that short-term CA storage can maintain instrumental and sensory quality of ‘Gala’ apples.

‘Gala’ is an apple (*Malus × domestica*) cultivar that has experienced a recent increase in popularity and is now a major cultivar in the United States. Forecast production for ‘Gala’ in the United States for 2001 is 3.95×10^5 t and production is on the rise (U.S. Apple Institute, personal communication). ‘Gala’ is characterized by a crisp, juicy flesh and a strong pleasant aroma and flavor when ripe (White, 1991). ‘Gala’ is a summer apple maturing in late August or early September, and can ripen and deteriorate rapidly during storage (Stebbins et al., 1994; Walsh, 1990). Extended storage and shelf life of ‘Gala’ would improve its profitability and marketing. Information is now beginning to accumulate on the quality of regular atmosphere (RA)- and controlled atmosphere (CA)-stored ‘Gala’ fruit (Boylston et al., 1994; Cliff et al., 1998; Kupferman, 1992; Lau, 1995; Mattheis et al., 1998a; Plotto et al., 1999). Controlled atmosphere storage of ‘Gala’, where the storage atmosphere is altered by maintaining both the O₂ and CO₂ partial pressures between 1.0 and 3.0 kPa, along with refrigeration, is now accepted as the commercial means to retain firmness and to extend the marketing period (Boylston et al., 1994; Cliff et al., 1998). Evaluations are also underway to determine the potential benefits of storing ‘Gala’ in ultra low ($\approx 0.7\%$) O₂ atmospheres. However, the apple industry,

based on consumer feedback, now believes that ‘Gala’ held in CA lose their flavor compared with those held in RA. CA storage is known to decrease fruit volatile compounds in ‘Gala’ (Mattheis et al., 1998a) and other apple cultivars (Brackmann et al., 1993; Guadagni et al., 1971; Patterson et al., 1974; Streif and Bangerth, 1988). These volatiles are thought to contribute to fruit aroma and flavor (Girard and Lau, 1995; Knee and Hatfield, 1981; Knee and Sharples, 1981; Plotto et al., 2000; Streif and Bangerth, 1988; Willaert et al., 1983; Young et al., 1996). The CA suppression of volatiles can be reduced, but not eliminated, by raising the O₂ concentration during storage (Mattheis et al., 1998a; Streif and Bangerth, 1988; Smith, 1984; Lidster et al., 1983), but this procedure reduces firmness retention (Lidster et al., 1983) and has not been commercially accepted. Using different CA storage regimes, trained taste panels have scored CA-stored ‘Gala’ as having more (Cliff et al., 1998) or less (Plotto et al., 1999) fruity flavor than those held in air. In the report of Plotto et al. (1999), the decrease in sensory scores for fruitiness of CA apples was correlated with a decrease in volatile levels analyzed by GC. To our knowledge, no report has evaluated both volatile levels and consumer sensory characteristics of ‘Gala’ fruit stored in RA and multiple CA regimes.

Postharvest heat treatments of fruit may be used as a nonchemical means to disinfect (Couey, 1989) and to alleviate pathological and physiological disorders of fruit during storage (Conway et al., 1994; Fallik et al., 1996; Klein and Lurie, 1990; Lurie et al., 1998). Apples exposed to 38 to 50 °C for 5 to 96 h before storage were firmer, had a higher soluble solids to acid

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ratio, and were more resistant to scald development than nonheated fruit (Liu, 1978; Lurie, 1998). A prestorage heat treatment for 4 d at 38 °C in air maintains fruit firmness, soluble solids, and titratable acidity (Lurie, 1998) while only transiently inhibiting quality-associated volatile emissions from 'Golden Delicious' apples during storage. After extended RA storage, heated 'Golden Delicious' fruit produced more total volatiles than nonheated fruit (Fallik et al., 1997). In addition, heated 'Golden Delicious' apples were perceived as crisper, sweeter, and overall were more acceptable than control fruit (Abbott et al., 2000; Klein et al., 1998). However, a trained sensory panel found no consistent superiority of heated apples over control fruit, but individual panelists either consistently liked or disliked the heated fruit (Liu, 1978). Consumers also can distinguish between heated and control apples (Abbott et al., 2000; Klein et al., 1998; Lurie and Nussinovitch, 1996). While prestorage heat treatment has been tested on 'Gala' apples in relation to decay control (Conway et al., 1999), its effects on total volatile levels and other quality characteristics in relation to sensory analyses and to CA storage have not been examined.

