J Sci Food Agric 84:1831–1838 (online: 2004)
DOI: 10.1002/jsfa.1894

Combined use of UV-C irradiation and heat treatment to improve postharvest life of strawberry fruit

Jerónimo Pan,[1] Ariel R Vicente,[1] Gustavo A Martínez,[2] Alicia R Chaves[1] and Pedro M Civello[2]*

[1]Centro de Investigación y Desarrollo en Criotecnología de Alimentos (CIDCA) UNLP-CONICET, 47 y 116, 1900, La Plata, Argentina
[2]Instituto de Investigaciones Biotecnológicas-Instituto Tecnológico de Chascomús (IIB-INTECH) UNSAM-CONICET. Camino de Circunvalación Laguna Km 6, (B7130IWA) Chascomús, Argentina

Abstract: The effects of UV-C (4.1 kJ m^{-2}) and heat treatment (45 °C, 3 h in air) either separately or combined on the quality of strawberries (*Fragaria* × *ananassa* cv Seascape) at the 75 or 50% surface red ripening stage were assessed, the latter stage being used only in the firmness test. In addition, the development of surface fungal infections was followed and *in vitro* germination assays on conidia of *Botrytis cinerea* and *Rhizopus stolonifer* performed. Both heat and combined treatments, decreased hue and delayed changes of the *L parameter. All treatments reduced the accumulation of anthocyanins. Control fruit softened most while fruit treated by the combined method were the firmest. The combined treatment reduced fungal infections and delayed *in vitro* germination of *Botrytis cinerea* conidia. After 2 days at 20 °C, treated fruit had lower amount of phenolics than the control. Neither the heat nor UV-C irradiation modified the total sugar content, although the combined treatment decreased it slightly relative to the control. Titratable acidity increased through storage at 20 °C in all fruit, but no differences between control and treated fruit were detected. The combination of UV-C and heat treatments enhanced the benefits of applying each treatment separately, and could be useful to improve and extend strawberry fruit postharvest life.**

Keywords: *Fragaria* × *ananassa*; fruit ripening; heat treatment; postharvest; UV-C; physical treatment

INTRODUCTION

A key feature to improve the postharvest shelf-life of strawberry fruit is to control the development of moulds. Producers and consumers are looking for economically and non-contaminant methods to achieve this goal, and UV-C irradiation and heat treatments have already been tested on an array of fruits. Pre-storage applications of UV-C light controlled storage rots in tomato[1] and bell pepper.[2] In strawberry, UV-C reduced both natural rots[3] and induced infection of *Botrytis cinerea* and *Monilinia fructigena*.[4] Both, the direct germicidal effect of UV-C on plant pathogens and the induction of disease resistance in the tissue contribute to diminish rot development during storage.[2,3,5,6] Phenylalanine ammonia-lyase (PAL) activity increases after UV-C irradiation.[3,7,8] The enzyme plays a key role in the biosynthesis of phenolic compounds, many of which have antifungal activity.[9] The production of several phytoalexins in response to UV-C treatments has been reported in carrot[6] and grape.[10]

The exposure to UV-C delays fruit softening, one of the main factors determining fruit postharvest life. Barka *et al*[11] found that UV-C light decreased the activity of enzymes involved in tomato cell wall degradation and delayed the fruit softening. Reduction of strawberry fruit softening by UV-C application has been also reported.[12]

Heat treatments have been successfully used to reduce pathogen levels and disease development,[13,14] and maintain fruit quality during storage in several fruits, including tomato and strawberry.[15–18] Heat treatments, performed either by hot water dips[17] or hot air exposure,[18,19] reduced pathogen attack in strawberry. The benefits of heat treatment application in strawberry fruit were not only the control of pathogens, but also the preservation of quality during storage.[19,20] García *et al*[20] found that hot water dips of strawberries cv Tudla, increased the soluble

* Correspondence to: Pedro M Civello, Instituto de Investigaciones Biotecnológicas-Instituto Tecnológico de Chascomús (IIB-INTECH) UNSAM-CONICET. Camino de Circunvalación Laguna Km 6, (B7130IWA) Chascomús, Argentina
E-mail: civello@intech.gov.ar
Contract/grant sponsor: Agencia Nacional de Promoción Científica y Tecnológica, Argentina; contract/grant number: PICT 08-07088
(*Received 20 April 2004; accepted 30 April 2004*)
Published online 4 August 2004

solid content and decreased titratable acidity, hence improving key factors related to sensorial acceptance by the consumer. Another type of treatment, using air as heating media and longer exposures, delayed strawberry ripening, reduced softening, decreased titratable acidity and did not affect the content of total sugars.[18,19] The benefits of heat treatment application were further improved by performing the treatment in the presence of low permeability films, to retain the CO_2 produced by the temporary increase in fruit respiration during the heating.[21]

The possibility of combining both types of physical treatments to reduce pathogen development has recently been explored in strawberry fruit. Marquenie *et al*[22] treated conidia of *Botrytis cinerea* using UV-C and heat treatment individually or in combination, and reported that the combined treatment reduced the required intensity of each treatment for fungi inactivation. Similar results were found when pulsed white light irradiation, with a significant UV-C component, was combined with heat treatment.[23] A combined treatment with UV-C and immersion in hot water (40–45 °C) delayed fungal growth in strawberry fruit inoculated with *Botrytis cinerea*.[4] The combination of a thermal treatment with light pulses delayed visible fungal growth in inoculated strawberries.[24]

The benefits of using UV-C in combination with heat treatment to reduce strawberry fruit decay have been proved. However, more research is needed to find optimal conditions of irradiation and heat treatment, and to evaluate the effect of the combined treatment on fruit quality parameters. In this work, a combined treatment of UV-C irradiation followed by a mild heating at 45 °C for 3 h in air was applied to strawberry fruit, and its effects on quality parameters (firmness, total sugars, phenols, superficial colour and anthocyanins) and postharvest life (external appearance and macroscopic fungal growth) were analyzed.

