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UV-C irradiation reduces breakdown and chilling injury of peaches during cold storage

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Abstract: Pre-storage exposure of peaches (*Prunus persica cv Jefferson*) with UV-C irradiation for 3, 5 or 10 min significantly reduced chilling injury after 14 and 21 days of storage at 5 °C plus 7 days of shelf-life at 20 °C. Similar reduction in fungal decay was also found by these treatments. Skin browning and UV damage were found to be moderate to severe in peaches after the 15 or 20 min of UV-C treatments. The 20 min of exposure accelerated deterioration. Fruit treated with UV-C for 3, 5 or 10 min remained firmer and softened more slowly than the control and those treated with longer durations of exposure. No differences were found in weight loss or respiration rates among the treatments. However, ethylene production was stimulated by all of the UV-C treatments compared with the control. Putrescine levels increased initially after 3 or 5 min of exposure to UV-C. A tendency toward higher accumulation of spermidine and spermine was found in peaches after UV exposure. These higher levels of polyamines apparently are a response to the UV-C irradiation and might be beneficial in increasing the resistance of fruit tissue to deterioration and chilling injury.

Keywords: UV-C irradiation; decay; chilling injury; polyamines

INTRODUCTION

A heavy reliance on synthetic fungicides has been necessary to control postharvest decay of produce, which results in about a 25% loss of fruits and vegetables in the USA.[1] In developing countries, these losses can exceed 50%. Fungicide residues have been found to pose a potential health threat to the consumer, and particularly to children.[2] Because of this problem, researchers have attempted to find alternatives to chemical pesticides for controlling postharvest diseases of horticultural products.[3–6]

Among the alternative methods used for controlling decay, ultraviolet-C irradiation (UV-C, 190–280 nm wavelength) offers interesting possibilities. UV treatment, especially with radiation at 254 nm, can cause weak stress responses, often associated with the phenomenon of inducible pathogen resistance.[7,8] This treatment enhances the biosynthesis of phenols (toxic to pathogens) by increasing the activity of the phenylalanine ammonia-lyase enzyme.[9] The increases of scoparone and scopoletin in citrus fruit induced by UV-C irradiation may also be related to enhanced resistance against pathogens.[10] UV-C irradiation also increased the levels of antioxidants (α-tocopherol, β-carotene and ascorbic acid) in several green vegetables.[11] It has been reported that the accumulation of the polyamines, putrescine and spermidine, can be considered as an indicator of stresses on fruit including the effects of low temperature storage.[12] We recently observed that UV-C treatment increased the polyamine levels in skin tissue of mango fruit.[13]

The optimal storage temperature of peaches is 0–0.6 °C.[14] However, storage at 5 °C has been reported to enhance internal breakdown and development of chilling injury symptoms.[15] UV-C irradiation has been shown to delay ripening and reduce decay of CVS Elberta and Loring peaches stored at 12 °C,[8] but, no studies have been reported using a combination of UV-C treatment and subsequent low temperature storage.

The aim of this study was to determine the effectiveness of UV-C treatment in reducing decay and preventing other physiological disorders while maintaining the quality of peaches stored at a chilling temperature (5 °C) and/or shelf-life temperature (20 °C).

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MATERIALS AND METHODS

Plant materials and experiments

Peaches (*Prunus persica* cv Jefferson) were obtained on the day of harvest from McLeod Farms Inc, SC, USA. Fruit of US Extra #9 grade used for this experiment initially had a firmness of 58–61 N and soluble solids content of 11.5°Brix. Fruits were sorted and randomized. Fruits of uniform size, shape and maturity and free from defects were used, and were divided into six lots of 60 fruits each for UV-C irradiation. Treatments used were: (1) control (non-treated); (2) UV-C irradiation for 3 min; (3) UV-C irradiation for 5 min; (4) UV-C irradiation for 10 min; (5) UV-C irradiation for 15 min; (6) UV-C irradiation for 20 min. Temperature changes during irradiation were negligible and, even with the highest dose tested, did not exceed 2 °C. After irradiation, the fruits were transferred to darkness immediately and stored for 14 or 21 days at 5 °C plus 7 days at 20 °C. Non-treated fruits stored under the same conditions were used as the control.

