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Effect of UV-C radiation and hot water on the calcium content and postharvest quality of apples

S. Hemmaty[1,2]*, N. Moallemi[2] and L. Naseri[3]

[1] *Academic Centre for Education, Culture and Research (ACECR). Urmia Branch. Urmia University. Urmia. Iran*
[2] *Department of Horticulture. Shahid Chamran University. Ahvaz. Iran*
[3] *Department of Horticulture. Urmia University. Urmia. Iran*

Abstract

To increase the storage shelf life of 'Red Delicious' and 'Golden Delicious' apples they were treated with UV-C irradiation at doses of 0, 5 and 15 min irradiation at 1.435×10^{-4} W cm^{-2} and with hot water containing 4% $CaCl_2$ at four levels (control, dipping at 25°C for 10 min, dipping at 38°C for 5 min and dipping in 54°C for 1 min) in a factorial design with 4 replicates. The results showed that UV-C irradiation and dipping of fruit in hot water increased the storage life and improved fruit quality factors in 'Red Delicious' and 'Golden Delicious' apples at the end of cold storage. Both UV-C and hot water treatments decreased pH and total soluble solids/titratable acids ratio and increased fruit titratable acids and firmness. UV-C and hot water treatment increased fruit Ca content during storage. The results showed that UV-C and hot water treatment can retard fruit ripening and maintain fruit quality in cold storage. These treatments can also increase Ca concentration of fruit flesh and thus increase the nutritional value of the apples.

Additional key words: calcium, dipping, irradiation, *Malus domestica.*

Resumen

Efecto de la radiación UV-C y del agua caliente en el contenido de calcio y calidad poscosecha de manzanas

Con el fin de prolongar el periodo de vida útil durante la conservación frigorífica de manzanas 'Red Delicious' y 'Golden Delicious', éstas se trataron con radiación UV-C en tres dosis (0, 5 y 15 min de irradiación a $1{,}435 \times 10^{-4}$ W cm^{-2}) y agua caliente con $CaCl_2$ al 4% en cuatro niveles (control 0, inmersión a 25°C 10 min, 38°C 5 min ó 54°C 1 min), en un diseño factorial con 4 repeticiones por tratamiento. La irradiación con UV-C y la inmersión de los frutos en agua caliente permitió alargar el periodo de conservación y mejoró la calidad de manzanas 'Red Delicious' y 'Golden Delicious' tras el almacenamiento en frío. Ambos tratamientos aumentaron la acidez titulable y la firmeza de los frutos, también disminuyeron el pH y la relación sólidos solubles/acidez. El tratamiento con UV-C y agua caliente incrementó el contenido en calcio de los frutos durante el almacenamiento. Los resultados muestran que estos tratamientos pueden retrasar los procesos de maduración de los frutos y mantener su calidad durante el almacenamiento frigorífico, así como aumentar el contenido en Ca de la pulpa del fruto y por tanto incrementar su valor nutricional.

Palabras clave adicionales: calcio, inmersión, irradiación, *Malus domestica.*

Introduction

Apple (*Malus domestica* Borkh.) fruits are commonly stored for long periods at low temperatures under controlled atmosphere. During storage fruit quality and nutritional value decreases. A number of techniques such as pre-storage heat treatment (Klein and Lurie, 1992), treatment with chemicals (Leverentz *et al.*, 2003) and modified atmosphere (Hertog *et al.*, 2001) have been used. However, some chemicals pose serious health hazard and environmental risks. Additionally, consumers increasingly prefer agricultural products without chemicals residues and, hence, alternative methods to control postharvest disease and to extend fruit shelf life are required.

Heat treatments and photochemical treatment with UV-C have proved beneficial in delaying postharvest fruit senescence in different species (Lurie, 1998; Maharaj *et al.*, 1999; Ait Barka *et al.*, 2000; Paull and

* Corresponding author: syavash.hort@gmail.com
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Chen, 2000; Marquenie *et al.*, 2002). Exposure to temperatures above 35°C has inhibited ripening in different fruits (Paull, 1990; Lurie, 1998). Heating mature green tomatoes for 2 or 3 d at 38°C reversibly inhibited ripening and decreased fruit decay in storage (Lurie and Sabehat, 1997). Garcia *et al.* (1995) found that hot water dipping of the strawberry (*Fragaria* × *ananassa* Duch., cv. Tudla) reduced fruit decay, increased the soluble solids content and decreased titratable acidity. Postharvest water dipping at 50°C for 5 min significantly increased the shelf life and maintained the quality of ber (*Zizyphus mauritiana* Lamk.) fruits, particularly late in storage (Lal *et al.*, 2002). Components of fruit ripening affected by heat treatments include ethylene production, respiration rate, fruit softening, pigment metabolism, membrane changes, flavour and the production of volatiles (Lurie, 1998; Paull and Chen, 2000). While artificial UV-C radiation also delays fruit ripening (Maharaj *et al.*, 1999) and affects fruit softening (Ait Barka *et al.*, 2000), the literature on photochemical radiation with UV-C is primarily related to its germicidal activity and induction of disease resistance.