The purpose of this research was to investigate the keeping quality of 'Gala' apples treated with heat before storage and/or stored at different temperatures and atmospheres. We evaluated the effects of two commercial CA regimes, one ultra low O₂ CA storage and one prestorage heat treatment on firmness, soluble solids content, titratable acidity, volatile levels, and consumer texture and flavor analyses in 'Gala' apples after cold storage at two temperatures.

Materials and Methods

FRUIT. 'Gala' apples (100 count per box) were harvested from a commercial orchard (Rice Bros., Biglerville, Pa.) in 1997 and 1998 at the beginning of the climacteric stage (ethylene production ≈ 0.003 nmol·kg⁻¹·s⁻¹ and CO₂ production ≈ 50 nmol·kg⁻¹·s⁻¹). The fruit had a starch index of 5 using Cornell generic starch scale 1 to 8 (Blanpied and Silsby, 1992) and Magness-Taylor (MT) firmness between 79 and 82 N. After harvest, unwashed fruit were randomized, separated into lots, and assigned to three replications of eight (year 1) or six (year 2) treatments. All fruit were placed on fruit pack trays and held overnight at 20 °C. Application of treatments began one day after harvest.

Control (nonheated, RA-stored) fruit were placed in boxes lined with perforated polyethylene bags and stored at 0 or 2 °C in air. For CA storage treatments, fruit were placed in 208-L storage chambers at 0 or 2 °C, and storage chamber atmospheres were established within 3 d of harvest using compressed air and liquid N₂. Chamber gas composition was analyzed at 4-h intervals and adjustments were made as necessary using a controller-software program (David Bishop Instruments, Heathfield, U.K.). Controlled atmosphere treatments used were 1.5 kPa O₂ plus 2.5 kPa CO₂ (CA 1.5–2.5) (years 1 and 2), 1.0 kPa O₂ plus 1.0 kPa CO₂ (CA 1.0–1.0) (year 1), and a noncommercial ultra low O₂ of 0.7 kPa O₂ plus 1.0 kPa CO₂ (CA 0.7–1.0) (year 2). Fruit for prestorage heat treatment were placed in boxes lined with perforated polyethylene bags. The prestorage heat treatment was initiated the day after harvest; fruit were heated to 38 °C in a thermostatically controlled (± 1.0 °C) walk-in chamber. The relative humidity in the chamber was maintained at >85%. Storage conditions were monitored with a hygrothermograph (Belfort Instrument Co., Baltimore, Md.). The fruit were removed from heat storage after 4 d, allowed to equilibrate to room temperature

overnight, and then placed in storage at 0 or 2 °C in RA on day six after harvest. Fruit from all treatments were measured after 7 d at 20 °C following 0, 2, 4, and 6 months at 0 or 2 °C. Storage includes the 7-d ripening period.

QUALITY MEASUREMENTS. Respiration and ethylene production rates of control fruit were monitored every 6 h during a 2-d period at 20 °C immediately after harvest. After fruit were placed in storage, respiration and ethylene production rates of CA-stored and of heat-treated and control RA-stored fruit were monitored during the 7-d period at 20 °C following 2, 4, and 6 months storage using an automated system (Izumi et al., 1996). Three 5-fruit replications were measured and results are reported as nmol·kg⁻¹·s⁻¹ CO₂ or ethylene produced.

On the day after harvest for control fruit and after 7 d at 20 °C for treated and control fruit following 2, 4, and 6 months of cold storage, fruit cavity CO₂ and ethylene levels were determined by inserting a steel hypodermic needle into the cavity through the calyx region of individually submerged fruit, then drawing 6-mL samples with a gas-tight syringe. Nine gas samples from each treatment were analyzed at each storage period. The levels of CO₂ were measured using a GC (model GC-3BT; Shimadzu, Kyoto, Japan) fitted with Porapak Q and molecular sieve 5A columns (≈ 2 m $\times$ 3 mm) and a thermal conductivity detector. The levels of ethylene were determined with a GC (model AGC-211; Carle, Tulsa, Okla.) fitted with an alumina column (≈ 2 m $\times$ 3 mm) and a photoionization detector.

Magness-Taylor and compression firmness, soluble solids content (SSC), titratable acidity (TA), volatile levels, and sensory evaluations were done on the same lots of fruit following 0, 2, 4, and/or 6 months cold storage plus 7 d at 20 °C.