During the storage period, changes in quality were determined. After cold storage (14 or 21 days at 5 °C) five fruits per treatment were taken and held at 20 °C to measure respiration rate and ethylene production. After 14 or 21 days at 5 °C and a subsequent shelf-life period (7 days at 20 °C), 15 fruits from each treatment were evaluated for weight loss, flesh firmness, chilling injury (CI) symptoms, browning index, decay, shriveling and UV-C damage. Samples (2 g) of skin tissue were taken from each of four fruits initially, after UV-C treatment, after cold storage (5 °C) and shelf life period for polyamine analysis. Polyamine quantities were determined according to Gonzalez-Aguilar *et al*.[16]

UV-C irradiation

The UV-C irradiation treatment was applied using unfiltered General Electric 15-W G15 T8 germicidal lamps. Of the irradiance emitted by these lamps, 82% was in the UV-C (250–280 nm) region.[17] Groups of 10 peaches were placed on a wide-mesh screen and irradiated on both upper and lower surfaces at a distance of 15 cm from the screen. At 1.5-, 2.5-, 5-, 7.5- and 10-min intervals, the fruits were rotated 180° to achieve complete irradiation for 3-, 5-, 10-, 15- and 20-min UV-C treatments, respectively. The UV-C setup was placed in a fume hood to remove any ozone generated during irradiation. As safety precautions, a polycarbonate facemask and protective gloves and clothing were used.

UV measurements were taken with an Optronic Model 752 UV-VIS spectroradiometer (Optronic Laboratories Inc, Orlando, FL, USA) to determine the spectral irradiance of the bare lamp. The integral value of spectral irradiance for the wavelength range of 250–280 nm was determined as 8220 mW m^{-2}.

Quality attributes

Peaches were weighed before and after the storage period to calculate percentage of fresh weight loss. Flesh firmness was determined at three different positions on each fruit (skin removed) using a firmness tester, Pressure Tester Model EPT-1R (Lake City Technical Products Inc, Kelowna, BC, Canada) with an 8-mm cylindrical plunger. The extent of decay was assessed visually based on the area of decay. Overall appearance was rated on a scale of 1–5, where 1 = very poor, 2 = poor, 3 = fair, 4 = good and 5 = excellent. Softening was determined by scoring (1–5) the degree of tissue yield by applying finger pressure: 1 = very firm, 2 = firm, 3 = moderately firm, 4 = slightly firm, and 5 = soft. The score of chilling injury (CI) and browning was based on the percentage of total surface area and flesh affected by sheet pitting and browning; 0 = no injury, 1 = slight, 2 = moderate, and 3 = severe according to Gonzalez-Aguilar *et al*.[16] Shriveling and UV-C damage were evaluated according to Erkan *at al.*[17] The pH, total soluble solids and titratable acidity were determined according to AOAC[18] methodology.

The analysis of variance and Tukey's multiple range test for comparison of means and least significant differences (LSD) ($P < 0.05$) were performed on the data using the SAS 6.03 system.[19] Subjective evaluations were transformed to arcsine values before statistical analysis.

RESULTS AND DISCUSSION

Figure 1 shows respiration rate and ethylene production at 20 °C after 14 or 21 days at 5 °C, in peaches treated with UV-C for different periods of time. The highest respiration rate was observed in fruit treated with UV-C for 3 min after 14 days of storage at 5 °C. A stable respiration rate was maintained after transferring the peaches to storage at 20 °C. After 21 days of storage, only fruits treated with UV-C for 3 or 10 min showed a higher respiration rate than that of the controls. The lowest respiration rate was observed in fruits treated with UV-C for 15 min (Fig 1A and B). UV-C treatments increased ethylene production of peaches. All UV-C treatments used in this study enhanced ethylene production of peaches at 20 °C after both 14 and 21 days of storage at 5 °C. After cold storage for 14 days, ethylene production in control fruits increased continuously upon transferring to 20 °C (Fig 1C). A similar pattern of ethylene production was observed in fruits treated with UV-C after 14 days at 5 °C. The highest ethylene production was observed in fruits treated for 3 or 15 min, followed by those treated for 20, 10 or 5 min, respectively. However, after 21 days at 5 °C, fruits treated with UV-C for 10 min showed the highest increase in ethylene production, followed by the 5 min UV-C treatment. Control fruits had significantly the lowest ethylene production, after 14 or 21 days at 5 °C (Fig 1C and D).

