Heat Treatment of Mature-green Tomatoes: Differential Effects of Ethylene and Partial Ripening

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ADDITIONAL INDEX WORDS. *Lycopersicon esculentum*, postharvest, chilling injury, quality, flavor volatiles, lipids

ABSTRACT. Mature-green 'Sunbeam' tomatoes (*Lycopersicon esculentum* Mill.) were treated in varying order with C₂H₄, 42 °C water for 1 hour, 38 °C air for 2 days, held 2 days at 20 °C (partial ripening), or not treated and then stored at 2 °C (chilled) for 14 days before ripening at 20 °C. Heat-treated fruit stored at 2 °C and transferred to 20 °C ripened normally, while 63% of nonheated fruit decayed before reaching the red-ripe stage. Partially ripened fruit developed more chilling injury, were firmer, were lighter, and were less red in color than fruit not partially ripened. Lycopene content and internal quality characteristics of fruit were similar at the red-ripe stage irrespective of sequence of C₂H₄ exposure, heat treatment, or a partial ripening period. Of the 15 flavor volatiles analyzed, 10 were reduced by storage at 2 °C. Exposure to C₂H₄ before the air heat treatment reduced the levels of four volatiles, while C₂H₄ application either before or after the water heat treatment had no effect on flavor volatiles. Two volatiles were decreased and two were increased by partial ripening. Storage at 2 °C decreased the level of cholesterol and increased levels of campesterol and isofucosterol in the free sterol pool. Exposure to C₂H₄ before or following heat treatments, the method of heat treatment, and partial ripening had little effect on free sterols, steryl esters, steryl glycosides, or acylated steryl glycosides in the pericarp of red-ripe fruit. A short- or long-term heat treatment of mature-green tomatoes could permit storage at low temperatures with little loss in their ability to ripen normally, whereas partial ripening did not reduce chilling injury.

The withdrawal of chemical fumigants for insect disinfestation purposes has meant that physical disinfestation treatments, especially cold and heat treatments, have been actively pursued as alternatives (Paull and McDonald, 1994). In addition, heat treatments alone have shown promise for delaying ripening and alleviating storage disorders in some commodities (Klein and Lurie, 1991; Paull, 1990). However, heat treatments, like cold treatments, can put severe stress on fresh horticultural commodities (Paull and McDonald, 1994). Exposure of plants to one stress can sometimes protect the plant against another stress (Lurie and Klein, 1991).

Mature-green tomatoes are sensitive to temperatures below ≈15 °C and may develop chilling injury (CI) if held for 2 weeks or longer below 13 °C (Hardenburg et al., 1986). Chilling injury symptoms include failure to ripen and increased decay, especially after fruit are transferred to a nonchilling temperature (Cheng and Shewfelt, 1988). Heat treatments have increased chilling tolerance in several chilling-sensitive tissues (Klein and Lurie, 1992). High-temperature conditioning treatments to reduce CI can be divided into two categories: long term (12 h to 4 d in air) at 38 to 46 °C and short term (up to 1 h in water) at 45 to 60 °C (Klein and Lurie, 1992). Lurie and Klein (1991) found that mature-green tomatoes held 3 d at 36 to 40 °C before storage at 2 °C did not develop CI, whereas unheated tomatoes did. McDonald et al. (1996) reported that tomatoes exposed to either a short- or long-term heat treatment

before storage at 2 °C followed by transfer to 20 °C ripened normally, while nonheated fruit decayed before reaching the red-ripe stage. However, Whitaker (1994) found that partial ripening of mature-green tomatoes before low-temperature storage may be more effective in reducing CI than a long-term heat treatment. The point in the ripening process at which a commodity is exposed to low temperatures can affect its chilling tolerance and ability to ripen normally (Bramlage and Meir, 1990). Treatment of mature-green tomatoes with C₂H₄ for 24 to 72 h is a standard practice and can be considered to be partial ripening. Because C₂H₄ was administered before heat treatment in our previous work, we wanted to determine the order of effectiveness of C₂H₄, heat treatments, and partial ripening on tomato ripening and fruit quality following low-temperature storage. Parameters evaluated included CI symptoms, ripening, lipid composition, and flavor volatiles.

