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Radiochromic film dosimetry for UV-C treatments of apple fruit☆

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ABSTRACT

UV-C can inactivate foodborne pathogens on surface of fruit such as apples. However, the practical application of the technology has been limited by lack of methods to measure UV-C doses received by fruit and difficulty of achieving uniform UV-C doses on the same pieces of fruit. In the present study, radiochromic films were evaluated for their suitability to estimate UV-C doses and dose uniformity on apple fruit surface. Parameters investigated included film type, color changes of the films in response to different UV-C doses, color stability of films, UV-C light intensity, and temperature. In addition, apples with films attached to six locations on the surface were exposed to UV-C in a treatment chamber without reflective material, with an aluminum foil and a stainless steel sheet in the bottom of treatment chamber as reflectors, in comparison with the use of a rotating device to study the UV-C dose uniformity of the fruit received. Results showed that the radiochromic films were sensitive to UV-C light as they changed to blue or pink upon exposure to UV. The developed color after UV-C irradiation was stable for at least 15 d at dark and ambient temperature (21 ± 2 °C). The temperature (21 °C vs 4 °C) at which the films were exposed did not affect the changes in color as a result of UV-C exposure. Films exposed to UV-C at an intensity of 60 W m^{-2} developed a more intense color compared to those at 94 W m^{-2}. The changes in color of the films as a function of UV-C dose were measured as absorbance at 510 and 600 nm. The relationship between A_{510nm} and the UV-C dose could be expressed as polynomial equations, and the equations were used to predict UV-C doses on the surface of apples. The rotating device provided higher UV-C uniformity on the apple surface than other UV-C reflective materials as indicated by the coefficient of variations and the ratio of maximum/minimum doses. Therefore, the radiochromic film can be used as a UV dosimeter to determine UV dose distributions on individual fruits. Fruits treated with UV-C on a roller received uniformed UV-C exposure.

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1. Introduction

Foodborne illnesses associated with fresh produce have been increasing in recent years. *Salmonella* spp., *Listeria monocytogenes*, and *Escherichia coli* O157:H7 are common foodborne pathogenic bacteria linked with the major outbreaks involving fresh produce (Cedric et al., 2010; Olaimat and Holley, 2012; Scallan et al., 2011). Microbial safety of fresh fruit due to contamination with foodborne pathogens particularly *L. monocytogenes* is a concern. A report by the Interagency Food Safety Analytics Collaboration Project (2015) indicated that 50% of *L. monocytogenes* illnesses were attributed to fruits for the most recent 5-years (2008–2012) when data were available for the project. A multistate outbreak of listeriosis causing 7 deaths has been linked to California Granny Smith and Gala apples, fruits that have rarely been associated with human pathogen contamination (US-FDA, 2015a). Additionally, in the last 4 years, there have been multiple recalls of fresh-cut and whole apples due to contamination with *L. monocytogenes* (US-FDA, 2012a,b, 2013, 2014, 2015b,c). The fruit industry is in

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urgent need of interventions to reduce the risk of *L. monocytogenes* contamination.

Ultraviolet (UV-C) irradiation is a nonthermal processing technology that can destroy microorganisms, and the efficiency of UV-C radiation against a wide variety of microorganisms has been reported by many researchers (Escalona et al., 2010; Gayan et al., 2011; Guan et al., 2012; Yun et al., 2013). The effect of UV-C treatment on populations of human pathogens is correlated with UV doses (Kim et al., 2013; Yaun et al., 2004; Yun et al., 2013). Our earlier study (Yun et al., 2013) showed that *E. coli* O157:H7 and *Salmonella* spp. populations inoculated onto apricot fruit decreased rapidly (1–2 log) with increasing UV-C doses from 0 to 0.74 kJ m^2. Further increases in UV-C dosage achieved only limited additional reductions in bacterial populations. Yaun et al. (2004) compared the efficacy of UV-C against *E. coli* O157:H7 inoculated on a number of fruits, and found UV-C was most effective on apple fruit (3.3 log reductions). Another study (Santo et al., 2016) demonstrated that UV-C at doses of 7.5 and 10 kJ m^2 produced greater reductions in *Cronobacter sakazakii* populations (2–2.4 log) than electrolyzed water(1.0–1.8 log), or chlorine (0.8–1.4 log) on fresh-cut apple, pears or melons. The UV-C inactivation of bacteria occurs when the absorption of a photon by DNA forms pyrimidine dimers between adjacent thymine bases, which render the microbe incapable of replicating. In addition to its well-known effects on human pathogens, UV as a postharvest treatment is known to reduce respiration rate, and spoilage development, and delay senescence and ripening of fruits and vegetables (Lagunas-Solar et al., 2006; Urban et al., 2016).