UV-C is generally harmful but it can give beneficial effect on horticultural crops at low doses, a phenomenon known as hormesis (stimulation of a plant response by low levels of inhibitors or stress) (Lukey, 1982). Purohit *et al.* (2003) concluded that ber fruits irradiated for 6 h with UV-C radiation had lower total soluble solids (TSS) and total soluble solids/titratable acids (TSS/TA) ratio and a higher TA than other treatments and control fruits. Fresh boysenberry (*Rubus* hybrid) fruits treated with UV-C radiation (9.2 kJ m^{-2}) or hot air (45°C for 1 h), after 2 days, had less damaged drupelets per fruit and were firmer than untreated fruit (Vicente *et al.*, 2004).

Dipping in a calcium (Ca) solution has been used as a firming agent to extend the postharvest shelf life of apples (Lurie and Klein, 1992; Conway *et al.,* 1999), strawberry (Garcia *et al*., 1996), highbush blueberry (*Vaccinium corymbosum*) (Hanson *et al.,* 1993), lemon (*Citrus limon* L.) (Tsantili *et al.,* 2002) and fresh cut cantaloupe (*Cucumis melo* L.) (Luna-Guzman *et al.,* 1999). Numerous investigations have suggested that many physiological and pathological disorders of apples are related to their tissue Ca. Adequate Ca concentration maintains fruit firmness, and lowers the incidence of disorders such as water core, bitter pit and internal breakdown (Faust and Shear, 1968; Bangerth *et al.*, 1972; Reid and Padfield, 1975) and reduces decay caused by postharvest pathogens (Conway *et al.*, 1991). Apple fruit cell walls with higher Ca concentrations are more resistant to cell wall degrading enzymes such as polygalacturonase and pathogens than are cell walls lower in Ca (Conway *et al.*, 1988). Researchers have reported that heat treatment increases fruit flesh Ca content (Lurie and Klein, 1992; Lurie *et al.*, 1996; Luna-Guzman *et al.*, 1999). It has also been shown that UV-C stimulates the efflux and influx of K^+ in cultured rose (*Rosa damascena* L.) cells (Murphy and Wilson, 1982; Murphy, 1988).

The aim of this work was to assess the impacts of hot water and UV-C irradiation on changes in the Ca content and postharvest quality parameters of 'Golden Delicious' and 'Red Delicious' apples.

Material and Methods

Plant material

'Golden Delicious' and 'Red Delicious' apple fruits were harvested manually at the optimal date for commercial harvesting (150 d after full bloom for 'Red Delicious' and 170 d after full bloom for 'Golden Delicious') (Naseri, 2004) from 15-yr old standard trees in a commercial orchard (37° 39' 5N, 45° 4' 28E, altitude: 1,313 m) located in Urmia, Iran, in 2004-2005. Apples uniform in shape and size and free of fungal infection were selected.

UV-C irradiation, hot water treatment and storage

In each cultivar, selected apples were divided into three identical groups for UV-C (288 apples $group^{-1}$), hot water dipping (384 apples $group^{-1}$) treatments, and the combination of the two treatments (672 fruits $group^{-1}$). UV-C radiation was provided by a fluorescent germicidal lamp (30 W, 90 cm) with a peak emission at 254 nm. Irradiation was carried out under ambient condition for 0, 5 and 15 min. The radiation intensity was 1.435×10^{-4} W cm^{-2}. Apples were placed at approximately 25 cm from the lamp and rotated so that their blossom and stem ends faced the lamp to ensure uniform irradiation. For hot water treatments, apples were dipped in water containing 4% $CaCl_2$ at 25°C for 10 min, 38°C for 5 min and 54°C for 1 min. Apples were then air dried at ambient temperature. Untreated apples were used as controls. To investigate the combined effect of UV-C radiation and hot water dipping, apples were irradiated as described above and then hot water

dipped. After treatment apples were placed in polyethylene boxes and stored at 1 ± 1°C and 85-95% relative humidity for 6 months. After sampling from cold stored fruits, they were stored for 7 d at 25°C.