Magness-Taylor firmness was measured with an electronic fruit firmness tester (model EPT-1, Lake City Technical Products, Kelowna, B.C., Canada) set in the MT-mode and interfaced to a personal computer. Firmness (bioyield force) was measured at two opposite points on the equator of each fruit after removing a thin slice of skin from each site. For compression firmness, a radial cylinder of apple flesh was removed at the equator using a 15-mm-diameter cork borer. A slice 3 mm thick including the skin was discarded and the next 10-mm segment was tested in axial compression. The sample was compressed between flat plates at 2 mm·s⁻¹ to a final height of 2.50 mm (75% compression). The force-deformation curve was analyzed for various forces, slopes, and areas (Abbott et al., 1984).

Soluble solids content and TA were determined using freshly prepared juice. Individual fruit were ground in an electric juice extractor. Soluble solids content was measured using a digital, temperature-compensated refractometer (model PR-101, Atago Co. Tokyo, Japan); and TA (expressed as malic acid) was determined by titrating 10-mL juice with 1.0 M KOH to pH 8.2 (Mitcham and Kader, 1996).

Analysis of volatile abundance using a solid-phase microextraction (SPME, Supelco Co., Bellefonte, Pa.) technique and gas chromatography was performed as described in Saftner (1999). Constructing calibration curves for each volatile analyte in each apple sample is not feasible and thus total volatile abundance is reported in FID area response units of pA rather than absolute amounts of individual analytes. At each storage period, three 3-fruit samples for volatile analyses were collected from each replication of each treatment.

For volatile identification, a GC-MS procedure was used. The GC procedure was the same as described above except that ultra purified helium was used as the carrier gas. The GC-MS transfer

line temperature was 250 °C. Volatile detection was performed by quadrupole MS (model 5973, Agilent Technologies, Rockville, Md.) using 70 eV electron impact ionization. Mass spectra were collected over a range of m/z 40 to 220. Identification of volatile components was confirmed by comparison of collected mass spectra with those of standards and spectra in the National Institute for Standards and Technology (NIST) mass spectral library, Search Version C.01.00 (Aldrich, Milwaukee, Wis.).

SENSORY PANELS. Apples were evaluated by 120 untrained volunteers from the Beltsville Agricultural Research Center who frequently consumed apples. Following the 4- and 6-month storage periods, replications of all treatments were tested on 3 consecutive days, with ≈ 40 different panelists in each replication.

Each panelist evaluated all treatments, one half of the treatments in the morning and the remainder in the afternoon of the same day. Evaluations were conducted in conference rooms under ambient conditions, with no interaction permitted among panelists. Each panelist received the treatments one at a time in random order. Just before serving, apples were halved through the firmness-test sites and the damaged tissue at the test sites was trimmed away. Each half was cut into two or three wedges, depending on fruit size. Wedges from at least five apples were combined per session and each panelist received two wedges from each treatment. They were asked to rate the intensity of each of the following attributes: crispness, firmness, mealiness, sweetness, sourness-acidity, and apple-fruity flavor. They were then asked to score acceptability of texture, flavor, and overall eating quality. All attributes were marked on 100-mm unstructured scales labeled "none" and "very much" at the ends, later digitized to 0 to 100, respectively. Terms are similar to those used for apple

evaluations by others, e.g., Williams and Carter (1977), Dever et al. (1995), and Abbott et al. (2000).

STATISTICAL ANALYSES. The experimental design was a randomized complete block with three replications. In the first year of experimentation, treatments were arranged in a $2 \times 4 \times 4$ factorial: $[0 \text{ or } 2^\circ\text{C}] \times [\text{control (RA), heat, CA } 1.0\text{--}1.0, \text{ or CA } 1.5\text{--}2.5] \times [0, 2, 4, \text{ or } 6 \text{ month storage}]$. In the second year, treatments were arranged in a $2 \times 3 \times 4$ factorial: $[0 \text{ or } 2^\circ\text{C}] \times [\text{control, CA } 0.7\text{--}1.0, \text{ or CA } 1.5\text{--}2.5] \times [0, 2, 4, \text{ or } 6 \text{ month storage}]$. In both years, compression and sensory measurements were made only after 4 and 6 months of 0°C storage plus 7 d at 20°C .