Baka *et al*[20] reported that UV-C treatment suppresses respiration rate and ethylene production of strawberries stored at 4 and 13 °C. However, we found that UV-C treatment increased respiration rate and

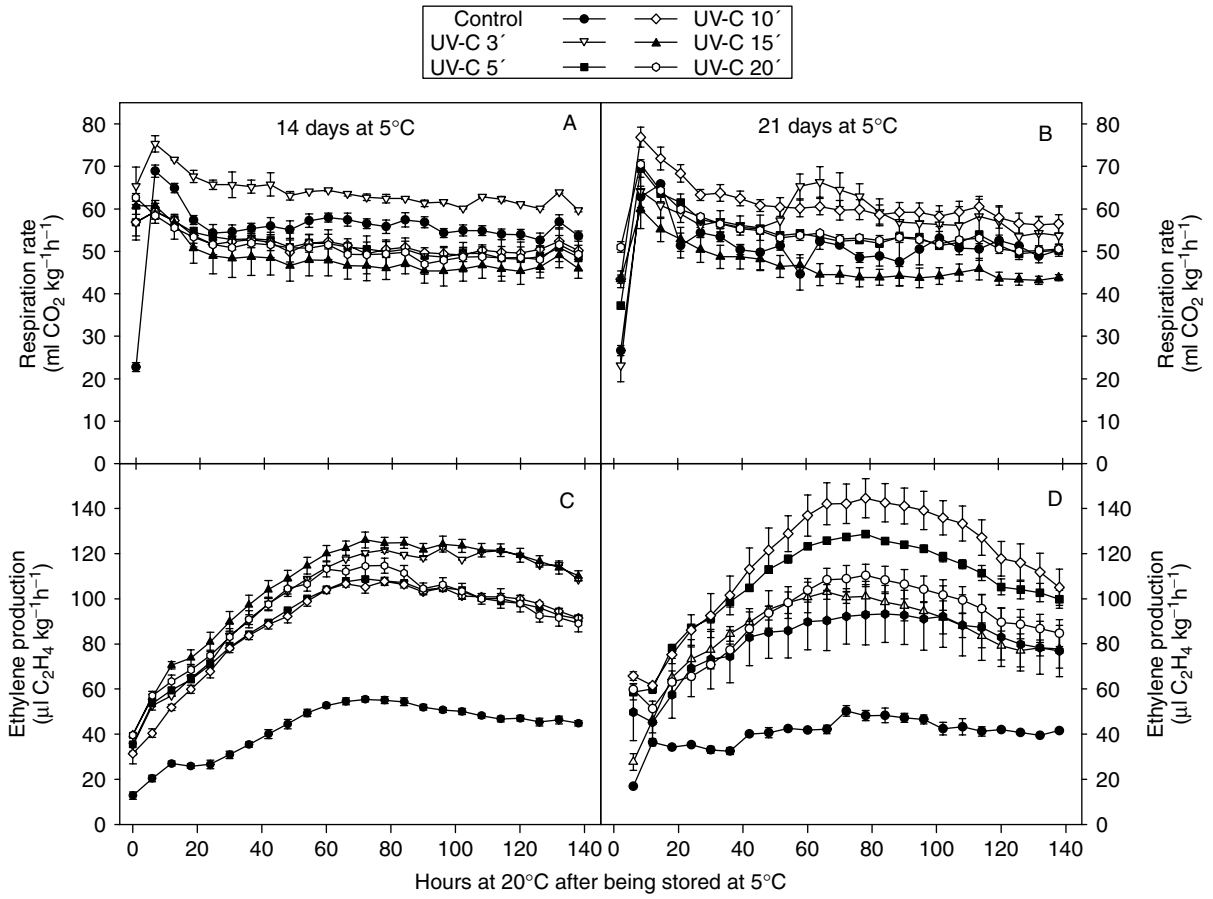

Figure 1. Effect of UV-C irradiation on respiration rate and ethylene production of peaches, after being stored for 14 and 21 days at 5 °C and transferred to 20 °C. Each value is the mean of four replications ± standard deviation.

ethylene production of peaches after being stored for 14 and 21 days at 5 °C (Fig 1). Crisosto *et al*[21] reported that peaches cv Summer Lady treated with pulsated ultraviolet light had an increase in the respiration rate and ethylene production of 18% and 50%, respectively. It has been observed that UV-C irradiation increased respiration rate of *Cucurbita pepo* tissue without significantly affecting ethylene production.[17] The UV-C treatment delayed respiration rate and ethylene production in tomatoes during storage at 16 °C.[22]

Figure 2 shows the weight and firmness loss of peaches, after being stored for 14 or 21 days at 5 °C plus 7 days at 20 °C. As expected, weight loss increased with a longer storage period and was more noticeable in all the treatments after 21 days at 5 °C plus 7 days at 20 °C. The control fruits had higher losses of weight than those fruits treated with UV-C. No significant differences in weight loss were observed among treated fruits with different treatment lengths. Firmness loss would be more the result of the UV-C treatment or physiological ripening during cold storage and shelf-life period. Softening of control fruits could be associated with the higher metabolic processes (deterioration), which in turn enhanced senescence of the peaches. Maharaj *et al*[22] reported that UV-C irradiation (3.7×10^3 J m^{-2}) prevented firmness loss and delayed senescence processes of tomato fruits stored at 16 °C.