Treatment with UV-C technology offers several advantages to food processors as it does not leave a residue, does not have legal restrictions and does not require extensive worker-protection equipment (Yousef and Marth, 1988; Wong et al., 1998). UV-C is used as an alternative to chemical sterilization and microbial reduction in food products and has been approved for use as a disinfectant for surface treatment of food (US-FDA, 2002). There has been a longtime interest in the application of UV-C for the disinfection of fruits and vegetables (Yaun et al., 2004). For example, Wilson et al. (1997) reported that it was feasible to treat apples on packing line during processing with UV-C light for controlling postharvest decay. In addition, high intensity UV-C lamps have become available and have a potential of destroying surface bacteria on foods (Koutchma et al., 2009). However, UV-C radiation is a relatively non-penetrating form of electromagnetic radiation (Koutchma et al., 2009; Sommers and Cooke, 2009).

As a result of UV-C being non-penetrative, the major issue with applying UV-C technology to fresh produce is the lack of UV-C uniformity on the same pieces of fruits or vegetables. Fast and on-site measurement and analysis of UV-C doses are the key steps for the evaluation of the dose uniformity, and for the commercialization of UV-C treatment to enhance microbial safety of fresh produce. Due to the irregular shape of fruits and vegetables, some surfaces of the same piece of fruits and vegetables may receive less UV dose than others. Therefore, the most significant challenge to the commercial application of UV-C technology is to ensure uniform exposure of UV light to all food surfaces. In commercial settings, some surface areas (such as the stem region of a fruit) likely receive less UV exposure than other parts of the same fruit as fruit pass through a packing line equipped with UV-C light. It is important to be able to determine the uniformity as well as maximum and minimum UV doses that each fruit receives. The minimum UV-C dose would be the dose that achieves the targeted benefits (such as certain reductions of human pathogens), while the maximum dose is the dose that the fruit can tolerate without changes in fruit quality, such as color. To accurately measure the UV doses that each fruit receives, a dosimetry system that can indicate doses on different locations of fruit surface is needed.

A promising material for use in a UV-C dosimeter is a plastic film with embedded dye that undergoes color change when exposed to ionizing irradiation (Butson et al., 2003, 2010). These colorless and transparent films are thin, strong, and flexible with good optical quality. The radiochromic films have been used as dosimeters for ionizing irradiation of food, and studied for monitoring UV radiation for occupational safety (Abdel-Fattah et al., 2000) and for medical and industrial applications (Devic 2011; Ebraheem et al., 2000; Saylor et al., 1988; Soares 2006). There has been no detailed study regarding the use of the radiochromic films for estimating UV-C doses for the food industry. Therefore, the objectives of the present study were to determine the suitability of radiochromic films as UV-C dosimeters, and to use the UV-C dosimetry system for the estimation of UV-C uniformity on apple surface.

2. Materials and methods

2.1. Sources of radiochromic films

FWT-60-00 radiochromic films (43.5 μm in thickness, 10 × 10 mm in size) were purchased from Far West Technology Inc. (Goleta, CA). B3WINDOSE films (19.4 μm in thickness, 10 × 10 mm in size) were obtained from GEX Corp. (Centennial, CO).

2.2. UV-C treatment apparatus

A UV treatment chamber containing two UV-C fixtures (SaniLIGHTTM, Atlantic Ultraviolet, White Plains, NY) was used to provide the required irradiation wavelength (254 nm). Each fixture had one 0.61-m long UV-C emitting tube (model PL-L-55W/HF, Philips, Somerset, NJ) mounted onto the hinged lid of a black tool box (78 × 44 × 35 cm). A UVX radiometer (UVP LLC, Upland, CA) was used to measure the intensity of UV light from the lamp. For UV-C exposure, the films were placed at the same distance as the UVX radiometer so that the UV intensity was measured at the same time as the films received UV-C exposure.