Data were analyzed by analysis of variance (ANOVA) within storage times to test for treatment $\times$ temperature interactions. Treatments were compared to one another by Sidak-adjusted multiple comparisons in a repeated measures ANOVA with either a variance component (respiration and ethylene production rate data) or a heterogeneous first order autoregression error structure among levels of the storage factor using SAS Proc Mixed (SAS Institute, 1999). To obtain a stable estimate for each measurement presented in Fig. 1B and D, 2 to 4, each of the three replications observed for a treatment is an average of measurements made following 0, 2, 4, or 6 months at 0°C and 7 d at 20°C . Additionally some treatment comparisons were made using *a priori* contrasts (SAS, 1999). Unless stated otherwise, only results significant at $\alpha = 0.05$ are discussed.

Results

RESPIRATION AND ETHYLENE PRODUCTION. Heat treatment transiently generally inhibited ethylene evolution but not CO_2 evolution compared to control fruit during storage at 0°C in RA (Fig. 1A and C). Controlled atmosphere storage more effectively inhibited respiration and ethylene production rates, with lower O_2 CA storage generally being more effective (Fig. 1A and C). At 2°C storage, the respiration and ethylene production rates of heated and control fruit were similar to corresponding fruit stored at 0°C . However, the respiration and ethylene production rates of CA-stored fruit were increased $\approx 20\%$ and 45% , respectively, at the higher temperature but were still lower than those for heated and control fruit stored at 0°C (data not provided). A climacteric peak in respiration and ethylene production rates had occurred by 4

months in CA-stored and control fruit, but rates continued to increase in heated fruit (Fig. 1A and C). Unlike most of the respiration and ethylene production rates, the internal CO_2 and ethylene concentrations of heated fruit were higher than most of those from control fruit. As with respiration and ethylene production rates, the internal CO_2 and ethylene concentrations of heated and control fruit were generally higher than those of CA-stored fruit (Fig. 1B and D).

FIRMNESS. Magness-Taylor firmness in heated and control fruit decreased similarly during storage at 0°C (Fig. 2A) and 2°C (Fig. 2C). After 6 months storage at 0 or 2°C , CA-stored fruit were $>10 \text{ N}$ firmer than heated or control fruit. Compression firmness followed the same patterns (data not provided). A consumer panel also scored heated and control fruit as being generally less firm (Fig. 2B and D) and less crisp (data

Fig. 1. Effects of heat, controlled atmosphere and regular atmosphere treatments on respiration and ethylene production rates and internal atmospheres of CO_2 and ethylene in 'Gala' apples. Control = RA cold storage; heat = prestorage heat treatment for 4 d at 38°C followed by RA cold storage; CA1.0–1.0 = controlled atmosphere storage with 1.0 kPa O_2 and 1.0 kPa CO_2 ; CA1.5–2.5 = controlled atmosphere storage with 1.5 kPa O_2 and 2.5 kPa CO_2 ; CA0.7–1.0 = controlled atmosphere storage with 0.7 kPa O_2 and 1.0 kPa CO_2 . Within time periods within plots, symbols labeled with the same letter are not significantly different at $\alpha = 0.05$ using Sidak-adjusted multiple comparisons in a repeated measures ANOVA with either a heterogeneous first-order autoregression (internal atmosphere data) or a variance component (respiration and ethylene production rate data) error structure among levels of the storage factor.

Fig. 2. Effects of heat, controlled atmosphere and regular atmosphere treatments on Magness-Taylor and sensory firmness. Treatments are described in the caption to Fig. 1. Measurements were made following 0, 2, 4, or 6 months at 0 °C (A and B) or 2 °C (C and D) and 7 d at 20 °C. Within time periods across plots of analytical or sensory data, symbols labeled with the same letter are not significantly different at $\alpha = 0.05$ using Sidak-adjusted multiple comparisons.

not provided) than CA-stored fruit, with no separation between the CA treatments or between the heated and control treatments. Because crispness, firmness, and mealiness were so closely related ($r^2 = 0.86$ to 0.98) in year 1, we scored only crispness in year 2. Crispness was also closely related to acceptability of texture ($r^2 = 0.94$) and contributed to overall acceptability ($r^2 = 0.86$) in both years.

FLAVOR AND AROMA. Combined temperature analyses are reported for titratable acidity (Fig. 3A) and sourness scores (Fig. 3B), since treatment comparisons between the two temperatures were inconsequential for titratable acidity and nonsignificant for sourness. The CA treatments reduced acidity loss during storage. Sourness scores were higher for CA-stored fruit than for either heated or control fruit.