MATERIALS AND METHODS

Plant material

Strawberries (*Fragaria* × *ananassa* Duch) cv Seascape, planted in a mulch system and grown under polyethylene-covered tunnels (row covers), were harvested from commercial fields. Fruit were transported to the laboratory within an hour and then selected according to uniform size and colour and absence of external damages. The experiments were performed on fruit at 75% red surface ripening stage, except the firmness assay which was done with 50% red surface fruit.

Selection of optimal experimental conditions for UV-C irradiation and heat treatment

For UV-C irradiation (peak emission at 254 nm) studies, fruit were carefully placed in plastic trays and placed under a bank of four germicidal UV lamps (TUV G30T8, 30W, Philips). Fruit were irradiated at a distance of 30 cm to obtain doses of 1.3, 4.1 and 6.9 kJ m^{-2}. The intensity of flux of lamps was measured by a UV digital radiometer (Cole-Parmer Instrument Company, Vernon Hills, Illinois, USA). A sample of 25 fruit was used for each irradiation dose and the control. Each fruit was rotated manually once to ensure even surface exposure to UV light.

Three different temperatures and two heat-transfer media (water and air) were evaluated to determine the optimal conditions for heat treatment. In one case, 30 fruit were carefully placed in plastic trays, covered with PVC film (15 μm thick) and set in an air oven for 3 h at 41, 43 or 45 °C. Ten non-treated (control) fruit were directly stored at 20 °C. Heat treatments applied by immersion of 30 fruit for 15 min in water at 41, 43 or 45 °C were also performed. Ten fruit considered as controls for the water-immersion assay were dipped in water at room temperature (25 °C) for 15 min. After treatments all the fruit were laid on tissue paper layers and then packed in PVC film and stored at 20 °C.

For both UV-C irradiation and heat treatments, the effect of the treatment was evaluated by monitoring daily the development of surface wounds and fungal infections over a storage period of 6 days at 20 °C in darkness.

Physical treatments and storage

Three different treatments were performed: (a) UV-C irradiation, (b) heat and (c) combination of UV-C followed by heat treatment. The fruit were irradiated as described previously at a dose of 4.1 kJ m^{-2}. In the case of heat treatment, the plastic trays were covered (not sealed) with PVC-film (15 μm thick) and put in an air oven without circulation at 45 °C for 3 h.

After treatment the trays were kept in darkness at 20 °C. Corresponding untreated fruit (control) were directly stored at 20 °C. Observations were made at different storage times and the fruit were immediately processed or frozen in liquid nitrogen and stored at −20 °C until analysis.

Evaluation of external appearance and fungal decay

Strawberries at the 75% surface red maturity stage were treated as described previously and stored at 20 °C. To prevent contamination among fruit, each fruit was put in an individual plastic tray and covered with PVC film. Sixty berries were used for each condition assayed. The external appearance of each fruit and the presence of macroscopic fungal growth were visually evaluated daily for a 7-day period.

In vitro assay on conidia germination

Aliquots of conidial suspensions of *Botrytis cinerea* and *Rhizopus stolonifer* from pure strains isolated at IIB-INTECH (strain ICFC377/00 -F18- and strain ICFC364/00 -F8-, respectively) were transferred to potato glucose agar plates and spread with a glass rod.

The Petri dishes were kept in the dark at 20 °C for 12 days.

The treatments described previously were then performed on plates with *Botrytis cinerea* or *Rhizopus stolonifer* cultures in duplicate:

(a) UV treatment: uncovered plates with growing mold were irradiated with an average dose of 4.1 kJ m^{-2}.
(b) Heat treatment: the plates were set covered in an air oven without air circulation at 45 °C for 3 h.
(c) Combined treatment: the plates were first irradiated uncovered with the average UV-C dose of 4.1 kJ m^{-2} and then set covered in an air oven at 45 °C without air circulation for 3 h.
(d) An untreated set of plates was used as a control.

Conidia were then suspended in 0.03% v/v Tween-20 and the suspension was filtered through a six-layer cloth filter. With the implementation of a haemocytometer, the filtrate was diluted to a concentration of 2×10^5 conidia ml^{-1}. Using a multi-well plate, conidia were sown in each well with 0.03% v/v Tween-20 and malt 2× extract. Germination was stopped every hour at 10 different times by adding an aliquot of 100 µl of formaldehyde. The germination percentage was estimated by counting 100 spores randomly in a microscope-field (400×). A conidium was considered germinated when the length of the germ tube was equal to or greater than the length of the conidium. Plates were counted in triplicate and the whole experiment was repeated twice. Since the same trend was found in both experiments, only the results of one are showed.