2.3. Color development of radiochromic film in response to different doses

Different UV-C doses were achieved by varying treatment times. The two types of films were exposed to UV-C for different times (0 to 120 s) at an intensity of 94 W m^{-2}. After UV-C exposure, a radiochromic reader (Model 92, UVP LL) was used to measure the color change of the films at two fixed wavelengths (510 and 600 nm). The UV-C light was turned on only when the chamber was closed to avoid any skin and eye exposure to UV.

2.4. Effect of UV-C intensity on radiochromic film color development

FWT-60-00 films were exposed to different times of UV-C at two UV-C intensities (60 W m^{-2} and 94 W m^{-2}) by turning on one or two UV-C lights. After the UV-C exposure, the films were measured with the radiochromic reader at 510 nm. Doses that the films received were then calculated with the following equation: UV dose (kJ m^{-2}) = irradiance (W m^{-2}) × exposure time (s) ÷ 1000. The absorbance at 510 nm (A_{510nm}) was graphed as a function of dose.

2.5. Use of radiochromic film at different temperatures

The FWT-60-00 films were exposed to different doses of UV-C at two different temperatures (4 and 21 °C). After exposure, the films were measured with the radiochromic reader at 510 nm.

2.6. Color stability of radiochromic films after UV-C exposure

After exposure to different doses of irradiation, the FWT-60-00 films were stored in enclosed container to avoid light exposure and ambient temperature (21 ± 2 °C). A_{510nm} of the films was measured on d 1, 7 and 15.

2.7. Effect of reflective material and rotating device on dose uniformity

Radiochromic films were attached to various surface locations on 12 apples ("Fuji") to study the uniformity of UV-C exposure. These locations included: blossom, stem, C1, C2, C3, and C4. Blossom was the cavity near blossom end; Stem was the cavity around the stem; C1 was fruit cheek surface facing the UV light source when starting to be UV exposed; C3 was the opposite of C1; C2 and C4 were the cheek areas on the opposite side ca. 90° from C1 and C3, respectively. The average diameter of the apples was 61 mm (55–65 mm). For UV-C treatment without the use of the roller, a piece of fruit was fixed onto a metal bar so that the cheek area faced directly under UV-C light tubes. Reflective materials of black cloth (as a control), aluminum foil (OnPoint Inc., Montvale, NJ), and a stainless steel sheet (304 finish #4) were put ~5 cm under the fruit for reflecting the UV-C light. The size of the stainless steel sheet and the aluminum foil was about 20 × 20 cm. The distance between the apples to the UV-C light tubes was about 6 cm. As a different treatment, a modified hot dog roller with five rotating bars (bar diameter: 25 mm) (Great Northern Popcorn Com., Mancelona, MI, USA) was placed inside the UV-C treatment chamber as a rotating device. The heater in the roller was disconnected, the original motor was removed, a new motor was installed, and the speed of the roller was set to 36 rpm. For the treatments with different reflective materials and a rotating device, the UV-C treatment time was 10 s at an intensity of 74 W m^{-2}. After UV-C treatment, absorbance of these films was measured at 510 nm by the radiochromic reader. UV-C doses were calculated using the following equation: Dose (kJ m^{-2}) = $-428.8 \times^3 + 1881.3 \times^2 - 1200.5 \times + 206.4$ where x is A_{510nm}. The above equation was established from a standard curve at a dose intensity of 74 W m^{-2} using Sigmaplot version 11 (Systat Software Inc., San Jose, CA).

2.8. Statistical analysis

Trials on film dosimeters were replicated at least three times for each UV dose, all of which were analyzed in duplicate at each sampling interval. For the dose uniformity study, experiments were repeated 12 times (12 apples). The data presented were the averages with standard deviations. Means and standard deviations were calculated using a spreadsheet software (Excel, Microsoft Corp., Redmond, WA). Data were subjected to Duncan's Multiple Range test using the ANOVA procedure of SAS Version 9.2 (SAS Institute, Cary, NC) to determine if there were significant differences ($p < 0.05$) among the treatments.