The present study is an attempt to enhance the effectiveness of the short-term water and long-term air heat treatments reported in our earlier work (McDonald et al., 1996), which permit the successful storage of mature-green tomatoes at chilling temperatures. Presently, we explore the effects on resulting fruit quality of sequencing C₂H₄ used commercially to initiate the ripening process and the heat treatments. Additionally, we wanted to directly compare partial ripening with heat treatments as a means to reduce chilling sensitivity.

Materials and Methods

PLANT MATERIAL AND TREATMENTS. 'Sunbeam' tomatoes were grown commercially near Ruskin, Fla., using standard horticultural practices. Fruit (196 ± 30 g fresh mass) were hand harvested in May 1995 at the mature-green stage (determined visually), washed with water, air dried at ambient temperature, and transported the same day to the U.S. Horticultural Research Laboratory

Received for publication 4 Aug. 1997. Accepted for publication 19 Nov. 1997. We thank Victor Chew, Statistician, USDA-ARS, Gainesville, Fla., for recommendations on statistical analyses and Roxanne Wiseman and Lisa Santiago, Biological Technicians, USDA-ARS, Orlando, Fla., for competent technical assistance during the course of this study. Mention of trademark, warranty, proprietary product, or vendor does not constitute a guarantee by the USDA and does not imply its approval to the exclusion of other products or vendors that may also be suitable. The cost of publishing this paper was defrayed in part by the payment of page charges. Under postal regulations, this paper therefore must be hereby marked *advertisement* solely to indicate this fact.

Table 1. Order of C₂H₄ application, heat treatments, or partial ripening of mature-green tomatoes.

Treatment no.	Treatment description ^z
A	C ₂ H ₄ ^y , then 14 d at 2 °C
B	C ₂ H ₄ , then 14 d at 20 °C ^x
C	C ₂ H ₄ , then 42 °C H ₂ O for 1 h, then 2 d at 20 °C ^w
D	42 °C H ₂ O for 1 h, then C ₂ H ₄
E	2 d at 38 °C ^v , then C ₂ H ₄
F	C ₂ H ₄ , then 42 °C H ₂ O for 1 h
G	42 °C H ₂ O for 1 h, then C ₂ H ₄ , then 2 d at 20 °C
H	C ₂ H ₄ , then 2 d at 38 °C

^zFollowing individual treatment, all fruit with the exception of treatment B, were stored 14 d at 2 °C before ripening at 20 °C and 92% ± 3% relative humidity (RH).

^yC₂H₄ applied at 100 µL·L⁻¹ at 22 °C and 90% ± 5% RH for 1 d.

^x92% ± 3% RH.

^wPartial ripening.

^v92% ± 3% RH.

at Orlando, Fla., where the fruit were sorted to eliminate defects and establish uniformity of size and color. Fruit were sorted into 10 groups (A–J) of 75 for treatment and then further divided into three replications per treatment (25 fruit) (Table 1). Fruit were sampled for condition and chemical analyses when they reached the red-ripe stage (USDA, 1975). At the time of sampling, pericarp tissue samples from five fruit per replication were frozen and stored at –20 °C until used for chemical analyses.

FRUIT CONDITION AND CHEMICAL ANALYSES. Chilling injury (CI) severity and decay incidence were subjectively rated. Depending on the percentage of surface area affected, fruit were classified in one of five CI categories, where 0 = 0%, 1 < 5%, 2 ≥ 5% < 25%, 3 ≥ 25% ≤ 50%, and 4 > 50%. A CI index was calculated from these classifications. Objective measurements included color, lycopene and chlorophyll content, soluble solids, acidity, pH, and flavor volatiles as described previously (McDonald et al., 1996). Fruit firmness was determined as described previously (McDonald et al., 1996), except that resistance to compression was measured with a food-testing system (model 4411; Instron Inc., Canton, Mass.).