Fruit quality evaluation

Physical and chemical quality factors were measured periodically after treatment and every 45 d of storage at 1 ± 1°C plus 7 d at 25°C in 12-apple samples per treatment (3 apples replicate^{-1}) per cultivar. Total soluble solids were determined with a hand-held refractometer. Titratable acids were measured by titration with 0.1 N NaOH and expressed as percentage of malic acid. Fruit firmness, determined on opposite sides of the fruit, after peeling using a hand-held penetrometer with an 8 mm diameter tip. The pH was measured with a digital pH meter. The TSS:TA ratio was calculated.

The Ca content of the apple flesh was measured after 1, 3 and 5 months storage at 1 ± 1°C. After removing the peel and core of the apples fruit Ca content was measured (AOAC, 1990) using atomic absorption spectrophotometer (Shimadzu AA-6300, Japan). Results are reported on a fresh weight basis.

Statistical analysis

A completely randomized factorial design with four replications was used. Every replicate cultivar^{-1} was 24 apples. An analysis of variance was used to analyze difference between means and the Duncan test was applied for mean separation at $P \leq 0.05$. All analyses were done with MSTAT-C statistical software.

Results

Fruit firmness

Fruit firmness declined during storage. Irradiation and heat treatments had no effect on fruit firmness after treatment plus 7 d storage at 25°C, but after 6 months storage, hot water and irradiation had a significant effect on apple firmness. Fruit firmness of 'Red Delicious' apples was affected by UV-C. At the end of storage apples irradiated for 15 min were significantly firmer than apples from the other treatments or the control (Table 1). However, UV-C had no effect on the apple

Table 1. Effect of different UV-C and hot water treatments on firmness, titratable acids, total soluble solids, pH and TSS/TA ratio of 'Red Delicious' apples during storage at 1 ± 1°C plus 7 days in 25°C

Treatment		Firmness (N)		Titratable acids (%)		Total soluble solids (%)		pH		TSS/TA ratio	
		Days stored at 1 ± 1°C plus 7 days in 25°C									
		7	187	7	187	7	187	7	187	7	187
Hot water	*UV-C*										
—	Control	42.9	32.4^{b}	0.237	0.151^{c}	11.4	14.2^{a}	4.13	4.32	48.96	100.0^{a}
—	5 min	43.7	32.9^{b}	0.241	0.156^{b}	11.6	13.7^{b}	4.12	4.31	49.10	83.40^{c}
—	15 min	44.9	34.4^{a}	0.226	0.166^{a}	11.0	13.7^{b}	4.14	4.32	49.73	88.69^{b}
Control	—	44.0	31.6^{b}	0.218	0.139	11.6	14.2	4.17^{a}	4.37^{a}	53.40^{a}	107.9^{a}
25°C for 10 min	—	43.4	33.8^{a}	0.231	0.163	11.1	13.8	4.15^{a}	4.28^{b}	49.35^{ab}	85.33^{bc}
38°C for 5 min	—	43.2	33.7^{a}	0.252	0.170	11.2	13.7	4.05^{b}	4.27^{b}	45.40^{b}	81.75^{c}
54°C for 1 min	—	44.8	33.7^{a}	0.237	0.158	11.5	13.8	4.17^{a}	4.33^{ab}	48.93^{ab}	87.83^{b}
Control		44.2	28.5^{c}	0.217	0.100^{c}	11.7	15.0	4.15^{ab}	4.45^{a}	54.05^{a}	150.0^{a}
25°C for 10 min	5 min	4.17	33.2^{ab}	0.245	0.177^{a}	11.2	14.0	4.07^{bc}	4.22^{c}	46.80^{b}	79.31^{cd}
	15 min	45.5	34.2^{b}	0.198	0.150^{b}	10.7	13.7	4.25^{a}	4.32^{abc}	55.89^{a}	91.67^{b}
38°C for 5 min	5 min	44.2	33.2^{ab}	0.277	0.177^{a}	11.5	13.5	4.10^{bc}	4.25^{c}	41.63^{c}	76.92^{d}
	15 min	45.0	34.2^{b}	0.235	0.150^{b}	11.0	13.5	4.00^{c}	4.32^{abc}	46.78^{b}	90.78^{b}
54°C for 1 min	5 min	45.0	33.0^{ab}	0.220	0.155^{ab}	12.0	13.5	4.17^{ab}	4.30^{bc}	54.82^{a}	87.06^{bc}
	15 min	45.2	35.0^{a}	0.255	0.157^{ab}	11.0	14.0	4.12^{ab}	4.40^{ab}	43.31^{bc}	88.93^{bc}

Means within the same treatment/period followed by the same small letters are not significantly different at $P \leq 0.05$.

firmness of 'Golden Delicious' apples after 6 months storage.

