

Changes in structure and color characteristics of irradiated chicken breasts as a function of dosage and storage time[☆]

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Abstract

Structural change and color characteristics of chicken breasts as a function of irradiation dose and subsequent storage process were investigated by visible spectroscopy and HunterLab measurement. Ratios of $R_1 = A_{485 \text{ nm}}/A_{560 \text{ nm}}$ and $R_2 = A_{635 \text{ nm}}/A_{560 \text{ nm}}$, which are related to absorbances of the visible bands at 485 nm (metmyoglobin), 560 nm (oxymyoglobin), and 635 nm (sulfmyoglobin), suggested that relative amount of oxymyoglobin either increases as a result of irradiation, or decreases with the storage process. The plot of R_1 and R_2 versus storage time showed that the increments of both R_1 and R_2 are dose-dependent and that the relative amount of oxymyoglobin species in irradiated meats begins to decompose 7–12 days later than raw meats. In addition, R_1 and R_2 values were correlated with color index E^* of chicken breasts. Published by Elsevier Science Ltd.

Keywords: Visible spectroscopy; Color; Irradiation; Chicken breast; Myoglobin

1. Introduction

Irradiation can eliminate food-borne pathogenic microorganisms in meats and help provide a safer food supply for human consumption. Previous studies have reported the effects of irradiation on meat quality and also the subsequent color changes related to irradiation dose, meat species and package environment (Ahn, Olson, Jo, Love, & Jin, 1999; Nanke, Sebranek, & Olson, 1998, 1999; Thayer, 1993, 1995; Thayer & Boyd, 1996; Thayer, Boyd, Fox, Lakritz, & Hampson, 1995). However, studies reporting irradiation effects on meat color have been inconsistent. For example, it was reported that HunterLab values and visual evaluation scores showed no color difference between control and beef steaks irradiated at 1.5 kGy (Fu, Sebranek, & Murano, 1995), and that a^* (redness) and chroma

values increased in chicken breasts as a result of 5.0 kGy of ionizing radiation (Millar, Moss, MacDougall, & Stevenson, 1995). The understanding of irradiation effect on meat color is important for federal and state regulators, the meat processing industry, and food/meat scientists.

There have been many investigations concerning meat color variations after irradiation treatment. Visual evaluation and a variety of techniques, including optical, physical, and analytical methods, have been developed to monitor the color changes. For example, Davies, Jones, and Yacowitz (1969) applied a HunterLab D-20 color difference meter to measure the skin color directly on the carcass, and later they reported the actual data in Hunter L , a , and b units (Yacowitz, Davies, & Jones, 1978). Such data characteristics are used widely in the meat industry.

Visible spectroscopy has long been an important method used for studying meat structure (Francis & Clydesdale, 1975). Nicol, Shaw, and Ledward (1970) reported the spectral differences among various myoglobin derivatives in the visible region. The spectral technique not only provides a better understanding of structural information, but also is very useful as an analytical tool in many applications, such as chicken

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meat safety and quality control (Chen & Marks, 1997, 1998; Chen, Huffman, Park, & Nguyen, 1996; Chen, Park, Huffman, & Nguyen, 1998; Fumiere, Sinnae, & Dardenne, 2000; McElhinney, Downey, & Fearn, 1999).

In more recent studies, we have shown that, with the aid of recently developed two-dimensional (2D) correlation analysis, four visible bands around 445, 485, 560, and 635 nm are identified as deoxymyoglobin (DeoxyMb), metmyoglobin (MetMb), oxymyoglobin (OxyMb), and sulfmyoglobin (SulfMb), respectively (Liu & Chen, 2000; Liu, Chen, & Ozaki, 2000a, 2000b). During external processes such as cooking and storage, derivatives of myoglobin interconvert and are degraded through oxidation and reduction reactions, ultimately influencing the appearance of meat color.

The objective of this study was to validate the previous report that the three visible bands at 485, 560, and 635 nm might be useful as indicators of meat color variation (Liu & Chen, 2001). Meanwhile, we presented a correlation between meat structure and its color characteristics from HunterLab measurements. In addition, we observed that the SulfMb species is undetectable in fresh-cut meats, and then it becomes stronger and distinctive with cold storage (Liu & Chen, 2000). It is of interest to see whether the SulfMb could be reduced to OxyMb/DeoxyMb with the irradiation.