LIPID EXTRACTION AND ANALYSIS. Pericarp tissue samples from five fruit (20 g fresh mass) were lyophilized and stored at –80 °C before extraction according to Whitaker (1991) with modification. Lyophilized samples (1.0 g dry mass) were homogenized in 25 mL of acidified (0.1% HOAc) CHCl₃–MeOH (2:1) for 20 s with a Brinkman tissue homogenizer (Brinkman Instruments, Westbury, N.Y.). The homogenate was filtered through a sintered glass funnel and reextracted with 20 mL of CHCl₃–MeOH. Volume of the combined extracts was reduced to ≈15 mL with a rotary evaporator. An equal volume of 0.8% NaCl was added to the extract, which was shaken and then centrifuged at 1,500 g_n for 5 min. The CHCl₃ layer was recovered, and an equal volume of 1 MeOH : 1 H₂O added, shaken, and centrifuged at 1,500 g_n for 5 min. The CHCl₃ phase was recovered and evaporated under a stream of N₂. Lipids were dissolved in 2 mL of CHCl₃ before silicic acid column chromatography. Neutral lipids containing free sterols (FSs) and steryl esters (SEs) were eluted with 20 CHCl₃ : 1 Me₂CO, acylated steryl glycosides (ASGs) with 2 CHCl₃ : 1 Me₂CO, and steryl glycosides (SGs) with Me₂CO.

Neutral lipids were separated on thin-layer chromatography (TLC) plates (500 µm thick, Merck G 60) according to Wang and Faust (1988) with modification. Before TLC, 15 µg lathosterol was added to the neutral lipid fraction as an internal standard. Cholesterol and cholesteryl palmitate were used as markers and the

plates were developed in a freshly made solvent mix of 80 hexane : 20 ethyl acetate : 2 formic acid (by volume). Spots corresponding to FSs and SEs were visualized by spraying with rhodamine and those that comigrated with cholesterol and cholesteryl palmitate were removed and eluted with 3 mL 2 CHCl₃ : 1 MeOH (by volume), including butylated hydroxytoluene at 4 µg·mL⁻¹. After adding 1 mL 0.8% NaCl, vortexing under N₂, and centrifugation, the CHCl₃ phase containing the FSs or deesterified FSs was evaporated to dryness under N₂. The FS fractions were resuspended in hexane before gas chromatography (GC) analysis. The SE fractions were saponified in 1 mL of 1 M KOH in 85% EtOH for 1 h at 80 °C (under N₂). After heating, 0.5 mL H₂O was added and the deesterified FSs were recovered by extraction with 2 mL of hexane. Samples were evaporated to dryness under N₂ and redissolved in hexane before GC analysis. Sterol composition of the FS and SE fractions was determined by GC–flame-ionization detection (FID) on a 0.32-mm-i.d. × 30-m Rtx-50 fused silica capillary column (Restek Corp., Bellefonte, Pa.). Injector, oven, and detector temperatures were 280, 280, and 300 °C, respectively. Individual sterols were identified by comparison with authentic standards.

Cholesterol was added as an internal standard to the SG and ASG fractions before acidic methanolysis with 1.0 mL of 1 N HCl in MeOH at 75 °C for 2 h. Volumes were reduced to ≈0.5 mL under a stream of N₂ and 1.5 mL of 0.85% NaCl added. Hydrolyzed SG and ASG fractions were extracted twice with 3 mL hexane to recover the liberated FSs. Hexane was evaporated under a stream of N₂ and the samples redissolved in hexane before GC analysis. Sterol composition of the SG and ASG fractions was determined as for the FS and SE fractions except on a 0.25-mm-i.d. × 30-m Rtx-1 fused silica capillary column (Restek Corp., Bellefonte, Pa.).

STATISTICAL ANALYSIS. A completely randomized design was used in the experiment. Data were analyzed with SAS's General Linear Model procedure (SAS Institute, Cary, N.C.), and orthogonal contrasts were used for treatment comparisons.

Results

Effects of C₂H₄, heat treatment, and partial ripening on CI, decay, and quality characteristics of red-ripe tomatoes are presented in Table 2. Nonchilled control fruit ripened in 7 d at 20 °C, whereas chilled fruit required 27 d (including 14 d at 2 °C) to reach red-ripe stage. Among the heat-treated fruit, there were no significant differences in the number of days to ripeness. Visible chilling injury, manifested as sunken areas on fruit surfaces, was observed only on fruit that were water heat treated and partially ripened before storage. Chilling resulted in a dramatic increase in decay following transfer to 20 °C. All heat treatments reduced decay significantly; however, there were no significant differences in decay among the heat-treated fruit, regardless of the method of heating or additional treatments.