After 6 months storage heat treated 'Golden Delicious' and 'Red Delicious' apples were firmer than the control fruits. There were no significant differences among apples immersed in hot water. However, the relatively greater firmness of apples dipped at 54°C for 1 min could be seen in both cultivars (Tables 1 and 2).

The interaction UV-C irradiation × hot water treatment significantly affected fruit firmness of both cultivars. After 6 months storage, irradiated, immersed 'Red Delicious' apples were firmer than control apples and apples irradiated for 15 min and dipped at 54°C for 1 min were firmer than the other treatments. The combined treatments of UV-C and hot water had no significant effect on fruit firmness in 'Red Delicious' apples (Table 1). In 'Golden Delicious' apples, after treatment, there were significant differences among combined treatments and apples irradiated for 15 min and dipped at 25°C for 10 min were firmer than apples from other treatments and the control. After storage, treatment had no significant effect on fruit firmness of 'Golden Delicious' apples (Table 2).

Total soluble solids

Total soluble solids increased during storage. Irradiation and hot water treatment had no effect on TSS of either cultivar after treatment (Tables 1 and 2). However, after 6 months storage, the TSS of 'Golden Delicious' apples were not affected by UV-C irradiation (Table 2), but, UV-C treatment had a significant effect on the TSS of 'Red Delicious' apples. Irradiated apples had a lower TSS than control apples (Table 1).

Postharvest hot water treatment affected TSS levels of 'Golden Delicious' apples and apples which had been immersed in hot water had lower TSS levels than control apples (Table 2). Hot water immersion had no effect on TSS of 'Red Delicious' apples after 6 months storage (Table 1). At the end of the storage period 'Golden Delicious' apples which had been immersed at 25°C for 10 min had a lower TSS than other treatments and control apples (Table 2).

The combination of UV-C and hot water had no effect on the TSS of 'Golden Delicious' or 'Red Delicious' apples after treatment and storage (Tables 1 and 2).

Table 2. Effect of different UV-C and hot water treatments on firmness, titratable acids, total soluble solids, pH and TSS/TA ratio of 'Golden Delicious' apples during storage at 1 ± 1°C plus 7 days in 25°C

Treatment		Firmness (N)		Titratable acids (%)		Total soluble solids (%)		pH		TSS/TA ratio	
		Days stored at 1 ± 1°C plus 7 days in 25°C									
		7	187	7	187	7	187	7	187	7	187
Hot water	*UV-C*										
—	Control	38.1	24.8	0.443	0.127^{b}	12.2	14.0	3.60	4.51^{a}	27.93	116.0^{a}
—	5 min	38.5	25.0	0.406	0.149^{a}	11.7	14.1	3.64	4.43^{b}	29.65	96.19^{b}
—	15 min	40.1	25.3	0.439	0.151^{a}	12.2	14.1	3.69	4.40^{b}	29.00	94.21^{b}
Control	—	38.5	23.9^{b}	0.422	0.135^{c}	11.9	15.1^{a}	3.62	4.45	28.32	119.4^{a}
25°C for 10 min	—	39.3	24.7^{ab}	0.412	0.139^{bc}	12.2	13.2^{c}	3.63	4.43	30.74	97.99^{b}
38°C for 5 min	—	39.2	25.5^{ab}	0.416	0.149^{b}	11.9	14.2^{b}	3.67	4.47	29.56	97.11^{b}
54°C for 1 min	—	39.9	26.1^{a}	0.467	0.145^{ab}	12.2	13.7^{bc}	3.66	4.44	26.83	94.07^{b}
Control		38.2^{c}	22.2	0.430	0.092^{e}	12.0	15.0	3.55^{dc}	4.70^{a}	28.05	162.5^{a}
25°C for 10 min	5 min	38.7^{c}	24.7	0.410	0.145^{c}	12.0	12.7	3.52^{d}	4.40^{b}	30.86	91.20^{b}
	15 min	42.0^{a}	24.5	0.385	0.137^{d}	12.5	13.7	3.82^{a}	4.42^{b}	33.34	100.1^{b}
38°C for 5 min	5 min	38.7^{c}	25.0	0.355	0.152^{ab}	11.7	14.5	3.80^{a}	4.50^{b}	33.13	97.18^{b}
	15 min	38.5^{c}	25.2	0.443	0.150^{b}	12.2	13.7	3.52^{d}	4.47^{b}	28.68	93.68^{b}
54°C for 1 min	5 min	39.5^{bc}	26.2	0.450	0.155^{a}	11.7	14.0	3.62^{c}	4.40^{b}	26.32	90.29^{b}
	15 min	40.7^{b}	26.0	0.497	0.145^{c}	12.0	13.5	3.70^{b}	4.47^{b}	25.39	93.33^{b}