3. Results and discussion

3.1. Color changes of radiochromic films as a function of UV-C doses

The FWT film after UV-C exposure turned blue (Fig. 1) and the intensity of the blue color increased with increasing UV-C dose. Consequently, the absorbance of films measured at 600 and 510 nm increased with increasing doses (Fig. 2). The A_{600nm} increased more rapidly than A_{510nm} as doses increased from 0 to 4 kJ m^{-2}. Afterward, the increase in A_{600nm} slowed and reached saturation around 5 kJ m^{-2}, indicating that the measurement of the color changes in the film at A_{600nm} would only be a good indicator for low doses of UV-C (< 4 kJ m^{-2}). A_{510nm} of the films continued to increase even in the dose range of 4 to 12 kJ m^{-2}, though at a slower rate. Therefore, A_{510nm} could be used to predict higher doses of UV-C radiation compared to A_{610nm}. The relationship between A_{510nm} and UV-C dose could be expressed as polynomial equations.

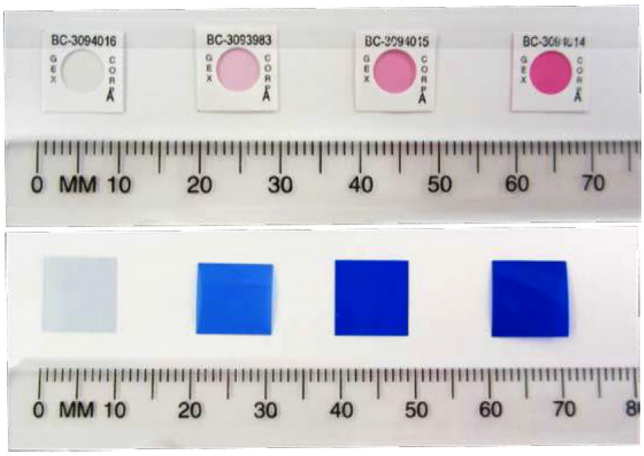

Fig. 1. Color changes of two radiochromic films after exposure to UV-C light. B3WINDOSE (top) and FWT-60-00 (bottom) films were exposed to UV-C at an intensity of 43 W m^{-2} for 0, 2, 10 and 30 s (left to right).

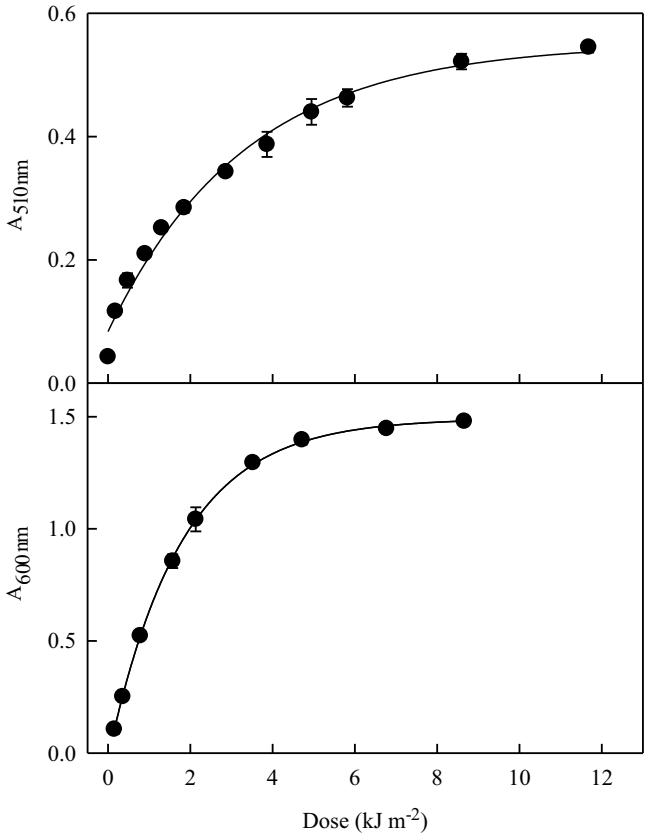

Fig. 2. Absorbance of FWT-60-00 radiochromic films at 510 nm (top) and 600 nm (bottom) as a function of radiation doses. Vertical bars represent standard deviations.