Chilled fruit were less firm than nonchilled fruit at the red-ripe stage. Among the heat-treated fruit, only partial ripening affected fruit firmness, with partially ripened fruit being firmer than those not partially ripened. Tomatoes that were partially ripened were lighter in color (higher L* value) compared with fruit that were not partially ripened. Fruit color was affected by method of heating, with air heat-treated fruit having a higher a*/b* value (more red in color) than water-heated fruit. In addition, C₂H₄ before water heat treatment resulted in fruit with higher a*/b* values than C₂H₄ treatment after water heat treatment. Water heat-treated fruit that were partially ripened had lower a*/b* values than fruit that were not partially ripened. However, there were no differences among

treatments with respect to tissue lycopene and chlorophyll levels (data not shown).

The pH was higher in chilled control fruit than nonchilled control fruit and in water-heated than air-heated fruit. There were no differences among treatments with respect to soluble solids content, titratable acidity, or solids to acids ratio (data not shown).

Ten of the fifteen flavor volatiles analyzed were decreased by chilling (Table 3). However, levels of most flavor volatiles in heat-treated chilled fruit were generally intermediate between the chilled and nonchilled controls. 2+3-Methylbutanol levels were lower in chilled controls than heat-treated fruit. Exposure to C₂H₄ before rather than following heat treatments resulted in lower levels of geranylacetone and β -ionone. Hexanal levels were higher and ethanol levels were lower in air-heated than water-heated fruit. In air-heated fruit, there were lower levels of hexanal, 6-methyl-5-hepten-2-one, geranylacetone, and β -ionone when C₂H₄ was administered before rather than following treatment. Levels of hexanal and β -ionone were lower and levels of ethanol and 2+3-methylbutanol were higher in partially ripened fruit than in fruit not partially ripened.

Cholesterol, campesterol, stigmasterol, β -sitosterol, and isofucosterol were the major sterols in all sterol lipid fractions at the red-ripe stage (Table 4). Storage at 2 °C decreased the level of cholesterol, increased the levels of campesterol and isofucosterol in the FS fraction, and increased the level of campesterol in the ASG fraction. Heat treatment increased the level of campesterol in the pericarp SE fraction. Treating with C₂H₄ following heat treatments resulted in increased levels of campesterol in SE and ASG fractions. There was, however, no difference in levels of sterol

lipids between heat treatments by air or water. In the air heat-treated fruit, administering C₂H₄ before treatment resulted in increases in β -sitosterol in the SE, SG, and ASG fractions, as well as an increase in isofucosterol in the SG fraction. With the water heat-treated fruit, administering C₂H₄ before treatment resulted in decreases in campesterol in the SE and ASG fractions. Partially ripening fruit led to a decrease in β -sitosterol in the SE fraction.

Discussion

One objective of this study was to determine the effect on quality of applying C₂H₄ before or following heat treatment of chilled mature-green tomatoes. A second objective was to determine whether partial ripening was as effective in reducing CI following a low-temperature storage. Water heat-treated fruit had more CI but less decay ($\approx$ 4-fold) than fruit that were not heat treated. It may be that visible CI symptoms were simply not apparent before decay developed on the fruit that were not heat treated, especially since 63% of nonheated fruit decayed. Cheng and Shewfelt (1988) considered susceptibility to decay to be the first, and perhaps the most sensitive, symptom of CI in tomatoes. Although more CI developed on fruit that were partially ripened, there was no statistical difference in decay development between them and those not partially ripened. It is interesting to note that CI developed on the partially ripened fruit and not on nonpartially ripened fruit, as it is assumed that immature fruit are less tolerant of chilling temperatures than mature fruit (Saltveit and Morris, 1990). The partially ripened fruit were 2 d more ripe when they were stored at the chilling temperature.

Table 2. Effects of C₂H₄, heat treatment, and partial ripening on chilling injury, decay, and quality characteristics of red-ripe tomatoes.