Means within the same treatment/period followed by the same small letters are not significantly different at $P \leq 0.05$.

Titratable acids and pH

Titratable acids in apples decreased with storage duration. Hot water and UV-C irradiation treatment had no effect on the TA of apples from both cultivars. However, various treatments applied to the apples maintained TA at higher level in storage. After 6 months, irradiated apples had higher TA levels than control apples (Tables 1 and 2). 'Red Delicious' apples irradiated for 15 min had a higher TA than apples irradiated for 5 min and control apples (Table 1). There was no significant difference in 'Golden Delicious' apple TA when irradiated for 15 min or 5 min (Table 2).

After storage, hot water immersion had no effect on the TA of 'Red Delicious' apples (Table 1). By the end of storage there were significant differences among hot water treated 'Golden Delicious' apples. Apples immersed for 5 min at 38°C had significantly higher TA than other treated or control apples (Table 2).

The interaction of UV-C irradiation × hot water treatment significantly affected TA after storage, while there was no significant effect on TA after treatment. In both cultivars immersed apples had higher TA levels than control apples (Tables 1 and 2). 'Red Delicious' apples irradiated for 5 min and immersed at 25°C for 10 min and 38°C for 5 min had higher TA than the other treatments (Table 1). In 'Golden Delicious' apples irradiated for 5 min and immersed at 54°C for 1 min had a higher TA (Table 2). After treatment 'Golden Delicious' apples had a higher TA than 'Red Delicious' apples, but after storage, the situation was reversed and 'Red Delicious' apples had a higher TA level than 'Golden Delicious' (Tables 1 and 2).

After treatment, UV-C radiation had no significant effect on apple juice pH of either cultivar (Tables 1 and 2). It also had no effect on the juice pH of 'Red Delicious' apples after 6 months storage (Table 1). However, by the end of storage the juice pH of 'Golden Delicious' apples had been decreased by UV-C treatment and irradiated apples had a lower juice pH than control apples (Table 2).

Hot water treatment significantly affected apple juice pH in 'Red Delicious' apples. After treatment, apples dipped at 38°C for 5 min had a significantly lower pH than apples from other treatments and control apples. At the end of storage 'Red Delicious' apples immersed at 25°C for 10 min and 38°C for 5 min had a lower pH (Table 1). Hot water treatment had no significant effect on juice pH of 'Golden Delicious' apples after treatment and after storage (Table 2). After treatment 'Golden Delicious' apples had a lower pH than 'Red Delicious' apples, but after 6 months storage, the situation was reversed and 'Red Delicious' apples had a lower pH than 'Golden Delicious' (Tables 1 and 2).

The interaction effect UV-C irradiation × hot water treatment was significant for apple juice pH of both cultivars after treatment and after 6 months storage (Tables 1 and 2). In 'Red Delicious' apples irradiated for 15 min and dipped for 5 min at 38°C had lower juice pH than apples from other treatments or the control after treatment. After storage, a lower juice pH was recorded in 'Red Delicious' apples which had been irradiated for 5 min and dipped for 10 min at 25°C and 5 min at 38°C (Table 1). In 'Golden Delicious', after treatment, there was a lower juice pH in apples irradiated for 5 min and dipped for 10 min at 25°C and irradiated for 15 min and immersed for 5 min at 38°C. After storage irradiated, immersed 'Golden Delicious' apples had significantly lower juice pH than control apples but there was no significant difference between treatments (Table 2).