Quality attributes

Fruit quality attributes were evaluated according to Vicente *et al*[19] with slight modifications. The fruit firmness was analyzed after 0, 1, 2, 3 and 4 days of storage at 20 °C using a Texture Analyzer (TA.XT2, Stable Micro Systems Texture Technologies, Scarsdale NY) fitted with a flat probe (3 mm diameter). Each fruit at 50% red stage was penetrated 7 mm at a rate of 0.5 mm s^{-1} and the maximum force (N) reached during the tissue breakage was recorded. Thirty berries were measured twice in opposite sides of its equatorial zone for each treatment and storage time assayed.

Surface colour was evaluated with a colorimeter (Minolta, Model CR-300, Osaka, Japan) by measuring the L^* parameter and hue angle in six zones of each fruit. Sixty fruits were analyzed for each treatment and storage time assayed (0, 1 and 2 days at 20 °C).

Samples containing 30 fresh fruit were taken for each treatment and storage time assayed (0, 1 and 2 days at 20 °C). The fruit were frozen and ground in a refrigerated mill and the powder was used to measure anthocyanin content, total phenolic compounds, total sugar content, pH and titratable acidity, as is described below.

One gram of the powder was poured into 10 ml of HCl–methanol (1% v/v) and held at 0 °C for 10 min. The slurry was centrifuged at 1500 × *g* for 10 min at 4 °C, the supernatant was saved and its absorbance at 515 nm was measured. The amount of anthocyanins was calculated using the extinction coefficient (ε)[25] equal to 3.6×10^6 M^{-1} m^{-1}. Measurements were performed in triplicate and the anthocyanin content was expressed as micromoles of pelargonidin-3-glucoside per kg of fresh fruit (µmol kg^{-1}).

One gram of the powder from frozen fruit was poured into 6 ml of ethanol, the mixture was centrifuged at 9000 × *g* for 10 min at 4 °C and 3 ml of the supernatant were brought to 100 ml with water. Two hundred microlitres of this extract were added to 1.11 ml of water and 200 µl of 1 N Folin–Ciocalteau reagent. After 3 min at 25 °C, 1.5 ml of saturated solution of Na_2CO_3 was added, and the reaction mixture was incubated for 1 h at the same temperature. The absorbance at 760 nm was measured, and total phenolic content was calculated using phenol as standard. Measurements were performed in triplicate and the results were expressed as g of phenol per kg of fruit.

One gram of the powder was extracted for 30 min with 10 ml of ethanol at 25 °C. The mixture was centrifuged at 2300 × *g* for 10 min and 1 ml of the supernatant was brought to 50 ml with H_2O. The samples were first hydrolyzed with 0.1 M HCl for 10 min and sugars were determined spectrophotometrically at 520 nm using a modification of the Somogyi–Nelson method.[26] Measurements were performed in triplicate and the results were expressed as g of glucose per kg of fresh fruit.

Ten grams of the powder from frozen fruit were suspended with H_2O to a volume of 100 ml. The pH and titratable acidity of the sample were determined by pH meter and titration with 0.1 M NaOH to pH 8.1, respectively.[27] Titratable acidity was expressed as millimoles of H^+ per kg of fresh weight (mmol kg^{-1}). Two independent extracts were prepared and each one was titrated in duplicate.

Statistical analysis

The entire experiment was done twice and performed according to a factorial design. Data were analyzed using ANOVA, and the means were compared by the LSD test at a significance level of 0.05.

RESULTS AND DISCUSSION

Selection of optimal experimental conditions

A reduction of damaged fruit after 6 days at 20 °C was found at all UV-C irradiation doses (Fig 1A). In addition, fruit irradiated with 4.1 or 6.9 kJ m^{-2} showed less surface reddening than the control (data not shown), indicating a delayed ripening. A 4.1 kJ m^{-2} irradiation dose was chosen for further experiments.

Two heat transfer methods, dipping in hot water and incubation in air oven at 41, 43 and 45 °C, were

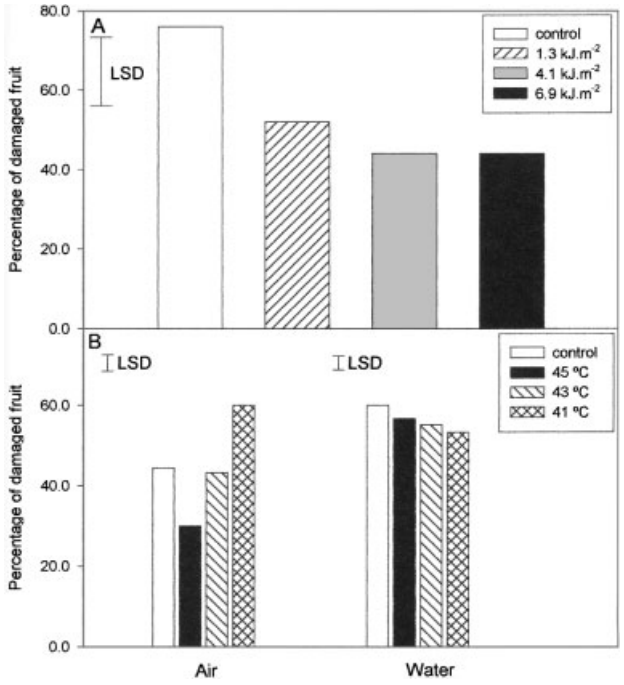

Figure 1. Fruit damage (bruising and surface damage) of strawberries at 20 °C after different UV-C irradiation doses (A) or heat treatments (B). A: Fruit were irradiated with UV-C at doses of 1.3, 4.1 or 6.9 kJ m^{-2}. Control fruit were not irradiated and left directly at 20 °C. B: Fruit were heat-treated in air oven (left) at 41, 43 or 45 °C for 3 h or by water immersion (right) at the same temperatures for 15 min. Control fruit were not heat-treated (left) but stored directly at 20 °C, or submerged in water at 25 °C for 15 min (right) and then stored at 20 °C. In all cases, after treatments, the fruit were stored at 20 °C for 6 days in darkness and the percentage of damaged fruit was determined. LSD (least significant difference) at $p = 0.05$ is shown.