Contrasts	Treatment no. ^z	Days to red ripe	Chilling injury (index) ^y	Decay (%)	Firmness (N)	pH	Objective color (L*)	(a*/b*)
Not heated, not chilled ^a	B	7	0.0	0	11.9	4.35	43.5	1.07
Not heated, chilled ^w	A	27	0.0	63	8.4	4.42	41.9	1.14
		*	NS	***	**	*	NS	NS
Not heated, chilled	A	27	0.0	63	8.4	4.42	41.9	1.14
Heated, chilled	C,D,E,F,G,H	23	0.5	16	9.4	4.44	42.7	1.07
		NS	***	***	NS	NS	NS	NS
C ₂ H ₄ preheating	C,F,H	23	0.3	16	9.5	4.43	42.9	1.10
C ₂ H ₄ postheating	D,E,G	24	0.7	15	9.3	4.46	42.6	1.04
		NS	***	NS	NS	NS	NS	NS
Hot air ^v	E,H	24	0	16	8.8	4.40	42.3	1.14
Hot water ^u	C,D,G,H	23	0.7	15	9.7	4.46	42.2	1.05
		NS	***	NS	NS	*	NS	**
Hot air, C ₂ H ₄ preheating	H	23	0	13	9.1	4.39	42.5	1.12
Hot air, C ₂ H ₄ postheating	E	25	0	17	8.5	4.42	42.0	1.17
		NS	NS	NS	NS	NS	NS	NS
Hot water, C ₂ H ₄ preheating	C,F	23	0.5	18	9.7	4.44	43.1	1.10
Hot water, C ₂ H ₄ postheating	D,G	23	1.0	14	9.8	4.48	42.8	0.98
		NS	***	NS	NS	NS	NS	*
Hot water, PR ⁱ	C,G	21	1.5	10	10.6	4.45	44.7	0.89
Hot water, not PR	D,F	21	0.0	22	8.9	4.47	41.2	1.18
		NS	***	NS	*	NS	***	***

^zSee Table 1 for treatment descriptions.

^yPercentage of surface area affected, where 0 = 0%, 1 < 5%, 2 $\geq$ 5% < 25%, 3 $\geq$ 25% $\leq$ 50%, and 4 > 50%.

^xC₂H₄, then 20 °C until ripe (nonchilled control).

^wC₂H₄, then 14 d at 2 °C (chilled control).

^vHeld 2 d at 38 °C and 92% $\pm$ 3% relative humidity.

^uHeld 1 h in 42 °C water.

ⁱPartially ripened at 20 °C for 2 d.

NS, *, **, *** Nonsignificant or significant at $P \leq 0.05$, 0.01, or 0.001, respectively.

There were no differences in fruit quality characteristics as a result of exposure to C₂H₄ before or following heat treatments. However, fruit partially ripened were firmer, lighter in color (higher L* value), and were less red in color (lower a*/b* ratio) than those that were not partially ripened. Even though ethylene treatment for 1 d initiates ripening, apparently 1 d is not a sufficient amount of time before subjecting fruit to chilling temperatures for fruit quality characteristics to be effected. However, the additional 2 d involved in partial ripening is enough to affect fruit quality characteristics.

As reported previously, storage at 2 °C reduced flavor volatiles in tomatoes (McDonald et al., 1996). In the present study, we found that storage at 2 °C reduced the levels of 10 volatiles including hexanal, *cis*-3-hexenal, *trans*-2-heptenal, 6-methyl-5-hepten-2-one, geranylacetone, acetone, methanol, ethanol, 2+3-methylbutanol, and 2-isobutylthiazole. Since there were no differences in contents of flavor volatiles between not heated, chilled fruit and heated, chilled fruit, except for 2+3-methylbutanol, it appears that heat treatments did not affect the reduction in volatiles induced by chilling. When averaged over air and water heat treatments, administering C₂H₄ before treatment resulted in decreased levels of geranylacetone and β -ionone. Considering only the air heat treatment, administering C₂H₄ before treatment resulted in decreased levels of four flavor volatiles including hexanal, 6-methyl-5-hepten-2-one, geranylacetone, and β -ionone. For the water heat treatment, there were no differences in flavor volatiles between pre- and posttreatment C₂H₄ exposure. Therefore, it appears that there is more of an interaction between C₂H₄ and air

heat treatment than with C₂H₄ and water heat treatment with respect to flavor volatiles. Kader et al. (1978) reported that C₂H₄ did not influence tomato flavor as determined by a sensory panel, and no influence of C₂H₄ was detected in an informal taste evaluation in this study (data not shown). However, a more detailed, larger scale sensory analysis would need to be conducted to determine the effect of these treatments on tomato flavor, since all volatiles measured, except for methanol and ethanol, contribute to tomato flavor based on odor threshold studies (Buttery et al., 1989).