Total soluble solids: titratable acids ratio

The TSS:TA ratio increased throughout the experiment. After treatment, UV-C irradiation had no significant effect on the TSS:TA ratio of either cultivar (Tables 1 and 2). But after 6 months storage, irradiation retarded the increased TSS:TA ratio and irradiated apples had a lower TSS:TA ratio than control apples. In 'Red Delicious' there was a lower TSS:TA ratio in apples irradiated for 5 min (Table 1) but in 'Golden Delicious' apples there were no significant differences among irradiated apples (Table 2).

Immersion in hot water had a significant effect on the TSS:TA ratio in 'Red Delicious' apples after treatment and at the end of storage. Treated apples had a lower TSS:TA ratio than control apples. After treatment and storage, immersed 'Red Delicious' apples immersed at 38°C for 5 min had a lower TSS:TA ratio (Table 1). After treatment, hot water immersion had no significant effect on 'Golden Delicious' apples. At the end of storage treated apples had a lower TSS:TA ratio than control apples but there were no significant differences among immersed apples (Table 2).

The interaction UV-C × hot water immersion for the TSS:TA ratio was significant. After treatment and storage, 'Red Delicious' apples irradiated for 5 min and dipped for 5 min at 38°C had a lower TSS:TA ratio than

apples from other treatments or control apples (Table 1). Following treatment, the interaction UV-C × hot water immersion had no significant effect on the TSS:TA ratio of 'Golden Delicious' apples. However by the end of the storage period treated apples had a lower TSS:TA ratio than control apples (Table 2). After 6 months storage, the UV-C and then heat treated apples had a significantly lower TSS:TA ratio. A lower TSS:TA ratio was observed in apples irradiated for 5 min and dipped for 10 min at 25°C (Table 2). By the end of the experiment, 'Golden Delicious' apples had a higher TSS:TA ratio than 'Red Delicious' apples (Tables 1 and 2).

Fresh apple flesh calcium content

In both apple cultivars treatment with UV-C irradiation and hot water affected apple flesh Ca content at 1, 3 and 5 months of storage in both cultivars (Tables 3 and 4). After 1, 3 and 5 months storage 'Red Delicious' apples irradiated for 15 min had a higher Ca level than apples from the other treatments and control apples. There were no significant differences between control and irradiated apples after 5 min of irradiation (Table 3). In 'Golden Delicious' apples, irradiated for 5 and 15 min had a higher Ca content than control apples, but there was no significant differences among treated apples (Table 4).

Hot water treatment increased the Ca content of apple flesh. After 1, 3 and 5 months storage, apples immersed at 54°C for 1 min had a higher Ca than apples from the other treatments or control apples in both cultivars. In 'Red Delicious' and 'Golden Delicious' apples there was no significant difference between apples immersed at 25°C for 10 min and at 38°C for 5 min during storage (Tables 3 and 4).

The interaction of UV-C × hot water immersion on the Ca content of apple flesh was significant. In storage, irradiated and hot water treated apples had a higher Ca content than control apples. In both cultivars after 1, 3 and 5 months storage, apples irradiated for 15 min and immersed at 54°C for 1 min had a significantly higher Ca content (Tables 3 and 4).

Throughout the experiment, treated 'Golden Delicious' apples had a higher Ca level than 'Red Delicious' (Tables 3 and 4).

Discussion

The results showed that a hormic dosage of UV-C light can alter fruit ripening during storage. In this work 'Red Delicious' apples treated with UV-C light for 15 min were firmer than apples from other treatment and control fruits. However UV-C treatment did not affect firmness of 'Golden Delicious' apples in storage.

Table 3. Effect of different UV-C and hot water treatments on the Ca content of 'Red Delicious' apples flesh after 1, 3 and 5 months storage at 1 ± 1°C

Treatment		Flesh Ca content (mg 100 g^{-1} fresh weight)		
		1 month	3 months	5 months
Hot water	*UV-C*			
—	Control	67.70^{b}	87.10^{b}	108.5^{b}
—	5 min	74.51^{b}	92.02^{b}	116.8^{b}
—	15 min	86.81^{a}	105.0^{a}	139.7^{a}
Control	—	47.30^{c}	64.89^{c}	101.7^{c}
25°C for 10 min	—	87.99^{ab}	96.87^{b}	132.5^{b}
38°C for 5 min	—	79.42^{b}	94.70^{b}	132.1^{b}
54°C for 1 min	—	90.64^{a}	122.4^{a}	159.7^{a}
Control		47.31^{d}	64.87^{d}	101.7^{d}
25°C for 10 min	5 min	83.93^{bc}	97.03^{bc}	124.4^{bc}
	15 min	95.87^{b}	101.2^{b}	133.0^{bc}
38°C for 5 min	5 min	77.70^{c}	86.57^{c}	115.9^{c}
	15 min	87.87^{bc}	100.3^{b}	139.1^{b}
54°C for 1 min	5 min	89.10^{bc}	99.89^{b}	125.1^{bc}
	15 min	116.2^{a}	153.6^{a}	185.0^{a}

Means within the same treatment/period followed by the same small letters are not significantly different at $P \leq 0.05$.