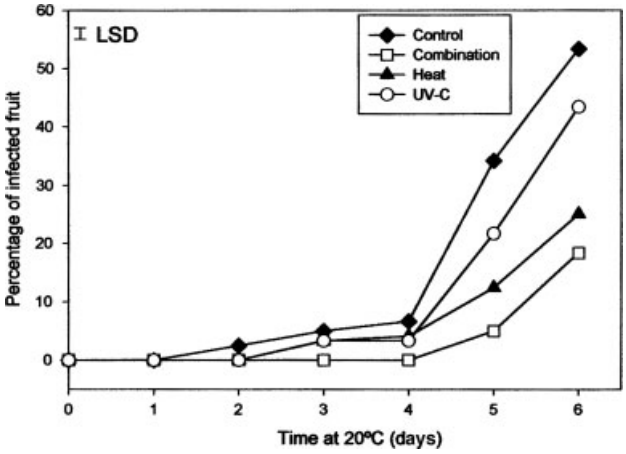

Figure 2. Effect of UV-C and heat treatment on fungal decay of strawberry fruit during storage at 20 °C. Strawberries were treated by UV-C (4.1 kJ m^{-2}), heating (45 °C, 3 h in air oven) or a combination of both methods (first irradiation with UV-C, and then heating). After treatment, all the fruit were stored at 20 °C for 6 days and the percentage of decayed fruit was determined. LSD (least significant difference) at $p = 0.05$ is shown.

assayed. When fruit were treated at 45 °C for 3 h in an air oven, a sharp reduction in the percentage of damaged fruit was found after 6 days at 20 °C (Fig 1B). In contrast, treatment at 43 °C did not reduce mould development and damage, while the treatment at 41 °C caused more fruit damage. When heat treatments were applied by water no differences with the control were detected. Therefore, a 45 °C air treatment for 3 h was chosen for subsequent experiments. These results obtained with 'Seascape' agree with previous work performed on 'Selva' variety.[18,19]

Evaluation of fungal decay

Control fruit had visible fungal infection from day 2 onwards (Fig 2), while heat and UV-C treated fruit had decay from day 3 onwards. Fruit treated with the combined method did not show visible infection until day 5. On day 6, approximately 55% of control fruit had symptoms of fungal attack, 45% in UV-C treated, 25% in heat-treated and 18% in fruit where the combined treatment was applied.

Reduced decay in heat treated 'Selva' strawberries has been reported previously.[18,19] Baka *et al*[12] showed reduced decay caused by *Botrytis cinerea* in UV-C treated strawberries. Moreover, Marquenie *et al*[4] showed that UV-C and hot water treatments can also reduce *Botrytis cinerea* infections, though the use of water as the heating media caused severe damage on strawberries at temperatures around 45 °C. As no damage was found in the fruits heat-treated in the air oven, this type of treatment offers better possibilities of being combined with another physical treatment such as UV-C, which could then improve conservation of strawberry fruit.

The effects of both treatments (UV-C and heat) on the reduction of fungal attack could be attributed to different causes. A direct detrimental effect of the UV-C light and heat on the fungus present on the fruit surface is possible, according to results obtained from *in vitro* experiments. The spore germination of *Botrytis cinerea* and *Rhyzopus* sp was delayed when conidia of both fungi were irradiated or heated under the same conditions used to treat the fruit in this study (see below). Moreover, Fallik *et al*[28] described that *Penicillum expansum* attack was reduced in heat-treated apples by retarding fungal spore germination. In addition to the direct effect of the treatments on the pathogens, an indirect effect on the fruit tissue should be considered. Different types of stress, such as irradiation or heat shock, can activate defence responses in fruit and thus contribute to alleviate and reduce tissue colonization by pathogens. Nigro *et al*[3] and Marquenie *et al*[24] inoculated *Botrytis* spores on UV-C treated strawberries and found a reduction of decay, indicating that fruit defensive responses could be involved. The synthesis of antifungal compounds in citrus was induced after UV-C irradiation and heat treatment.[5] After UV-C irradiation of carrot slices, the induction of an antimicrobial compound, 6-methoxymellein, was found.[6] D'hallewin *et al*[29] found that the reduction of pathogen attack in 'Star ruby' grapefruit irradiated with UV-C was associated with an increase of the phytoalexins scoparone and scopoletin in the flavedo tissue. In summary, either heat or UV-C

treatments could trigger the production of defensive compounds.[28,30–32]

In vitro assays on mould conidia germination

Strains of *Botrytis cinerea* and *Rhizopus stolonifer*, two of the most common postharvest pathogens that attack strawberry, were used in *in vitro* assays to find out whether there was a direct effect of the UV-C light and heat treatment on fungal spore germination. *Botrytis cinerea* spores started germination after 2 h (Fig 3A), and all the control spores had germinated after 6 h. The application of UV-C or heat treatment delayed the spore germination but no differences between treatments were detected. The combined treatment reduced the percentage of spore germination to the greatest extent. The effect of the three treatments assayed was not deleterious for the fungus as all the spores germinated finally. The reduction of *Botrytis cinerea* spore germination by UV-C light has been described by Mercier *et al*.[2] It is noteworthy that although UV-C light and heat treatment delayed the spore germination of *Botrytis cinerea*, the combined treatment improved on the results found for each treatment separately.