2. Materials and methods

2.1. Meat samples

Skinless and boneless chicken breasts were obtained from a local supermarket. Two breasts were vacuum-packaged in each air-permeable package (E-300, Cryovac, Deerfield, IL) with an approximate oxygen transmission rate of 4000 ml/m²/24 h at 1 atm at 22.8 °C. All operations were performed in a meat processing room with a temperature of 6±2 °C. After packaging, 48 sample packages containing a total of 96 chicken breasts were transferred to a 0 °C refrigerator for overnight storage. The packages were randomly divided into eight groups of six packages, with each group containing 12 chicken breasts. One group was used as the non-irradiated control (0 kGy) while the other seven groups were designated for the irradiation process at the target dosages of 0.2, 0.5, 1.0, 2.0, 3.0, 4.0, and 5.0 kGy.

3. Irradiation processing

Irradiation was performed using the gamma radiation facility at the USDA's Eastern Regional Research Center, Pennsylvania. Irradiation was conducted using a self-contained, Lockheed Corporation ¹³⁷Cs gamma radiation source. The custom-made, self-contained

gamma-radiation source (Lockheed Georgia Company) has 23 ¹³⁷Cs pencils placed in an annular array around a 63.5-cm-high stainless steel cylindrical chamber with a 22.9-cm internal diameter. The source strength at the time of this study was ca. 109,159 Ci (4.039 PBq) with a dose rate of 0.10 kGy min⁻¹. The dose rate was established using alanine transfer dosimeters from the National Institutes of Standards and Technology, Gaithersburg, MD. Corrections for source decay were made monthly. Routine dosimetry was performed using 5-mm-diameter alanine dosimeters (Bruker Instruments, Rjeomstettem, Germany), and the free-radical signal was measured using a Bruker EMS 104 EPR Analyzer (ASTM, 1996). Variations in radiation dose absorption were minimized by placing the samples within a uniform area of the radiation field, by irradiating them within a polypropylene container (4-mm wall) to absorb Compton electrons, and by using the same geometry for sample irradiation during the entire study.

To maintain product temperature, meat samples were transferred from refrigerated storage to the facility immediately prior to irradiation. Samples were kept at the set temperature of 4±2 °C during irradiation by injecting the gas phase of liquid nitrogen into the radiation chamber. There were six packages of chicken breasts per dose, and one 5-mm-diameter alanine dosimeter (Bruker Instruments, Germany) was inserted into each sample. The target doses were 0, 0.2, 0.5, 1.0, 2.0, 3.0, 4.0 and 5.0 kGy. Actual absorbed doses were measured by a Bruker EMS 104 EPR Analyzer (ASTM, 1996) to be 0, 0.18, 0.46, 0.88, 1.77, 2.69, 3.53, and 4.57 kGy with variation less than 7.1.

Immediately after irradiation, the chicken breasts were taken out from the radiation chamber and stored in a cooler filled with ice. It took less than 3 min to transport the irradiated meats from the radiation facility to the meat processing room at USDA's Eastern Regional Research Center, PA. The meat samples were divided into two parts equally and randomly for each dosage level; one for visible spectral measurement and another for HunterLab measurement. Following the recording of visible spectra and HunterLab values, the meat samples were re-packed. Half of the meat samples were left at USDA's Eastern Regional Research Center, PA, for HunterLab measurement, and the rest were taken to USDA's Beltsville Agricultural Research Center, MD, for visible spectral measurement. During the 3-h transport by car, the meat samples were kept in a plastic cooler filled with ice. The samples in both places were stored in a 0 °C cold room.