In addition to the FWT film, the B3WINDOSE film was tested as a comparison. The B3WINDOSE film turned pink, and the pinkness of the film intensified with increasing doses (Fig. 1). Measurement of the film color using radiometer indicated that A_{510nm} increased

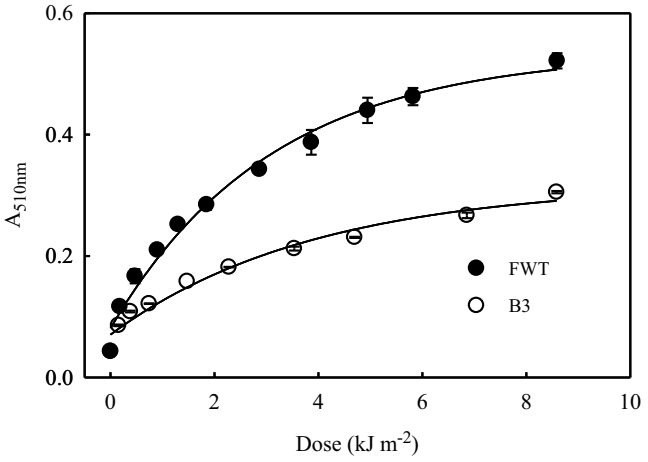

Fig. 3. Comparison of two different films in response to UV-C exposure. The absorbance of FWT-60-00 (FWT) and B3WINDOSE (B3) films was measured after the films were exposed to different doses of UV-C. Vertical bars indicated standard deviation.

with radiation doses (Fig. 3). In comparison with FWT film, the increase in A_{510nm} was slower for the B3WINDOSE film, especially after 2 kJ m^{-2}. It seems that the FWT film had a larger increase of A_{510nm} in response to same doses of UV-C exposure and was more sensitive to UV-C. Therefore, the FWT film was used in subsequent experiments.

3.2. Effect of UV-C light intensity on the development of radiochromic film color

In order to study the effects of the UV-C intensity on A_{510nm} of the FWT film, we used either one or two UV-C lights to achieve two UV-C intensities of 60 W m^{-2} and 94 W m^{-2}, respectively. The results showed that A_{510nm} of the film exposed to the lower UV-C intensity was slightly higher than the absorbance at a higher intensity when exposed to the same doses of UV-C (Fig. 4). It seems that the low intensity (longer treatment time) allowed the film to develop a deeper blue color.

The relationship between the UV-C dose and A_{510nm} of the film color could be expressed by polynomial equations with R^2 of 0.997. At the intensity of 94 W m^{-2}, the relationship between A_{510nm} and UV-C dose could be described as: Dose (kJ m^{-2}) = 38. 2 $\times^3$ + 100.0

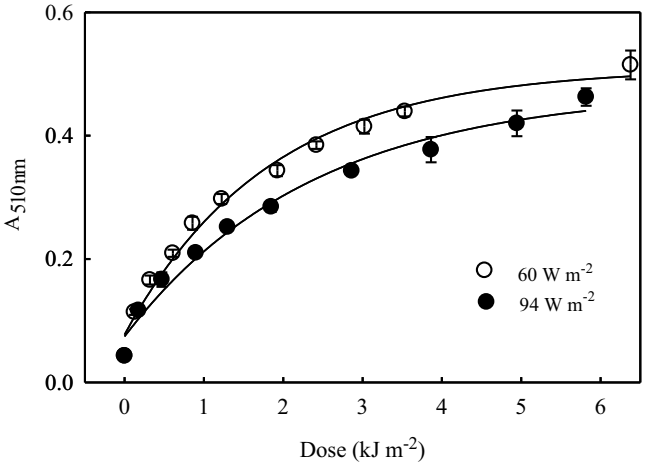

Fig. 4. Effects of UV-C light intensity on the film color changes. FWT-60-00 film was exposed to the same doses of UV-C at two different UV-C intensities (60 vs 94 W m^{-2}). A_{510nm} of the films were then measured. Vertical bars indicate standard deviations.