A similar experiment was carried out with conidia of *Rhizopus stolonifer* (Fig 3B). The germination of *Rhizopus stolonifer* conidia started after 5 h of incubation in all cases. The direct treatment of the mould by UV-C or heating at 45 °C for 3 h did not affect the germination percentage of the conidia. In the case of the combined treatment, a significant reduction was observed after 9 h.

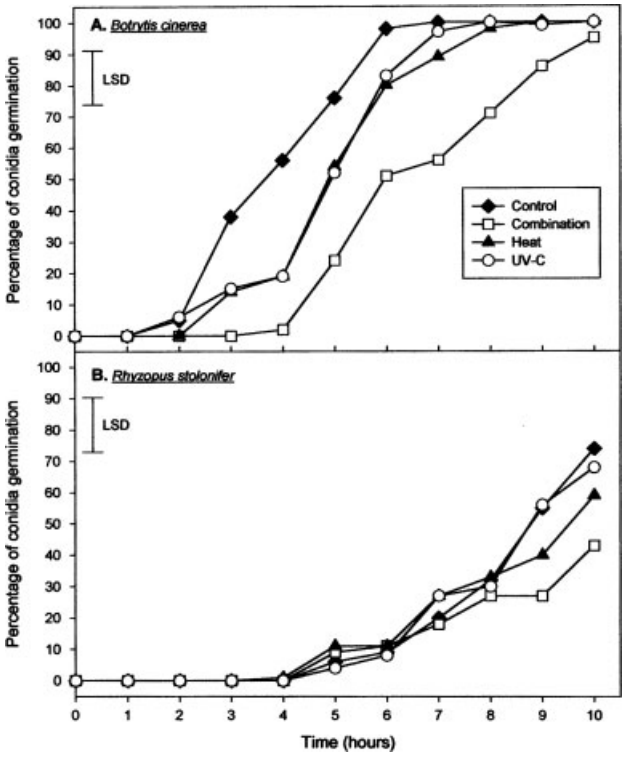

Figure 3. Effect of heat treatment, UV-C irradiation and combined treatment on *in vitro* spore-germination of *Botrytis cinerea* (A) and *Rhizopus stolonifer* (B) strains. Plates with 12 day-old cultures of each strain were treated by UV-C (4.1 kJ m^{-2}), heating (45 °C, 3 h in air oven) or a combination of both methods (first irradiation with UV-C and then heating). After treatment, a suspension of conidia was prepared and the germination percentage was determined. LSD (least significant difference) at $p = 0.05$ is shown.

Quality attributes

Firmness

The experiments were performed with more immature fruit (50% red) to analyze the effect of treatments on softening in more detail. All fruit softened over the 4 days of the experiment (Fig 4). Control fruit softened most rapidly, while the combined treatment softened least. Intermediate softening was found for heat and UV-C treated berries. The application of heat treatment on tomato and strawberry fruit has been associated with a delay of ripening and changes in protein synthesis.[18,33] Since the activity of many cell wall hydrolases, like *endo*-1,4-β-D-glucanase, pectin methyl esterase[34] and β-galactosidase,[35] increases during strawberry fruit ripening, the higher values of firmness observed in heat-treated fruit could be due to the diminution of cell wall degrading enzymes, caused in turn by the delay of ripening.

The higher values of firmness found in UV-C-treated fruit could be associated with the effect of the radiation on the activity of enzymes involved in cell wall degradation. Barka *et al*[11] suggested that cell wall degrading enzymes are one of the targets of UV-C, leading to slowed cell wall degradation.

Surface colour and anthocyanins

A diminution in the hue value, indicating surface reddening, occurred in all treated and control fruits (Fig 5A). However, surface reddening was greatest in control and UV-C-treated fruit, being reduced by heating only or combined with the UV-C irradiation. A decline in L^* values, indicating increasing darkening in fruit, occurred in all treatments (Fig 5B); however,

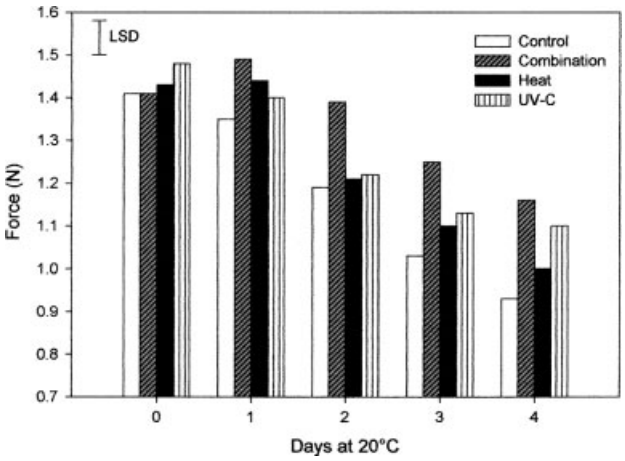

Figure 4. Effect of UV-C and heat treatment on firmness of strawberry fruit during storage at 20 °C. Strawberries (50% red) were left untreated (control), treated by UV-C (4.1 kJ m^{-2}), by heating (45 °C, 3 h in air oven) or by a combination of both methods (first irradiation with UV-C, and then heating). After treatment, all the fruit were stored at 20 °C for 4 days and the fruit firmness was measured. LSD (least significant difference) at $p = 0.05$ is shown.