Steryl lipid composition changes dramatically during tomato ripening (Whitaker, 1988; 1991). In the present study, the most prominent change was a large increase in the stigmasterol to β -sitosterol ratio, particularly in the FS fraction (data not shown). At the red-ripe stage, the stigmasterol to β -sitosterol ratio in the FS fraction was 4.9 in nonchilled fruit compared with a ratio of 3.5 in chilled fruit, which supports the findings of Whitaker (1993). There were 59% more FSs in chilled fruit compared with non-chilled tomatoes (data not shown). The increase in the proportion of FSs in chilled fruit could result from decreased rates of glycosylation and esterification or from increased rates of deglycosylation and deesterification (Whitaker, 1993). Whitaker (1988) concluded that the steryl lipid changes are ripening specific and are much more pronounced with ripening than merely with aging of the fruit. The glycosylated sterols (SGs + ASGs) accounted for >75% of the total sterols in red-ripe fruit (data not shown). It is thought that the glycosylated sterols serve as membrane structural lipids (Mudd, 1980; Mudd and McManus, 1980)

Table 3. Effects of C₂H₄, heat treatment, and partial ripening on flavor volatiles^a of red-ripe tomatoes.

Contrasts	Treatment no.	Aldehydes				Ketones					Alcohols				Miscellaneous	
		Hex	Chex	Thex	Hept	Meth	Gern	Pent	Ace	Ione	Meoh	Etoh	Mebu	Heol	Isob	Phen
Not heated, not chilled ^b	B	11.4	11.8	10.7	0.06	0.71	3.2	0.39	0.87	0.24	332	24.0	1.65	0.18	0.08	0.07
Not heated, chilled ^w	A	4.8	5.2	8.1	0.03	0.40	1.1	0.31	0.34	0.09	224	17.1	0.54	0.06	0.06	0.05
		***	**	NS	*	***	***	NS	*	NS	**	*	***	NS	*	NS
Not heated, chilled	A	4.8	5.2	8.1	0.03	0.40	1.1	0.31	0.34	0.09	224	17.1	0.54	0.06	0.06	0.05
Heated, chilled	C,D,E,F,G,H	4.2	6.8	7.1	0.04	0.45	1.5	0.27	0.41	0.20	227	21.1	0.93	0.11	0.08	0.08
		NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	*	NS	NS	NS
C ₂ H ₄ preheating	C,F,H	3.8	6.6	6.4	0.04	0.42	1.3	0.26	0.42	0.13	225	21.2	0.91	0.10	0.07	0.10
C ₂ H ₄ postheating	D,E,G	4.6	7.1	7.7	0.04	0.48	1.8	0.29	0.40	0.27	229	21.0	0.95	0.11	0.08	0.06
		NS	NS	NS	NS	NS	**	NS	NS	*	NS	NS	NS	NS	NS	NS
Hot air ^v	E,H	5.4	8.4	7.9	0.05	0.48	1.8	0.29	0.37	0.19	235	18.0	0.83	0.09	0.07	0.06
Hot water ^u	C,D,G,H	3.6	6.1	6.6	0.04	0.44	1.4	0.27	0.43	0.21	223	22.7	0.98	0.12	0.08	0.09
		**	NS	NS	NS	NS	NS	NS	NS	NS	NS	*	NS	NS	NS	NS
Hot air, C ₂ H ₄ preheating	H	4.2	7.5	6.6	0.04	0.39	1.2	0.27	0.37	0.05	232	17.2	0.68	0.08	0.06	0.05
Hot air, C ₂ H ₄ postheating	E	6.5	9.3	9.2	0.05	0.57	2.3	0.31	0.37	0.32	238	18.8	0.97	0.09	0.08	0.07
		**	NS	NS	NS	**	**	NS	NS	*	NS	NS	NS	NS	NS	NS
Hot water, C ₂ H ₄ preheating	C,F	3.6	6.1	6.4	0.04	0.44	1.3	0.26	0.45	0.17	222	23.2	1.02	0.11	0.08	0.13
Hot water, C ₂ H ₄ postheating	D,G	3.6	6.0	6.9	0.04	0.44	1.6	0.28	0.41	0.24	225	22.2	0.94	0.13	0.09	0.06
		NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS
Hot water, PR ^z	C,G	2.7	5.5	6.3	0.04	0.44	1.2	0.29	0.48	0.12	229	26.5	1.14	0.09	0.08	0.13
Hot water, not PR	D,F	4.5	6.7	7.0	0.04	0.44	1.6	0.25	0.38	0.30	217	18.9	0.83	0.15	0.09	0.06
		**	NS	NS	NS	NS	NS	NS	NS	*	NS	**	*	NS	NS	NS