Table 4. Effect of different UV-C and hot water treatments on the Ca content of 'Golden Delicious' apples flesh after 1, 3 and 5 months storage at 1 ± 1°C

Treatment		Flesh Ca content (mg 100 g^{-1} fresh weight)		
		1 month	3 months	5 months
Hot water	*UV-C*			
—	Control	86.73^{b}	94.58^{b}	140.9^{b}
—	5 min	94.93^{a}	120.9^{a}	157.2^{a}
—	15 min	97.68^{a}	123.8^{a}	163.9^{a}
Control	—	68.50^{c}	75.90^{c}	124.2^{c}
25°C for 10 min	—	99.43^{b}	117.4^{b}	157.1^{b}
38°C for 5 min	—	93.63^{b}	114.3^{b}	152.1^{b}
54°C for 1 min	—	110.9^{a}	144.7^{a}	182.6^{a}
Control		68.50^{d}	75.90^{d}	124.2^{e}
25°C for 10 min	5 min	85.13^{c}	103.8^{bc}	157.9^{b}
	15 min	100.7^{b}	125.0^{b}	150.8^{bc}
38°C for 5 min	5 min	83.20^{c}	99.07^{c}	138.8^{d}
	15 min	90.17^{bc}	114.6^{bc}	151.6^{bc}
54°C for 1 min	5 min	99.60^{bc}	110.1^{bc}	142.8^{c}
	15 min	131.4^{a}	168.3^{a}	202.3^{a}

Means within the same treatment/period followed by the same small letters are not significantly different at $P \leq 0.05$.

Lu *et al.* (1991) also found that UV-C light had no effect on fruit firmness of 'Golden Delicious' apples. Previous work on strawberry, boysenberry and tomatoes showed that fruit softening can be delayed by UV-C light (Maharaj *et al.*, 1999; Ait Barka *et al.*, 2000; Vicente *et al.*, 2004). Cell wall disassembly is a key event associated with ripening that determines the extent of fruit softening and contributes to the ultimate fruit deterioration. The cell wall degrading enzymes, i.e. polygalacturonase, pectin methyl esterase, xylanase, β-D-galactosidase and protease, are disrupted by UV-C (Ait Barka *et al.*, 2000; Stevens *et al.*, 2004). Heat treated apples often soften more slowly than non-heat treated apples (Klein *et al.*, 1990; Sams *et al.*, 1993; Conway *et al.*, 1994). This could be partially explained by recrystallisation or «melting» of the wax layer which sealed barely visible cracks. Similar observations were reported with heated apples (Roy *et al.*, 1994; Lurie *et al.*, 1996). Alternatively, a short heat treatment may stimulate increased wax synthesis to fill the cracks (Baker, 1974). It has also been reported that cell wall degrading enzymes are disrupted by heat treatment (Lazan *et al.*, 1989; Lurie, 1998; Paull and Chen, 2000). The above factors may be reasons for great firmness of apples immersed in hot water than control apples.

Increased TSS may be related to the moisture loss and polysaccharides hydrolysis. UV radiation checks moisture loss, thereby increasing TSS retardation (Lu *et al.*, 1993). Thus the lower rate of TSS increase in UV-C treated apples may be attributed to reduced moisture loss and reduced polysaccharide hydrolysis. After 6 months storage at 1 ± 1°C plus 7 days at 25°C, hot water treated 'Golden Delicious' apples had a lower TSS than control apples. Diaz-Perez *et al.* (2001) reported that sapote mamey (*Pouteria sapota*) fruit immersed at 60°C for 60 min ripened more slowly and had lower soluble solids and pH than untreated fruit. Heat treatment can alter fruit senescence by reducing the rate of ethylene production, respiration, protein syntheses, and softening (Paull, 1990; Lurie, 1998). It is possible that the hot water immersion inhibited the action of enzymes responsible for starch, protein and other macromolecule breakdown.