3.1. Spectroscopic measurements and data analysis

Sections of chicken meats (1 cm thick and 3.8 cm diameter) were cut from each chicken breast and sized to fit into the spectrophotometer's quartz-windowed

cylindrical cup. All the reflectance spectra were recorded on a scanning monochromator NIRSystems 6500 spectrophotometer (NIR Systems, Silver Spring, MD, USA) equipped with a rotating sample cup. Each spectrum was collected over the 400–2500 nm wavelength range at 2 nm intervals and 32 scans (Liu & Chen, 2000; Liu et al., 2000a, 2000b). After the measurement, the slices were packaged into polyethylene bags which were placed in a plastic cooler filled with ice, and transported to USDA's Instrumentation and Sensing Laboratory in Beltsville, MD. The plastic cooler was placed in a 0 °C cold room and dark environment. The following day (designated as day 1), visible spectra were obtained, and then the slices were returned to the storage condition until the next measurements were taken. The same measurement procedures were repeated on the third day after irradiation (day 3), the fourth day after irradiation (day 4), up through the 21st day (day 21).

The obtained spectra were imported into Grams/32 by using Grams/32 software (Galactic Industries Corp., Salem, NH, USA), and the second derivative spectra were calculated with the Savitzky–Golay derivative function and 11 smoothing points. All the evaluations of the intensities for the bands due to MetMb, OxyMb, and SulfMb species were made using the wavelength region between 458–520, 520–615, and 620–664 nm, respectively, from the individual second derivative spectrum (Liu & Chen, 2001). They are, respectively, denoted to $A_{485 \text{ nm}}$, $A_{560 \text{ nm}}$, and $A_{635 \text{ nm}}$.

3.2. Color measurement and analysis

Color measurements were also conducted immediately after irradiation and after 10 and 20 days storage at 0 °C using a HunterLab MiniScan XE colorimeter (Hunter Laboratory Inc., Reston, VA) with D65 illuminant and 10° standard observer. The instrument was calibrated against blank and white references prior to use. Two random readings (either side) per sample were taken and averaged. CIE L^* (lightness), a^* (redness), and b^* (yellowness) were measured. A numerical total color difference (ΔE) was calculated by

$$\Delta E = \left[(L^* - L^*_{\text{ref}})^2 + (a^* - a^*_{\text{ref}})^2 + (b^* - b^*_{\text{ref}})^2 \right]^{1/2} \quad (1)$$

the average values of non-irradiated controls were used as reference values.

Obviously, Eq. (1) represents the comprehensive contributions from the variations of three color indexes. Alternatively, to enhance the fraction of redness relative to those of yellowness and lightness, we rewrite the Eq. (1) as the following:

$$E^* = a^*/b^* + a^*/L^*. \quad (2)$$

3.3. Statistical analysis

Samples were completely and randomly assigned to the treatments. There were six replicates per dose. The effect of dose and storage, and the interaction between irradiation and storage, were analyzed using the General Linear Model procedure of SAS System, version 7 (SAS Institute, Inc., Raleigh, NC). The least significant difference (LSD) was used to compare differences between treatments. The linear relationship between dose and the color parameters was analyzed using regression analysis.

4. Results and discussion

4.1. Dose effect

Irradiation is an effective method to reduce microbial numbers, but also can significantly influence the color appearance of meat (Nanke et al., 1998, 1999; Thayer, 1993). Irradiated meat muscles have increased redness, and the degree of the increases due to irradiation varies depending on species, muscle type, and irradiation dose level (Ahn et al., 1999; Nanke et al., 1998, 1999).

Fig. 1 shows the representative visible reflectance spectra of the chicken breasts measured immediately after the irradiation process at 0.88 and 4.57 kGy, as well as unirradiated breasts. In the present study, the carcasses were well-bled and thus myoglobin is the primary heme pigmentation responsible for the color of meats (Francis & Clydesdale, 1975; Kinsman, Kotula, & Breidenstein, 1994; Lawrie, 1985; Price & Schweigert, 1987). Our systematic study on visible spectra of chicken meats under a variety of conditions, such as cooking, cold storage, wholesome and unwholesome, has revealed that the bands at 445, 485, 560, and 635 nm arise mainly from DeoxyMb, MetMb, OxyMb, and sulfmyoglobin (SulfMb) species, respectively (Liu & Chen, 2000; Liu et al., 2000a, 2000b). Spectral intensity variations of the peaks at 485, 560, and 635 nm likely indicate a dynamic conversion and reduction/oxidation reaction for myoglobin derivatives, for example, DeoxyMb, MetMb, OxyMb, and SulfMb.