In general, UV-C treatment reduced firmness loss of peaches during cold storage and shelf-life period. However, UV-C treatments for 3 or 5 min were the most effective in maintaining the firmness of peaches during storage. No significant differences were obtained after 21 days at 5 °C plus 7 days at 20 °C between controls and those treated with UV-C for 10, 15 or 20 min. Stevens *et al*[8] reported that UV-C treatment maintained firmness and reduced weight loss of peaches and apples. Also, the content of ascorbic acid was higher in UV-C-treated fruit than in controls. It has been reported by several authors for different fruits that the lower the ascorbic acid loss, the higher quality of fruit during cold storage and shelf-life.

Chilling injury symptoms, measured as browning of the skin and internal breakdown, were significantly diminished by the 3-, 5- and 10-min UV-C treatments (Fig 3A). This reduction was more evident for longer storage periods (21 days at 5 °C plus 7 days at 20 °C). The effectiveness of the UV-C treatment was reduced with length of application, the 15- and 20-min UV-C treatments being least effective. Control fruit exhibited severe chilling injury symptoms and decay, but the UV-C treated fruit remained free from browning or fungal decay except for the 20 min treatment (Fig 3B). UV-C treatment for 15 and 20 min enhanced browning of skin and pulp. It has been reported that

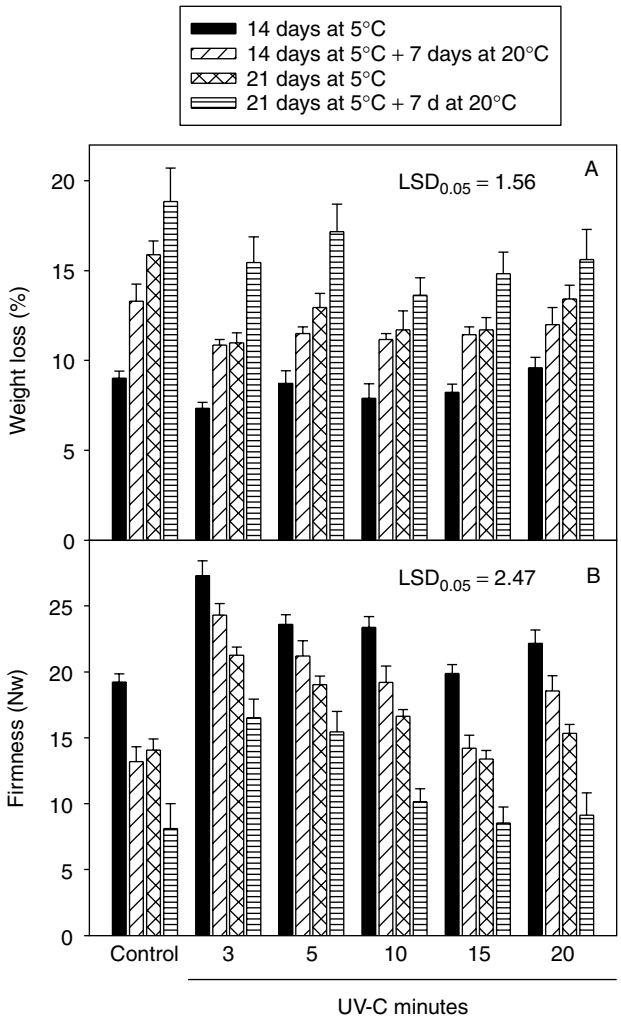

Figure 2. Effect of UV-C irradiation on weight loss (%) and firmness (N) of peaches after being stored for 14 and 21 days at 5 °C plus 7 days at 20 °C. Each value is the mean of 15 replications ± standard deviation. LSD ($P < 0.05$) = least significant difference.