^aData expressed in mg·L⁻¹. Four aldehyde volatiles were quantified: hexanal (Hex), *cis*-3-hexenal (Chex), *trans*-2-hexenal (Thex), and *trans*-2-heptenal (Hept); five ketone flavor volatiles were quantified: 6-methyl-5-hepten-2-one (Meth), geranylacetone (Gern), 1-penten-3-one (Pent), acetone (Ace), and β -ionone (Ione); four alcohol flavor volatiles were quantified: methanol (Meoh), ethanol (Etoh), 2+3-methylbutanol (Mebu), and *cis*-3-hexenol (Heol); and two miscellaneous flavor volatiles were quantified: 2-isobutylthiazole (Isob) and 1-nitro-2-phenylethane (Phen).

^bSee Table 1 for treatment descriptions.

^cC₂H₄, then 20 °C until ripe (control).

^wC₂H₄, then 14 d at 2 °C (control).

^vHeld 2 d at 38 °C and 92% $\pm$ 3% relative humidity.

^uHeld 1 h in 42 °C water.

^zPartially ripened at 20 °C for 2 d.

NS, *, **, *** Nonsignificant or significant at $P \leq 0.05$, 0.01, or 0.001, respectively.

Table 4. Effects of C₂H₄, heat treatment, and partial ripening on steryl lipids of red-ripe tomatoes.

Contrasts	Treatment no. ^a	Free sterols (% of total)					Steryl esters (% of total)					Steryl glycosides (% of total)					Acylated steryl glycosides (% of total)				
		Chol ^b	Camp	Stig	Bsit	Isof	Chol	Camp	Stig	Bsit	Isof	Chol	Camp	Stig	Bsit	Isof	Chol	Camp	Stig	Bsit	Isof
Not heated, not chilled ^c	B	4.4	5.1	73.3	14.7	2.6	3.2	5.1	46.3	25.9	20.0	1.8	7.5	64.5	23.7	2.6	2.0	9.9	59.5	25.4	3.2
Not heated, chilled ^d	A	2.5	5.8	66.9	19.4	5.3	5.9	4.6	41.5	25.2	22.8	1.6	8.2	64.9	23.4	1.9	2.0	11.4	58.7	24.0	3.9
		***	**	NS	NS	*	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	*	NS	NS	NS
Not heated, chilled	A	2.5	5.8	66.9	19.4	5.3	5.9	4.6	41.5	25.2	22.8	1.6	8.2	64.9	23.4	1.9	2.0	11.4	58.7	24.0	3.9
Heated, chilled	C,D,E,F,G,H	3.1	5.8	69.2	18.8	3.1	3.4	5.3	44.4	29.4	17.6	1.7	8.3	64.1	23.9	1.9	2.4	10.7	57.3	25.8	3.8
		NS	NS	NS	NS	NS	NS	*	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS
C ₂ H ₄ preheating	C,F,H	3.2	5.7	68.3	19.5	3.0	3.0	4.9	44.1	30.4	17.6	1.6	8.3	63.2	24.7	2.2	2.5	10.3	57.6	26.0	3.8
C ₂ H ₄ postheating	D,E,G	3.1	5.9	70.1	18.1	2.8	3.7	5.7	44.7	28.4	17.5	1.5	8.4	65.0	23.0	1.9	2.3	11.2	57.1	25.6	3.8
		NS	NS	NS	NS	NS	NS	**	NS	NS	NS	NS	NS	NS	NS	NS	NS	*	NS	NS	NS
Hot air ^e	E,H	2.9	5.9	69.3	19.0	3.0	2.9	5.5	46.6	30.1	15.1	1.6	8.0	64.9	23.0	2.5	2.7	10.8	57.4	25.7	3.6
Hot water ^f	C,D,G,H	3.1	5.8	69.2	18.8	3.2	3.6	5.2	43.3	29.1	18.8	1.8	8.4	63.7	24.3	1.9	2.2	10.7	57.3	25.9	3.9
		NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS
Hot air, C ₂ H ₄ preheating	H	2.8	5.9	66.9	20.7	3.7	3.1	5.2	44.0	33.6	14.1	1.7	7.6	61.9	25.0	3.8	3.2	10.5	54.6	27.8	3.8
Hot air, C ₂ H ₄ postheating	E	3.0	5.8	71.8	17.2	2.2	2.7	5.7	49.1	26.5	16.1	1.5	8.4	67.8	21.0	1.2	2.1	10.9	60.1	23.5	3.4
		NS	NS	NS	NS	NS	NS	NS	NS	*	NS	NS	NS	NS	*	*	NS	NS	NS	*	NS
Hot water, C ₂ H ₄ preheating	C,F	3.1	5.7	69.1	19.0	3.3	3.0	4.7	44.2	28.8	19.4	1.8	8.3	63.9	24.6	1.4	2.2	10.1	59.1	25.1	3.8
Hot water, C ₂ H ₄ postheating	D,G	3.2	6.0	69.3	18.6	3.1	4.2	5.8	42.5	29.4	18.2	1.9	8.5	63.6	24.0	2.3	2.3	11.4	55.6	26.7	4.1
		NS	NS	NS	NS	NS	NS	***	NS	NS	NS	NS	NS	NS	NS	NS	NS	*	NS	NS	NS
Hot water, PR ^g	C,G	3.2	5.8	71.9	16.5	2.7	4.1	5.3	45.4	26.3	19.0	1.6	8.0	64.9	23.4	2.2	2.1	10.7	58.6	25.1	3.6
Hot water, not PR	D,F	3.1	5.9	66.5	21.1	3.6	3.1	5.2	41.3	32.0	18.6	1.9	8.8	62.6	25.2	1.6	2.3	10.8	56.1	26.7	4.3
		NS	NS	NS	*	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS

^aSee Table 1 for treatment descriptions.^bFive sterols were quantified: cholesterol (Chol), campesterol (Camp), stigmasterol (Stig), β -sitosterol (Bsit), and isofucosterol (Isof).^cC₂H₄, then 20 °C until ripe (nonchilled control).^dC₂H₄, then 14 d at 2 °C (chilled control).^eHeld 2 d at 38 °C and 92% $\pm$ 3% relative humidity.^fHeld 1 h in 42 °C water.^gPartially ripened at 20 °C for 2 d.ns,*,**,**Nonsignificant or significant at $P \leq 0.05$, 0.01, or 0.001, respectively.

and may play a role in determining fluidity and permeability of cellular membranes. Legge et al. (1986) found a decrease in lipid fluidity of the plasma membrane as tomatoes ripened.

Aside from the steryl lipid differences between chilled and nonchilled fruit, particularly in the FS fraction, there were few significant differences between the individual sterols in the steryl lipid fractions when making other treatment comparisons. It may be assumed that the sequence of C₂H₄ exposure, method of heat treatment, and partial ripening had a minimal effect on the resulting steryl lipid profiles in the pericarp of red-ripe fruit. Similarly, differences in flavor volatiles were most apparent between chilled and nonchilled fruit. However, to avoid reductions in flavor volatiles, it may be better to treat mature-green tomatoes with C₂H₄ following heat treatment, particularly the air heat treatment.

Flavor volatiles were variably affected by partial ripening; levels of two were increased, two were decreased, and the other 11 were unchanged. Likewise, CI and decay were variably affected by partial ripening. Partially ripened fruit were firmer but had more CI than those not partially ripened. Because of mixed results found with partial ripening in this study, no recommendation can be made for its use in place of heat treatments to extend shelf life and preserve quality. Based on the heat treatments and cultivar used in this study, the results support earlier findings on the benefits of heat treatments (Klein and Lurie, 1991; Lurie and Klein, 1991; McDonald et al., 1996) and are contrary to the report of beneficial effects of partial ripening by Whitaker (1994). However, it appears that all tomatoes do not respond similarly to a prestorage heat treatment (Lurie and Sabehat, 1997). In addition, the 'Rutgers' fruit in the

study by Whitaker (1994) were grown in the greenhouse and the 'Sunbeam' fruit in the present study were field grown.

The purpose of this study was to optimize the heat treatments by studying the sequence of C₂H₄ treatment in conjunction with air and water heat treatments and to consider the effects of a 2 d partial ripening before low-temperature storage. Although the results were not clear cut, it appears that a C₂H₄ treatment would be more beneficial when applied following rather than before heat treatment. Because partial ripening had beneficial and detrimental effects on the resulting fruit ripening and fruit quality parameters determined, its usefulness was not fully clarified.

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