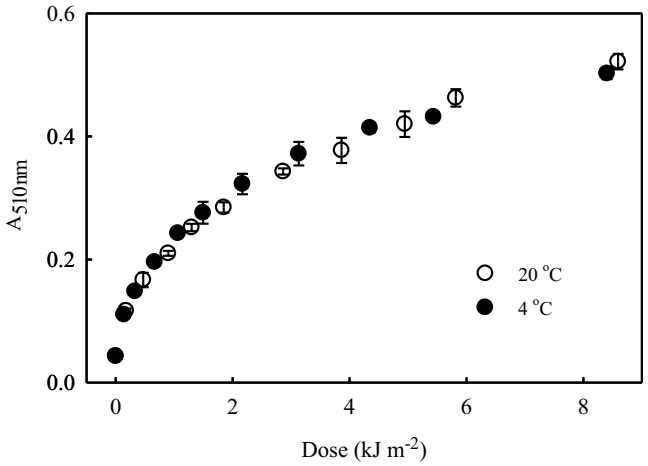

Fig. 5. Effect of temperature on the color development of FWT-60-00 radiochromic film. FWT-60-00 film was exposed to various doses of UV-C at 4 and 21 °C. A_{510nm} of the films was measured afterward. Vertical bars indicate standard deviations.

$\times^2$ + 74.1 x − 78.4; and at 60 W m^{-2}, Dose (kJ m^{-2}) = 96.5 $\times^3$ − 419.2 $\times^2$ + 921.5 x − 406.5, where X is absorbance value of radiochromic film at 510 nm.

3.3. Effect of temperature on the film color change in response to UV-C

The UV treatment was performed at two temperatures: 21 °C and 4 °C. The A_{510nm} of the film increased with increasing doses at a similar rate regardless of treatment temperature, suggesting that the temperature did not affect the color changes of the films in response to UV-C exposure (Fig. 5). Many fresh fruits and vegetables are cooled down after harvest and handled in cold environment while fresh-cut products are processed at low temperatures. Our results suggested that the radiochromic film could be used in cold processing conditions. Furthermore, the standard curve established at ambient temperature can be used to predict UV-C dose in low temperatures.

3.4. Color stability of radiochromic film after UV-C exposure

The radiochromic film was stored for 15 d in dark with about 40% relative humidity at 21 °C. The results showed that the absorbance of film at 510 nm did not have any significant changes during storage (Table 1). Similar results were reported by Ebraheem et al. (2000) that dyed poly(vinyl butyral) films showed a good post-irradiation stability when stored in the dark. The evaluation of film color requires the use of a radiochromic reader. When the reader is not available, the radiochromic films may be shipped to a central location for the estimation of UV-C doses if the color of the film is stable. Our results suggested that the film after UV-C exposure was stable for at least two weeks in dark, allowing the shipment of the film to a centralized location for measurement. High temperature or high humidity may affect the color stability of the films after UV-C exposure. In addition, there is a slow natural color development that takes place in the film over time, and exposure to sunlight will speed up the color change.

3.5. Effect of reflective material and a rotating device on dose uniformity of apple fruit

To evaluate the practical applications of the film, the UV dose uniformity on apple fruit surface was evaluated using the film dosimeter. Radiochromic films were attached at six locations on the surface of 12 apples. Results showed that the dose received by

Table 1
Stability of radiochromic films during post-exposure storage in the dark for 15 d at 22 °C. The numbers are means followed by standard deviations (n = 5). Means with the same letters in the same rows are not significantly different (P > 0.05).

Dose (kJ m^{-2})	1 d	7 d	15 d
0	0.043 ± 0.006a	0.043 ± 0.044a	0.043 ± 0.001a
0.18	0.121 ± 0.001a	0.122 ± 0.020a	0.122 ± 0.001a
0.47	0.169 ± 0.002a	0.168 ± 0.000a	0.168 ± 0.000a
0.93	0.214 ± 0.003a	0.212 ± 0.021a	0.212 ± 0.000a
1.31	0.252 ± 0.007a	0.252 ± 0.007a	0.254 ± 0.000a
1.82	0.294 ± 0.005a	0.29 ± 0.015a	0.29 ± 0.003a
2.88	0.348 ± 0.007a	0.342 ± 0.031a	0.344 ± 0.001a
3.78	0.376 ± 0.004a	0.378 ± 0.054a	0.378 ± 0.005a
3.94	0.392 ± 0.004a	0.388 ± 0.013a	0.388 ± 0.002a
4.95	0.422 ± 0.001a	0.422 ± 0.022a	0.424 ± 0.001a
5.85	0.478 ± 0.002a	0.466 ± 0.005a	0.472 ± 0.002a