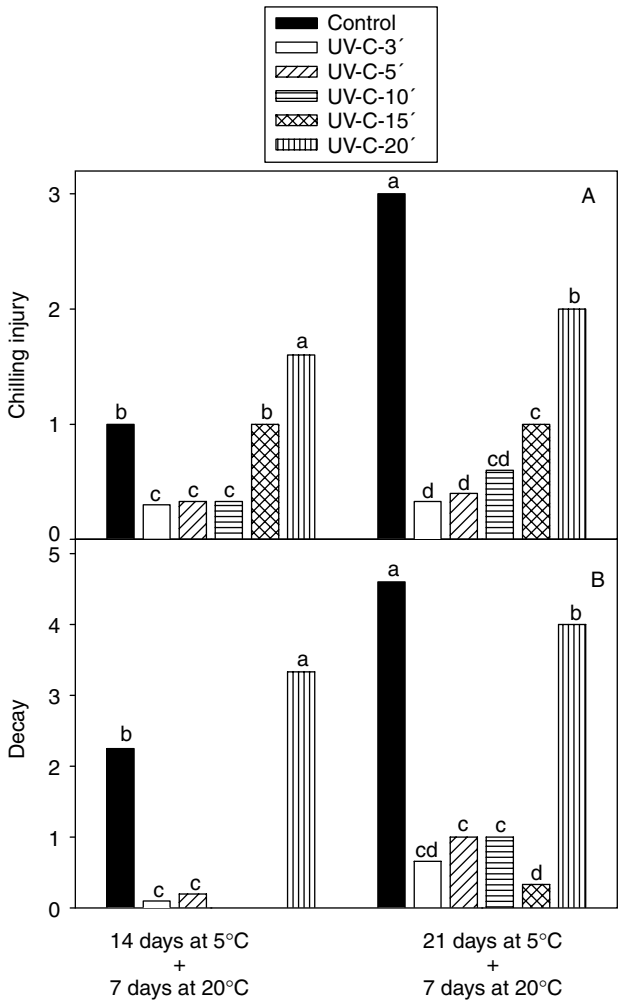

Figure 3. Effect of UV-C irradiation on chilling injury index and decay of peaches after being stored for 14 and 21 days at 5 °C plus 7 days at 20 °C. Each value is the mean of 15 replications. Means with the same letter at the same storage period are not significantly different according to Tukey's test ($P < 0.05$).

peaches develop chilling injury symptoms more rapidly at 3–5 °C than at 0 °C.[23] UV-C treatment prevented development of chilling injury symptoms of peaches stored for up to 21 days at 5 °C + 7 days at 20 °C.

The most effective treatments in reducing decay symptoms were 3 and 15 min in duration (Fig 3B). UV-C treatments for 3 and 5 and 10 min reduced both decay and browning, but the 10 min treatment led to moderate UV-C damage at the end of the storage period (Figs 3 and 4). Fruits treated with UV-C for 20 min and control fruits developed decay to a similar extent (Fig 3B). The browning index of the peaches was significantly reduced by the 3-, 5- and 10-min UV-C treatments (Fig 4A). However, 15 and 20-min treatments enhanced browning of the skin and affected the quality. The 3-min treatment resulted in the lowest scores in all of the subjective evaluations. Peaches treated with UV-C for longer than 5 min exhibited significantly higher UV-C damage, this being more evident after longer storage periods (Fig 4B). The longer the treatment, the greater the UV-C damage to the skin, observed as pink–red strands throughout the surface of the fruit.

It appears that the effectiveness of UV-C treatment is related to the dose applied, maturity stage and type of skin tissue of the fruit. This study agrees with previous reports where UV-C treatment was very effective in preventing fungal decay caused by various microorganisms in table grapes, citrus fruit, kumquat, strawberries and mangos.[6,16,24,25] However, the optimal dose of UV-C for controlling infections in various crops seems to vary greatly. In the case of peaches, the dose appears to be quite small and is similar to those reported for inducing disease resistance in carrots and peppers.[26,27] Higher doses were used for inducing disease resistance in tomatoes and lemons.[6,28] Porat *et al*[29] reported the UV-C-induced resistance in grapefruit against P*enicillium digitatum* is associated with increases in the chitinase and β-1,3-endoglucanase activities in peel tissue. The enhancement of the resistance of citrus fruit by UV-C irradiation was explained in part by induction of key enzymes in the secondary metabolite pathway, such as phenylalanine ammonia lyase (PAL) and peroxidase, and accumulation of antifungal compounds.[30] UV-C