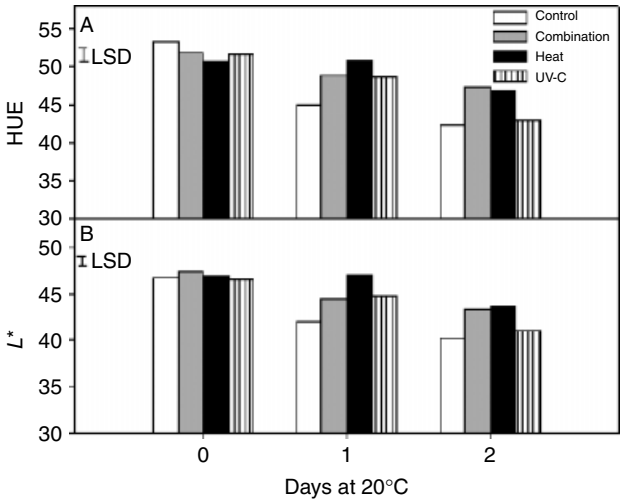

Figure 5. Surface colour (A) and lightness (B) of strawberry fruit at 20 °C after heat treatment, UV-C irradiation and combined treatment. Strawberries were treated by UV-C (4.1 kJ m^{-2}), heating (45 °C, 3 h in air oven) or a combination of both methods (first irradiation with UV-C, and then heating). After treatment, all the fruit were stored at 20 °C for 2 days and the hue angle and L^* parameter were measured. LSD (least significant difference) at $p = 0.05$ is shown.

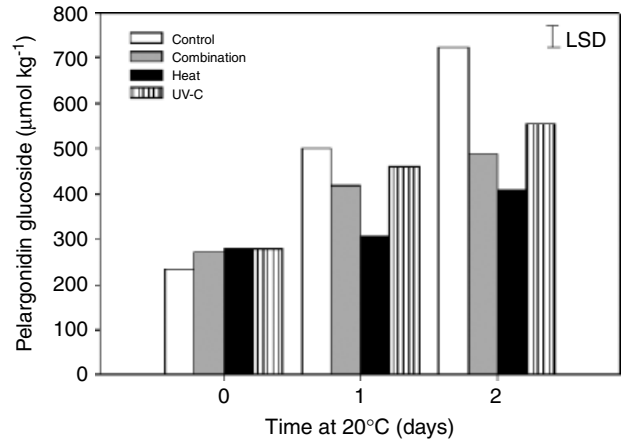

Figure 6. Anthocyanin concentration in strawberry fruit at 20 °C after heat, UV-C irradiation and combined treatments. Strawberries were treated by UV-C (4.1 kJ m^{-2}), heating (45 °C, 3 h in air oven) or a combination of both methods (first irradiation with UV-C, and then heating). After treatment, all the fruit were stored at 20 °C for 2 days and the amount of anthocyanins (perlagonidyn glucoside, µmol kg^{-1}) was determined. LSD (least significant difference) at $p = 0.05$ is shown.

combined and thermally treated fruit showed slower skin darkening. The results are in concordance with previous reports of Vicente *et al*[19] who found that heat-treated fruit darkened less than fruit without treatment. No negative effect on calix colour (drying or staining of leaves) was observed in fruit treated with this dose of UV-C (4.1 kJ m^{-2}). Instead, higher doses of UV-C (eg 10–15 kJ m^{-2}) caused calix deterioration in strawberry.[4]

Anthocyanin concentration changes were similar to those of surface colour; differences between treatments and control fruit consisted mainly in differential rates of anthocyanin increases (Fig 6). A sharp increase of the anthocyanin concentration was found in control fruit from day 1 onwards, and especially on day 2. The heat-treated fruit had the lowest anthocyanin increase. Ultraviolet-treated fruit showed a steady increase in anthocyanin concentration, but less than that observed in control fruit. The combined treatment showed an intermediate pattern of anthocyanin increment between that of heat or UV-C treatments.

Heat treatments inhibit PAL activity in strawberry fruit,[18] which may explain the delay in anthocyanin accumulation observed in the fruit treated by heating alone or in combination with UV-C. Nigro *et al*[3] reported that low doses of UV-C (0.50 kJ m^{-2}) increase PAL activity whereas higher doses (2.50 kJ m^{-2}) caused a lower activity increment. The amount of anthocyanins in fruit treated with a dose of 4.1 kJ m^{-2} of UV-C was similar or slightly lower than the controls (Fig 6), probably because at this dose the activity of PAL is not significantly increased.

Total phenolic compounds

Total phenol concentration remained approximately constant in control fruit for 2 days at 20 °C (Table 1). Immediately after UV-C or heat treatment, no difference in the total phenol concentration was found, but a slight loss was detected when both treatments were combined. After 1 day, the level decreased in fruit treated by UV-C or heating separately, while remained constant in fruit treated by the combined method. After 2 days at 20 °C, fruit treated by either method showed lower phenol concentration than the control.