each apple (by averaging the six locations) was not significantly different among the four treatments. Apples without reflective material (black cloth) received the lowest doses of UV (Table 2). When the apples were static (without use of the roller) during UV-C treatment, there were significant differences in the absorbed UV-C doses among the six locations of apples (Fig. 6A, B, C). The position (C1) that faced to the UV light source, as expected, received the highest doses while the C3 (the opposite of C1) and stem had the lowest doses regardless of the use of the stainless steel sheet or aluminum foil as UV reflectors. In comparison to the control (black cloth), the stainless steel sheet and aluminum foil provided some UV-C reflection to the bottom of apples (C3 position). However, large dose variations were still obvious among the locations. On the other hand, the rotating device provided uniform UV-C exposure as no significant difference in UV-C doses was observed among the six locations of apples (Fig. 6D). To further estimate dose uniformity on fruit surface, coefficient of variation (CV) and the maximum/minimum ratio were calculated (Table 2). CVs of UV-C doses were 32.2, 59.6, 29.9 and 7.7% and maximum/minimum ratios were 147.6, 86.4, 132.7 and 2.1 on fruit treated in the UV-C chamber without reflective material, with the stainless steel sheet and aluminum foil, and with the rotating device, respectively. The apples treated with the use of the rotating device had at least 4 times less CV and more than 40 times lower maximum/minimum ratio than those without the use of rotating device. Therefore, our results suggested that the rotating device provided uniformed UV-C exposure on fruit surface even though the fruit did not receive significantly higher average UV-C dose compared with the use of reflective material. Lagunas-Solar et al. (2006) suggested that fruit must be handled to ensure UV-C uniformity, and UV-C light can be combined with dispersing reflectors to increase decontamination efficiency. Our results suggest that the rotating device is the best choice to maximize UV-C dose uniformity. Reflective materials such as stainless steel sheet and aluminum foil provide very limited improvement over dose uniformity.

Film dosimeter has been routinely used to measure and verify the dose received by food after ionizing irradiation (Fan and Thayer, 2001; Mehta and O'Hara, 2012). A radiation dosimeter is a device that measures or evaluates, either directly or indirectly, the exposure of dose of radiation (Izewska and Rajan, 2005). A dosimeter along with its reader is referred to as a dosimetry system. Radiochromic film contains a special dye that is polymerized upon exposure to radiation, resulting in color changes that can be measured by a radiometer (Izewska and Rajan, 2005). The FWT

Table 2
UV-C dose uniformity on apples after being exposed to UV-C with different reflective materials and the rotating device.

Reflective material or rotating device	Average (kJ m^{-2})	CV (%)	Maximum/minimum
Cloth	0.173 ± 0.056a	32.2	147.6 ± 48.8a
Stainless steel	0.232 ± 0.138a	59.6	86.4 ± 81.0a
Aluminum foil	0.276 ± 0.082a	29.9	132.7 ± 102.7a
Rotating device	0.254 ± 0.019a	7.7	2.1 ± 0.6b