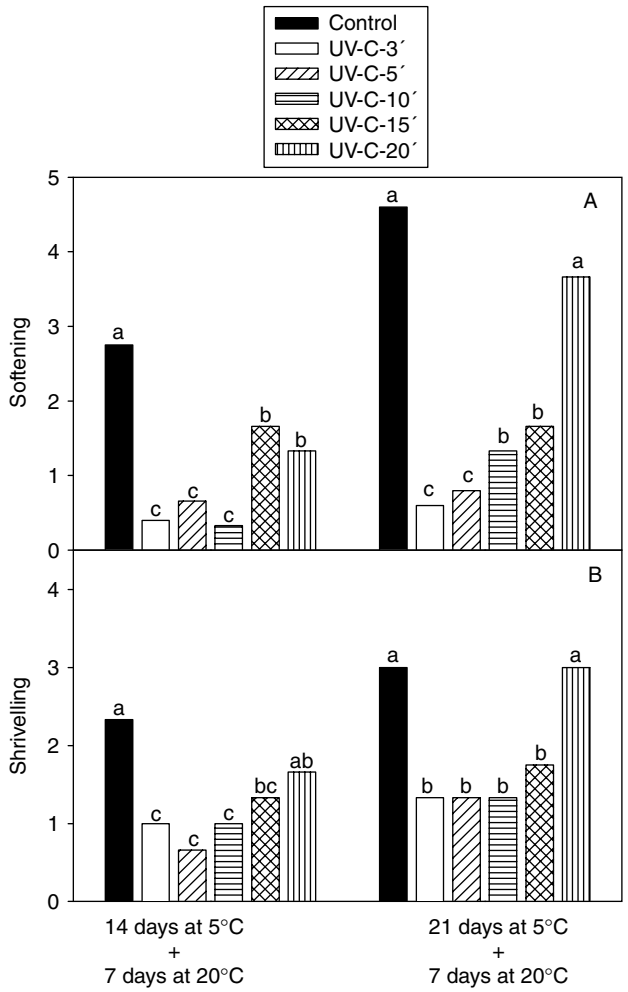

Figure 4. Effect of UV-C irradiation on softening and shriveling of peaches after being stored for 14 and 21 days at 5 °C plus 7 days at 20 °C. Each value is the mean of 15 replications. Means with the same letter at the same storage period are not significantly different according to Tukey's test ($P < 0.05$).

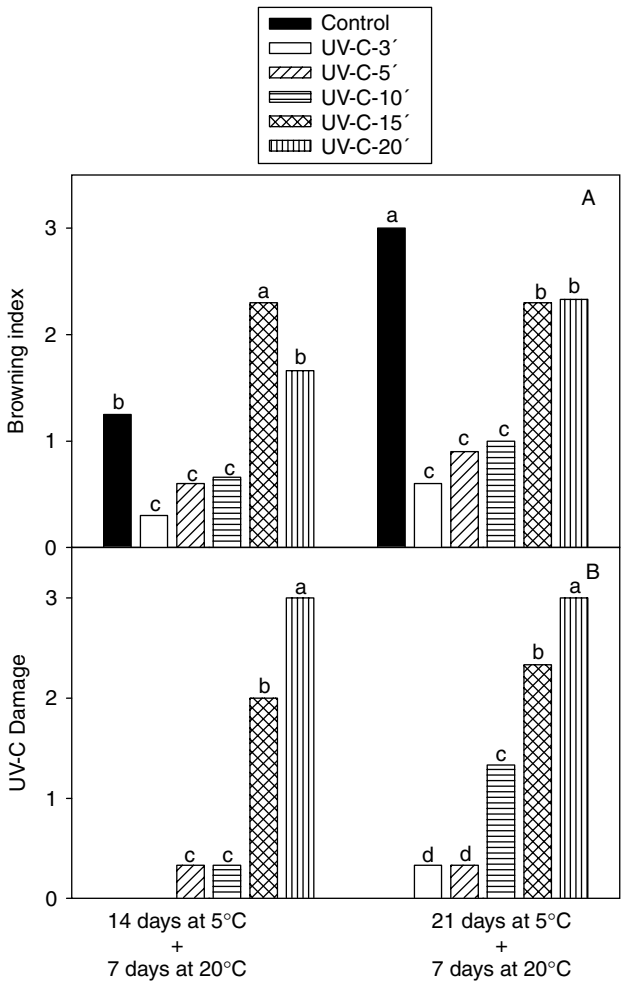

Figure 5. Effect of UV-C irradiation on browning index and UV-C damage of peaches after being stored for 14 and 21 days at 5 °C plus 7 days at 20 °C. Each value is the mean of 15 replications. Means with the same letter at the same storage period are not significantly different according to Tukey's test ($P < 0.05$).