Sugars

Total sugar content decreased slightly immediately after UV-C or heat treatments applied separately (Table 1). A decreasing amount of total sugar was found during storage in control and fruit treated by UV-C or the combined method; no difference during storage was found when the heat treatment was applied alone. After 2 days at 20 °C, neither the heat treatment nor the UV-C irradiation applied separately modified the total sugar content, while the combined treatment caused a small decrease.

pH and titratable acidity

Immediately after the treatments, the UV-C and the heat treated fruit had the highest pH value whereas the control had the lowest (Table 1). However, after 2 days of storage only the UV-C fruit had higher pH values than the control fruit. The titratable acidity increased through storage at 20 °C in all the control or treated fruit, and no differences between control and treated fruit were detected. These results differ from data reported for 'Selva', which showed a diminution of fruit acidity after the application of heat treatment,[19] and for 'Kent' in which the titratable acidity decline during storage was delayed by the application of UV-C.[17]

Table 1. Effect of UV-C (4.1 kJ m^{-2}), heat treatment (45 °C, 3 h) and combination of both treatments on phenolic compounds, total sugars, pH and titratable acidity of strawberry fruit during storage at 20 °C; LSD (least significant difference) at $p = 0.05$ for each parameter is shown

Quality parameter	Days at 20 °C	Control	UV-C	Heat	Combined
Total phenols (g kg^{-1})	0	2.00	1.93	1.82	1.75
	1	1.80	1.53	1.59	1.62
	2	2.10	1.65	1.36	1.78
LSD ($p = 0.05$): 0. 26					
Total sugars (g kg^{-1})	0	55.9	51.2	50.9	53.0
	1	46.8	47.1	50.0	48.9
	2	47.8	43.9	49.2	42.0
LSD ($p = 0.05$): 4.5					
pH	0	3.33	3.67	3.68	3.48
	1	3.45	3.59	3.52	3.51
	2	3.55	3.67	3.57	3.55
LSD ($p = 0.05$): 0.09					
Titratable acidity (H^+ mmol kg^{-1})	0	121.6	118.9	131.4	125.8
	1	125.8	126.4	128.5	131.5
	2	138.4	132.1	140.1	133.8
LSD ($p = 0.05$): 7.7					

CONCLUSIONS

The results of this work support the use of heat treatment as a possible strategy to improve postharvest storage of strawberry fruit, particularly using air instead of water as the heating medium. In addition, previous irradiation with UV-C enhances the benefits of the heat treatment and further reduced decay, softening and reddening of the strawberry fruit. The treatments did not modify significantly the total sugar content and titratable acidity, two key factors associated to fruit flavour and consumer acceptance. Instead, a reduction of total phenolic compounds was found in fruit treated by UVC or heat. The decay reduction during storage is in part due to a direct effect of the heat and UV-C light on fungal inoculum. The combination of UV-C and heat treatments enhanced the benefits of applying each treatment separately, and could be useful to improve and extend strawberry fruit postharvest life.

ACKNOWLEDGEMENTS

This work was based on funding from Agencia Nacional de Promoción Científica y Tecnológica (Argentina) PICT 08-07088. The authors would like to thank Miss L Piskulic for her valuable help with the *in vitro* assays on spore germination.

REFERENCES

1 Liu J, Stevens C, Khan VA, Lu JY, Wilson CL, Adeyeye O, Kabwe MK, Pusey PL, Chalutz E, Sultana T and Droby S, Application of ultraviolet-C light on storage rots and ripening of tomatoes. *J Food Prot* **56**:868–872 (1993).

2 Mercier J, Baka M, Reddy B, Corcuff R and Arul J, Shortwave ultraviolet irradiation for control of decay caused by *Botrytis cinerea* in bell pepper: induced resistance and germicidal effects. *J Am Soc Hort Sci* **126**:128–133 (2001).

3 Nigro F, Ippolito A, Lattanzio V, Di Venere D and Salerno M, Effect of ultraviolet-C light on postharvest decay of strawberry. *J Plant Pathol* **82**:29–37 (2000).

4 Marquenie D, Michiels CW, Geeraerd AH, Schenk A, Soontjens C, Van Impe JF and Nicolaí BM, Using survival analysis to investigate the effect of UV-C and heat treatment on storage rot of strawberry and sweet cherry. *Int J Food Microbiol* **73**:187–196 (2002).

5 Ben-Yehoshua S, Rodov V, Kim JJ and Carmeli S, Preformed and induced antifungal materials of citrus fruits in relation to the enhancement of decay resistance by heat and ultraviolet treatments. *J Agric Food Chem* **40**:1217–1221 (1992).

6 Mercier J, Arul J, Ponnampalam R and Boulet M, Induction of 6-methoxymellein and resistance to storage pathogens in carrot slices by UV-C. *J Phytopathol* **137**:44–54 (1993a).

7 Hadwiger LA and Schwochau ME, Ultraviolet light-induced formation of pisatin and phenylalanine ammonia lyase. *Plant Physiol* **47**:588–590 (1971).

8 Ensminger PA, Control of development in plants and fungi by far-UV radiation. *Physiol Plant* **88**:501–508 (1993).

9 Chappel J and Hahlbrock K, Transcription of plant defence genes in response to UV light or fungal elicitor. *Nature (London)* **311**:76–78 (1984).