Total quality-associated volatile levels peaked after 2 months in control and CA-stored fruit during storage at 0 °C (Fig. 4A) and 2 °C (Fig. 4C), but increased continuously in heated fruit at both temperatures (Fig. 4A and C). Total volatile abundance is the summation of the relative volatile levels collected from the headspace above 'Gala' extracts and were mostly esters; the rest were alcohols, an aldehyde, a ketone and an aryl ether (Table 1). Relative to control fruit, volatile levels were transiently inhibited in heated fruit at 2 months but were similar at 4 and 6 months regardless of temperature (Fig. 4A and C). At both storage temperatures, CA treatments inhibited volatile levels >50% relative to control fruit after 4 and 6 months storage and relative to heated fruit stored 6 months. Heated and control fruit stored at 2 °C for 4 and 6 months had >40% higher volatile levels than those stored at 0 °C, while volatile levels did not differ with temperature in the CA-stored fruit. Specific 'Gala' volatiles having an apple and/or fruity aroma (Table 1) followed the same patterns as corresponding total volatile levels (data not provided). Panelists found that CA-stored fruit generally had more apple-fruity flavor than heated and control fruit after 4 and 6 months storage, but these results were only significant after 6 months storage at 2 °C

(Fig. 4B and D). However, acceptability of flavor was scored just above neutral (midpoint of acceptability scale) for CA-stored and just below neutral for heated and control fruit stored in RA (data not provided); both were within the acceptable range. Overall, panelists scored CA-stored fruit as having more apple-fruity flavor and a more acceptable flavor even though they had less than one-half the level of total volatiles and of volatiles having an apple and/or fruity aroma as those in heated and control fruit stored in RA.

Intensity of apple-fruity flavor contributed to acceptability of flavor and to overall acceptability ($r^2 = 0.90$ and 0.76 , respectively). Sweetness was not highly related to acceptability in either year, probably because 'Gala' is a moderately sweet apple and did not vary greatly. On the other hand, sourness-acidity was related to apple-fruity flavor, acceptability of flavor, and overall acceptability ($r^2 = 0.51$, 0.59 , and 0.56 , respectively; $\alpha = 0.05$).

Discussion

Controlled atmosphere storage of 'Gala' apples minimized respiration and ethylene production rates, internal concentrations of CO₂ and ethylene, MT and compression firmness and titratable acidity losses, and maintained sensory scores for intensity of firmness, crispness, sourness, apple-fruity flavor and for overall acceptability compared to RA storage of heat-treated and control fruit. However, reduced levels of aroma-flavor-associated volatile compounds were also observed following CA storage of 'Gala' (Fig. 4A and C). This is in agreement with our preliminary results from a replicated sensory aroma test by four laboratory personnel having above average sensitivities to environmental and food odors that CA-stored fruit had lower scores than RA-stored control fruit for intensities of apple and floral-fruity-sweet aromas. These volatile and sensory aroma findings also agree with the earlier finding of a decrease in aroma quality following CA storage of 'Gala' and other apples (Plotto et al., 1995; Stebbins et al., 1994). The greater overall acceptability of CA-

stored fruit may be attributed, at least in part, to retention of firm-

Fig. 3. Effects of heat, controlled atmosphere and regular atmosphere treatments on titratable acidity and sensory sourness-acidity scores in 'Gala' apples. Treatments are described in the caption to Fig. 1. Measurements were made following 0, 2, 4, or 6 months in cold storage (0 °C and 2 °C data combined) and 7 d at 20 °C. Within time periods within plots, symbols labeled with the same letter are not significantly different at $\alpha = 0.05$ using Sidak-adjusted multiple comparisons.