irradiation for 10 and 20 min significantly reduced microbial activity and deterioration of C*ucurbita pepo* fruit tissue.[17]

Subjective assessment of quality attributes demonstrated that UV-C treatment significantly reduced deterioration symptoms (Figs 4 and 5). Subjective measurements of softening and shriveling were correlated with objective data of firmness and weight loss (Fig 2 and Figs 3–5). Softening and shriveling was significantly more evident in control and fruits treated with UV-C for 20 min, after 21 days at 5 °C + 7 days at 20 °C (Fig 5). Peaches treated for 3 and 5 min with UV-C presented significantly the lowest softening values followed by the 10- and 15-min treatments (Fig 5A).

UV-C treatment for 3 and 5 min significantly increased the putrescine content initially (Fig 6A). However, control fruits had significantly the highest putrescine levels, followed by those treated with UV-C for 3 and 5 min, after 14 days at 5 °C plus 7 days at 20 °C. Afterwards, putrescine levels decreased only in the controls, but increased for the UV-C treatments of 10, 15 and 20 min and were maintained at constant levels in fruits treated with UV-C for 3 and 5 min. No significant differences were found in putrescine content among treatments after 21 days at 5 °C + 7 days at 20 °C.

Spermidine levels, in general, increased initially after UV-C treatment (Fig 6B). This increase was significantly higher in peaches treated with the UV-C treatments for 10 and 15 min. After cold storage, the spermidine content only increased in fruits treated with UV-C for 3 min. Spermidine levels were maintained at constant levels in the other treatments after 14 and 21 days at 5 °C plus 7 days at 20 °C. All UV-C treatments increased spermine levels to the same extent. However, these levels were significantly reduced after cold storage and shelf-storage in most of the treatments, except in that of fruit treated with UV-C for 3 min. In general, no significant changes in spermine content were observed in the control and UV-C treatments, after 21 days at 5 °C plus 7 days at 20 °C (Fig 6C). UV-C treatment for 3 min resulted in significantly the highest levels of spermine after cold storage and shelf storage.