Irradiation of apples with UV-C light gave a higher TA retention than in control apples. This work supports studies that showed UV-C radiation can retard TA decrease in storage of ber fruits and peaches (Lu *et al.*, 1991; Purohit *et al.*, 2003). The respiration rate and ethylene production was reduced after UV-C treatment of tomato and boysenberries (Maharaj *et al.*, 1999; Vicente *et al.*, 2004). The higher TA in irradiated apples may have been due to a lower respiration rate in these apples and a lower respiratory use of these compounds. Higher TA retention in hot water immersed apples might be due to reduced respiration, later senescence

and slower ripening as found in other heat treated fruits (Nain *et al.*, 1999; Fallik *et al.*, 2001; Lal *et al.*, 2002).

In this work with increased irradiation duration apple Ca content increased. Ait Barka *et al.* (2000) reported that after exposure of tomatoes to UV-C light, the electrolyte leakage of potassium (K) and Ca was in two phases. During first 5 d of storage irradiation caused an immediate increase in tissue leakage. After this time, the pattern was reversed with higher leakage in control than in treated fruits. This persisted throughout the remaining storage period. They suggest that higher K and Ca leakage was presumably due to perturbation of membrane transport after exposure to UV-C and the lower leakage rate in irradiated fruits after 5 d may due to activation of a membrane repair mechanism including increased synthesis of membrane lipids. Increase in electrolyte leakage, after irradiation, has been reported in cauliflower (*Brassica oleracea* var. botrytis) florets (Voisine *et al.*, 1991), tomatoes (El Assi *et al.*, 1997), rose cells (Murphy and Wilson, 1982; Murphy, 1988; Huerta and Murphy, 1989) and tobacco (*Nicotiana tabacum*) cells (Lawrence *et al.*, 1978). The higher Ca content of irradiated fruit could be due to increased electrolyte leakage after irradiation. Most organisms have means of protection from UV radiation. Largely, this amounts to shielding sensitive radiation targets by structural characteristics and pigments that screen out much of the most damaging radiation (Caldwell *et al.*, 1983; Vogelmann, 1993). Phenolic pigments, especially flavonoids that effectively absorb in the UV waveband are an important constituent of this shielding. This UV shielding is combined with DNA repair, antioxidants and polyamins that reduce membrane damage (Kramer *et al.*, 1991). For example, anthocyanin-deficient maize mutants were more sensitive to UV-B than wild plants (Stapleton and Walbot, 1994). Possibly because 'Red Delicious' apples contain more phenolic compounds than 'Golden Delicious' apples, irradiation for 5 min had no significant effect on electrolyte leakage or their Ca content during storage. Immersion of apples in hot water significantly increased fruit Ca content. These results are similar to those of Lurie and Klein (1992) and Luna-Guzmán *et al.* (1999). Microviscosity, electrolyte leakage and membrane permeability is increased in heated apples (Lurie and Klein, 1990; Lurie *et al.*, 1995; Whitaker *et al.*, 1997).

Cracks and other breaks in the cuticular surface may have an important effect on Ca penetration. Meyer (1944) found that cuticle crack width and number increase during fruit development in 'Golden Delicious' apples. The depth and width of cuticular cracks vary with apple cultivar. For example in 'Golden Delicious' apples these cracks are more extensive than in 'Red Delicious' (Faust and Shear, 1972). For this reason, Ca infiltration is higher in 'Golden Delicious'. The apple Ca content increased during storage at 1 ± 1°C (Tables 3 and 4). Calcium moves from coated layer Ca compounds into the apple flesh during storage when it is wet and not yet dried. Research indicates that calcium chloride is hydrophilic and can adsorb water under conditions of high relative humidity. Thus, in storage with a 90% relative humidity the Ca layer is not dried on the peel and Ca can move from peel into the flesh during storage (Betts and Bramlage, 1977; Lidsters *et al*., 1977).

In conclusion, the data presented here shows that UV-C and hot water treatment, alone or in combination, are methods of extending the shelf life of apples in storage. Irradiation for 15 min or dipping for 1 min at 54°C (alone or in combination) are more effective than other treatments in delaying changes in apple firmness and quality. 'Golden Delicious' and 'Red Delicious' apples differ in their response to postharvest UV-C and hot water treatments. Both treatments can alter cell membrane permeability and increase infiltration active substances such as minerals into the apple flesh.

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