Fig. 4. Effects of heat, controlled atmosphere and regular atmosphere treatments on total volatile levels and sensory apple-fruity flavor scores in 'Gala' apples. Treatments are described in the caption to Fig. 1. Measurements were made following 0, 2, 4, and 6 months at 0 °C (A and B) or 2 °C (C and D) and 7 d at 20 °C. Note the difference in scale for volatiles in plots A and C. Within time periods across plots of analytical or sensory data, symbols labeled with the same letter are not significantly different at $\alpha = 0.05$ using Sidak-adjusted multiple comparisons.

ness and titratable acidity or a lower soluble solids–titratable acidity ratio. However, we were surprised to find in our study that CA-stored fruit scored higher by a consumer panel for apple–fruity flavor than control fruit stored in RA despite having less than one-half the total volatile levels of control fruit. One explanation for this finding may relate to the interaction of acidity and flavor perception (Amerine et al., 1965; Malundo et al., 2001; Stampanoni, 1993), i.e., higher acidity in CA-stored 'Gala' may have increased panelists' perception of flavor-related compounds. This finding is in agreement with that of a trained taste panel which found that CA-stored fruit had better flavor and overall acceptability than RA-stored fruit (Cliff et al., 1998), but is in contrast with a consumer panel which rated RA-stored apples as being more acceptable than apples stored in a delayed CA or a sequential CA and RA storage regime (Anderson and Abbott, 1975; Boylston et al.,

1994). Alcohols, especially ethanol, and certain ethyl esters also are known to increase human perception of flavors but identified alcohol and ethyl acetate levels in 'Gala' extracts from fruit held in CA always were lower than those held in RA, at least during storage for up to 6 months. Alternative, but less likely, explanations for the observed higher apple–fruity flavor and lower volatile level in CA-stored vs. RA-stored 'Gala' can be envi-

Table 1. Volatile compounds in the headspace above extracts collected from control 'Gala' apples after 7 d at 20 °C following 4 months storage in RA at 0 °C.

Peak ^z	Volatile compound	Retention ratio ^y	Percent of total GC–FID response	Volatile aroma
1	Ethyl acetate	0.26	0.2	Pineapple–ethereal ^w
2	Butanol	0.34	1.4	Medicinal ^w
3	Propyl acetate	0.48	0.3	Celery ^w
4	Propyl propionate	0.57	0.3	Fruity ^x , oily–sherry ^w
5	2-Methylpropyl acetate	0.71	0.3	Sweet–fruity ^w
6	Butyl acetate	0.84	30.5	Nail polish–gala ^x , fruity ^w
7	<i>trans</i> -2-Hexenal	0.93	1.1	Sweet–fruity–apple ^w
8	Hexanol	0.98	1.7	Fragrant–sweet ^w
9	2-Methylbutyl acetate	1.00	10.6	Solvent–gala ^x , fruity ^w
10	Propyl butyrate	1.04	0.2	Sharp ^w
11	Butyl propionate	1.06	0.4	Fruity–apple ^x , banana–ethereal ^w
12	Pentyl acetate	1.08	1.7	
13	6-Methyl-5-hepten-2-one	1.21	0.5	Fruity–tape ^x , green–oily ^w
14	Butyl butyrate	1.23	2.0	Rotten apple ^x , fruity ^w
15	Unknown	1.24	0.4	
16	Hexyl acetate	1.26	43.9	Gala–ripe–pear ^x , apple–pear–floral ^w
17	Butyl 2-methylbutyrate	1.31	0.3	Fruity–apple ^{wx}
18	Hexyl propionate	1.41	0.2	Apple ^x , pear–fruity–musty ^w
19	Propyl hexanoate	1.44	0.3	Wine-like ^w
20	Hexyl butyrate and Butyl hexanoate	1.54	1.0	Green apple ^x , fruity ^w
21	4-Allylanisole	1.56	0.5	Anise–licorice ^x , anise–sweet–minty ^w
22	Hexyl 2-methylbutyrate	1.60	0.5	Apple–grape–fruit ^x , sweet–fruity–apple ^w
23	Hexyl hexanoate	1.80	0.3	Fruity ^w
24	α -Farnesene	1.96	0.9	

^zTrace peaks not included in total volatile level.

^yRetention time of volatile compound relative to retention time of 2-methylbutyl acetate.

^xOrganoleptic properties of individual, volatile compounds isolated from headspace of 'Gala' apples (Plotto et al., 2000).

^wOrganoleptic properties for individual, purified compounds (Aldrich, 2000).

sioned. One may be that CA induced a decrease of volatile compound(s) having off-odors that may mask or otherwise interact with volatiles having an apple-fruity sensory impact, e.g., azeotrophs such as butanol and butyl acetate. The other possibility is that some volatiles having apple or otherwise pleasant aromas occur during tissue mastication which can be perceived by consumers but which occur too transiently to be detected by SPME or other volatile trapping techniques. In this regard, our preliminary results from a four-member aroma panel showed that a very transient sweet aroma was often noted upon snapping a 'Gala' slice, but not on the cut surface of the fruit slice only minutes after cutting. The same aroma panel sometimes noted an off-odor in heat-treated fruit, but volatiles associated with heat processed apples, such as β -damascenone (Roberts and Acree, 1995), were not detected by our volatile analyses.