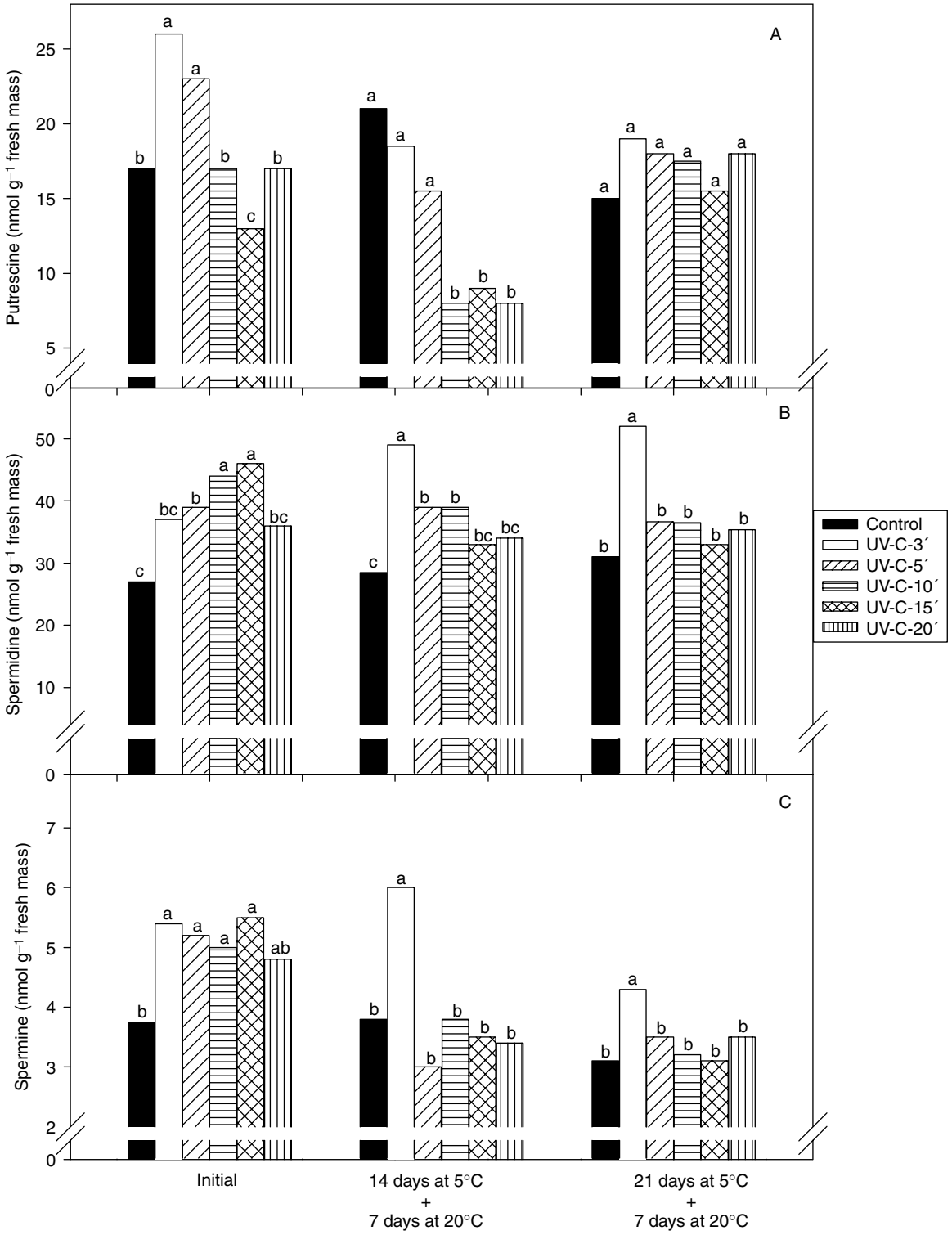

Figure 6. Effect of UV-C irradiation on polyamine content of peaches after being stored for 14 and 21 days at 5 °C plus 7 days at 20 °C. Each value is the mean of four replications. Means with the same letter at the same storage period are not significantly different according to Tukey's test ($P < 0.05$).

The increased firmness of UV-C treated fruit compared with the controls could be associated with increased levels of polyamines. Polyamines are assumed to function via mechanisms similar to that of calcium, involving the formation of cation cross-links with pectic acid and other polysaccharides, thus limiting accessibility of the cell wall to degradative enzymes.

Rastogi and Davis[31] reported that the high putrescine levels in Alcobaca tomatoes were related to slower ripening and thus prolonged keeping quality. In addition, Kramer *et al*[32] have shown that polyamines inhibit softening by reducing the activity of cell wall degrading enzymes such as polygalacturonase. Levels of polyamines usually decrease with age in plants[33] but UV treatment appears to contribute

to the maintenance of higher levels of putrescine and spermidine in peaches (Fig 5). It has been reported that increasing ethylene production could reduce polyamine synthesis.[34] However, in this study we observed that UV-C treatment increased both ethylene and polyamine synthesis. These results contrast with those reported by Maharaj *et al*[22] where UV-C irradiation reduced softening, respiration rate and ethylene production and subsequently delayed senescence of tomato fruits. It has been observed that UV-C irradiation of table grapes can be beneficial in terms of increasing the content of potentially health-promoting phenols.[24] Reductions in deterioration and chilling symptoms were observed in cv Tommy Atkins ripe mangos treated with UV-C irradiation after previous storage at 5 °C. The effectiveness of the treatment was correlated with the higher levels of polyamine found in the skin tissue.[16]

The effectiveness of UV-C irradiation in controlling decay of peaches, even at the lowest dose (3 min), may be correlated with the induction of polyamines. Although the induction of defense mechanisms by UV-C in peaches was not specifically studied, resistance induced by UV-C against fungal decay could also be associated with other defensive compounds. It has been observed that resistance against decay induced in oranges by UV-C treatment is related to increases of phytoalexins, scoparone and scopoletin.[10] Droby *et al*[30] reported a marked inhibition of sporulation of fungi in grapefruit as well as significant increase in phenylalanine ammonia lyase (PAL) and peroxidase in the peel. Other effects of UV-C treatment related to quality loss have been observed in other horticultural products. UV-C irradiation at 0.117 mW cm^{-2} for 1 min increased by two- or threefold the vitamin D2 content in mushrooms.[35] However, enhanced surface discoloration that might influence the acceptability of the product in the fresh market was seen.

We conclude that UV-C treatments for 3 and 5 min can be used to reduce chilling injury symptoms, deterioration and prolong the shelf-life of peaches during storage at 5 °C. UV-C appears to be a new option to reduce physiological disorders of peaches during cold storage. However, further studies are necessary to elucidate the mode of action of this treatment.

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