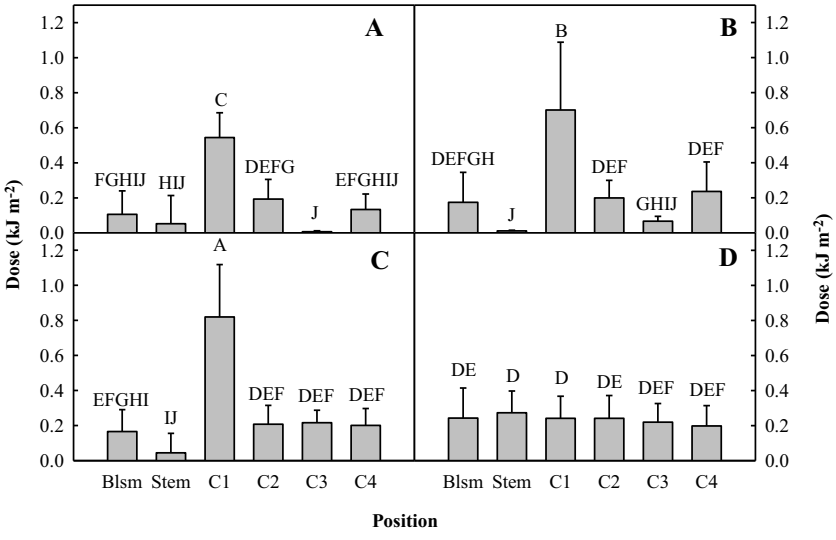

Fig. 6. Effects of reflective materials and a rotating device on UV-C dose uniformity of apple fruit surface. Vertical bars represent standard errors. Means with same letter are not significantly (P < 0.05, Duncan's multiple range test) different (N = 12). A: no reflective material (black cloth), B: Stainless steel, C: aluminum foil, D: rotating device. Blsm = blossom. C1 was fruit surface facing the UV light source in the beginning of UV-C treatment; C3 was the opposite of C1; C2 and C4 were the cheek areas on opposite sides ca. 90° from C1 and C3, respectively.

film, a nylon with hydrophobic substituted triphenylmethane leucocyanides, is commonly used for high-dose ionizing radiation applications such as radiation processing, food irradiation, and sterilization. Ideally, the dosimeter should have a linear response in relationship to the dose. However, many dosimeters have limitations and may have a linear response only in certain dose range. Our results showed that the color change of the films we tested was not linear in the UV-C ranges we tested. Nevertheless, the radiochromic film could be used to estimate UV-C doses on fruit. The film is easy to use, relatively independent to the UV-C intensity and treatment temperature. Other films may be evaluated in the future (Soares, 2006).

In the present study, we used a radiochromic reader that was capable of reading the films at 510 and 600 nm. In the case of a radiochromic reader not available, a desktop scanner may be utilized for scanning the films operated in transmission mode. The scanned images can be analyzed using commercial software and a graphical user interface (Huet et al., 2012).

It is difficult to get uniformed UV-C doses for all surfaces of fruit when fruit are static even with the use of reflective material. Reflecting materials such as aluminum foil could increase irradiation doses on certain area on the surface of apples by reflecting UV-C light. However, the reflection is limited in terms of the amount and direction. The roller, as a simple random movement device, could help fruit get uniformed UV-C exposure on all fruit surface. Generating random movement of fruit in a conveyorized operation that provides uniformed UV exposure to all fruit surfaces is necessary for a large-scale commercial application. Ideally, fruit should be rapidly and randomly rotated in multiple planes, allowing all surface exposure from multiple directions and angles of the UV light.

In the present study, we applied radiochromic films onto apples, and demonstrated that apples received uniformed UV-C doses when a rotating device was used. The film dosimetry system along with UV-C technology may be applicable to other geometrically round fruit, such as peaches, apricot, orange etc. as long as the fruit can be rapidly and randomly rotated in multiple planes without causing mechanical damage. In fact, we have used the radiochromic film system on apricot fruit in a commercial trial (Yan et al., 2014). UV-C lamps may be integrated into current apple packing line, perhaps installed above roller conveyers where fruit are rapidly rotated. Whether currently-used packing lines are capable of generating enough rotation to ensure uniform UV exposure needs further evaluation.

Radiochromic film could also be used to monitor the uniformity of the UV-C exposure of the process over time. The intensity of UV-C lamps (tubes) decreases with increasing usage. The film may be sufficient to determine the changes in lamp UV-C, output lamp failure or stability of UV-C treatment systems to ensure fruit receiving the targeted doses.

The results presented in this paper demonstrated that the radiochromic film responded to UV-C radiation by changing color which could be measured at 610 nm and 510 nm. Compared to B3WINDOSE film, the FWT radiochromic film was more sensitive to UV-C radiation with ranges from 0 to 12 kJ kJ m^{-2} when measured at A_{510nm}. Treatment temperature (21 °C or 4 °C) did not affect the development of film color. Higher UV-C intensity produced less color changes in the film compared to lower UV-C intensity. The color of radiochromic film after UV-C exposure was stable during 15 d in the dark and 21 °C. Most importantly, evaluation with the radiochromic film dosimeters suggested that the use of reflective materials could not ensure the dose uniformity on apple fruit while the rotating device provided UV-C dose uniformity. Overall, our results demonstrate that radiochromic film is valuable in estimating UV-C doses and uniformity of UV-C irradiation on apple fruit.

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