Despite differences in extraction and concentration techniques, the aroma-flavor-associated volatiles identified in this study of U.S. East Coast-grown 'Gala' (Table 1) were in general agreement with those found previously in U.S. West Coast-grown 'Gala' (Mattheis et al., 1998a; Plotto et al., 2000). Additional volatiles, primarily esters, not identified in our study were described by Plotto et al. (2000), but their volatile extraction period was ≈ 90 times longer than ours. We observed peaks with retention times corresponding to most of those volatile compounds but they were below the level needed for identification. In contrast, we identified an aldehyde (*trans*-2-hexenal) and found peaks with retention times corresponding to *cis*-3-hexenal and hexenal that are produced in 'Gala' (Mattheis et al., 1998b) but which were not captured by the sampling technique used by Plotto et al. (2000). Fruit maturity at harvest, storage duration, storage atmosphere composition (Mattheis et al., 1998a), and other factors such as 'Gala' strain, rootstock, and preharvest climatic conditions may affect volatile emissions. However, most of the differences in volatile profiles between 'Gala' volatile studies can probably be attributed to differences in extraction and concentration techniques rather than to climatic differences in where the 'Gala' were grown in the United States. The odor activity of transient volatile compounds that may be formed and released during tissue mastication (chewing) of apples has not been investigated.

Measured differences in titratable acidity between CA- and RA-stored fruit corresponded to sensory differences in sourness-acidity scores (Fig. 3B). Sensory sourness scores for RA and CA storage were separated by Sidak-adjusted comparisons in a repeated measures ANOVA following 4 months storage (Fig. 3B). A priori ANOVA contrasts also indicated significant differences (data not presented). The greater loss of malic acid by fruit respiration in RA vs. CA is well documented (Anderson and Penney, 1973; Smock, 1979) and is generally perceived by taste panels (Plotto et al., 1999; Watada et al., 1980). There were generally no differences in measured soluble solids and sensory sweetness scores between CA- and RA-stored fruit. However, differences between CA and RA fruit in perceived sourness could be due to our observed sensory interactions among sweetness, sourness, apple-fruity flavor, firmness, and crispness. Instrumental firmness measurements corresponded to sensory firmness and crispness scores (Fig. 2) with higher ratings for CA than for RA fruit, which is in agreement with a previous CA storage study in 'Gala' (Cliff et al., 1998). While 0 °C storage did not effectively inhibit ripening compared to 2 °C, the lower temperature tended to accentuate the differences between CA and RA storage. However, 2 °C storage may unacceptably increase the risk of

decay which was not evaluated in this study. The lower O₂ concentrations during CA storage appeared to accentuate the effects of CA storage. Based on the lack of difference between apples stored in commercial and ultra low O₂ CA in this study, the increased cost of monitoring and maintaining the ultra low O₂ levels, and the risk of anaerobic respiration, the use of ultra low O₂ in CA storage of 'Gala' cannot be advised. The generally better sensory and instrumental quality values following CA storage at lower O₂ concentrations and lower temperature in this study are also well documented in other apple studies (Boylston et al., 1994; Cliff et al., 1998; Mattheis et al., 1998a; Smock, 1979).

Brief exposures of apples to high temperatures before cold storage attenuates some ripening characteristics while enhancing others. The heat treatment may inhibit ripening through its inhibitory effects on ethylene biosynthesis (Lurie, 1998). The ability of heat treatments to inhibit apple ripening while only transiently inhibiting aroma volatile production in 'Golden Delicious' apples (Fallik et al., 1997) indicated to us that heat treatment might be an alternative to CA storage for maintaining 'Gala' quality without sacrificing apple aroma, at least during prolonged storage. However, a heat treatment of 4 d at 38 °C was much less beneficial than the CA storage treatments, even though the inhibition of aroma volatile levels by the heat treatment was less persistent.

Use of CA storage allowed maintenance of quality of 'Gala' apples during prolonged storage compared to RA storage alone. However, the question remains whether or not the improved quality associated with prestorage heat and CA-storage treatments is worth their added costs for 'Gala' apples.

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