10 Douillet-Breuil AC, Jeandet P, Adrian M and Bessis R, Changes in phytoalexin content of various *Vitis* spp in response to Ultraviolet C elicitation. *J Agric Food Chem* **47**:4456–4461 (1999).

11 Barka EA, Kalantari S, Makhlouf J and Arul J, Impact of UV-C irradiation on the cell wall-degrading enzymes during ripening of tomato (*Lycopersicon esculentum* L) fruit. *J Agric Food Chem* **48**:667–671 (2000).

12 Baka M, Mercier J, Corcuff F, Castaigne F and Arul J, Photochemical treatment to improve storability of fresh strawberries. *J Food Sci* **64**:1068–1072 (1999).

13 Lurie S, Postharvest heat treatments. *Postharvest Biol Technol* **14**:257–269 (1998).

14 Paull RE and Chen NJ, Heat treatment and fruit ripening. *Postharvest Biol Technol* **21**:21–37 (2000).

15 Conway WS, Sams CE, Wang CY and Abbott JA, Additive effects of postharvest calcium and heat treatment on reducing decay and maintaining quality in apples. *J Am Soc Hort Sci* **119**:49–53 (1994).

16 McDonald RE, McCollumn TG and Baldwin EA, Temperature of water treatments influences tomato fruit quality following low temperature storage. *Postharvest Biol Technol* **16**:147–155 (1999).

17 García JM, Aguilera C and Albi MA, Postharvest heat treatment on Spanish strawberry (*Fragaria* × *ananassa* cv.Tudla). *J Agric Food Chem* **43**:1489–1492 (1995).

18 Civello PM, Martínez GA, Chaves AR and Añón MC, Heat treatments delay ripening and postharvest decay of strawberry fruit. *J Agric Food Chem* **45**:4589–4594 (1997).
19 Vicente AR, Civello PM, Martinez GA and Chaves AR, Quality of heat-treated strawberry fruit during refrigerated storage. *Postharvest Biol Technol* **25**:59–71 (2002).
20 García JM, Aguilera C and Jiménez AM, Gray mold in and quality of strawberry fruit following postharvest heat treatment. *HortScience* **31**:255–257 (1996).
21 Vicente AR, Martinez GA, Chaves AR and Civello PM, Influence of self-produced CO_2 on postharvest life of heat-treated strawberries. *Postharvest Biol Technol* **27**:265–275 (2003).
22 Marquenie D, Lammertyn J, Geerared AH, Soontjens C, Van Impe JF, Nicolaí BM and Michiels CW, Inactivation of conidia of *Botrytis cinerea* and *Monilinia fructigena* using UV-C and heat treatment. *Int J Food Microbiol* **74**:27–35 (2002).
23 Marquenie D, Geeraerd AH, Lammertyn J, Soontjens C, Van Impe JF, Michiels CW and Nicolaí BM, Combinations of pulsed white light and UV-C or mild heat treatment to inactivate conidia of *Botrytis cinerea* and *Monilia fructigena*. *Int J Food Microbiol* **85**:185–196 (2003).
24 Marquenie D, Michiels CW, Van Impe JF, Schrevens E and Nicolaí BN, Pulsed white light in combination with UV-C and heat to reduce storage rot of strawberry. *Postharvest Biol Technol* **28**:455–461 (2003).
25 Woodward JR, Physical and chemical changes in developing strawberry fruits. *J Sci Food Agric* **23**:465–473 (1972).
26 Southgate DAT, *Determination of Food Carbohydrates*. Applied Science, London, pp 105–106 (1976).
27 AOAC, *Official Methods of Analysis*, 13th ed. Asociation of Official Analytical Chemists, Washington, DC (1980).
28 Fallik E, Grinberg S, Gambourg JD, Klein JD and Lurie S, Prestorage heat treatment reduces pathogenicity of *Penicillium expansum* in apple fruit. *Plant Pathol* **45**:92–97 (1995).
29 D'hallewin G, Schirra M, Pala M and Ben-Yehoshua S, Ultraviolet C irradiation at 0.5 kJ m^{-2} reduces decay without causing damage or affecting postharvest quality of star ruby grapefruit (*Citrus paradisi* Macf). *J Agric Food Chem* **48**:4571–4575 (2000).
30 Mercier J, Arul J and Julien C, Effect of UV-C on phytoalexin accumulation and resistance to *Botrytis cinerea* in stored carrots. *J Phytopathol* **139**:17–25 (1993b).
31 Rodov V, Ben-Yehoshua S, Kim JJ, Shapiro B and Ittah Y, Ultraviolet illumination induces scoparone production in kumquat and orange fruit and improves decay resistance. *J Amer Soc Hort Sci* **117**:788–792 (1992).
32 Adrian M, Jeandet P, Douillet-Breuil AC, Tesson L and Bessis R, Stilbene content of mature *Vitis vinifera* berries in response to UV-C elicitation. *J Agric Food Chem* **48**:6003–6005 (2000).
33 Lurie S, Handros A, Fallik E and Klein JD, Reversible inhibition of tomato fruit gene expression at high temperature. *Plant Physiol* **110**:1207–1214 (1996).
34 Manning K, Soft fruit, in *Biochemistry of fruit ripening*. Chapman & Hall, London, pp 347–377 (1993).
35 Trainotti L, Spinello R, Piovan A, Spolaore S and Casadoro G, β-Galactosidases with a lectin-like domain are expressed in strawberry. *J Exp Bot* **52**:1635–1645 (2001).