In an earlier study, we reported that changes in the relative intensity ratios of $R_1 = A_{485 \text{ nm}}/A_{560 \text{ nm}}$ and $R_2 = A_{635 \text{ nm}}/A_{560 \text{ nm}}$, which are related to absorbances of the visible bands at 485 nm (MetMb), 560 nm (OxyMb), and 635 nm (SulfMb), could be used to monitor the variation of meat color under a variety of conditions (Liu & Chen, 2001). To observe the effect of irradiation dosage level on chicken meats and the subsequent storage process, the second derivative of visible reflectance spectra of chicken meats was calculated and then the intensities for the bands due to MetMb, OxyMb, and SulfMb species were estimated

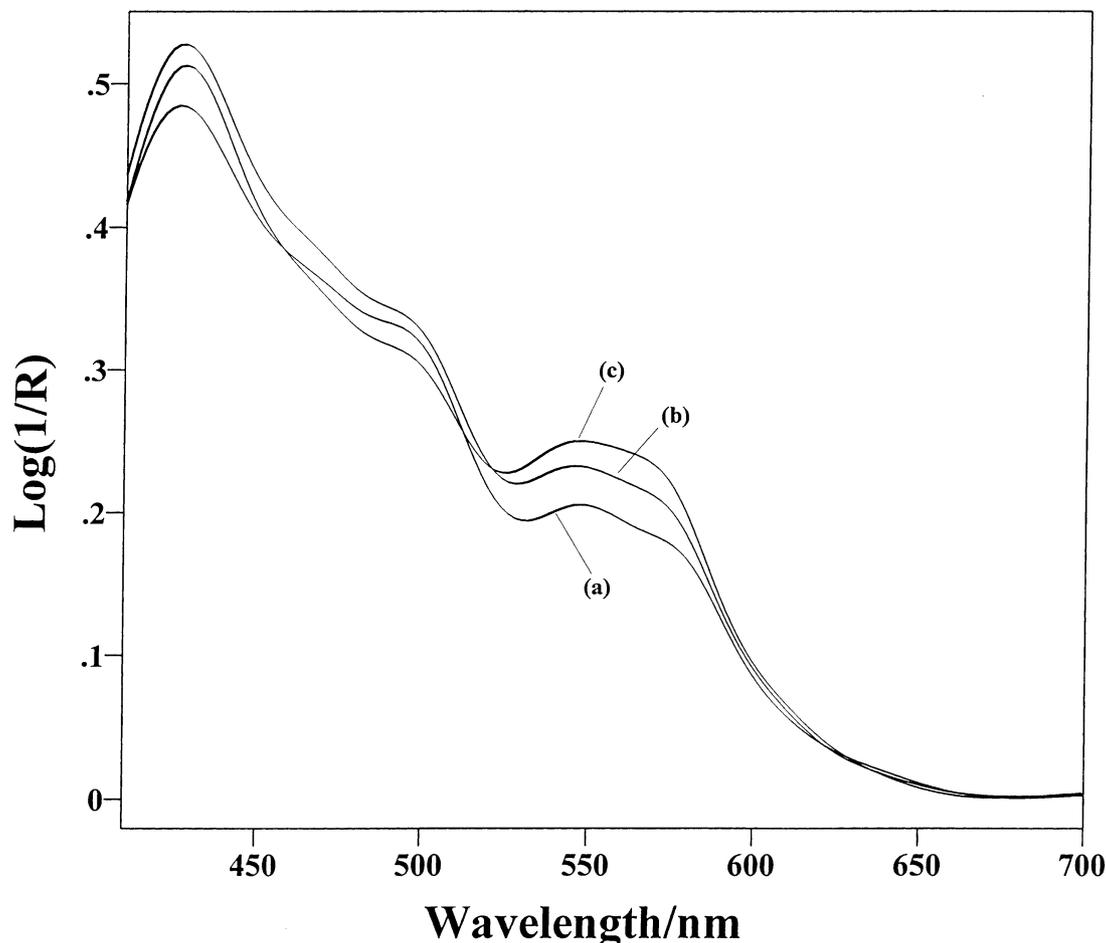


Fig. 1. Representative visible reflectance spectra of chicken breasts scanned immediately after the irradiation at (a) 0 kGy; (b) 0.88 kGy; (c) 4.57 kGy.

using the same strategy as a previous study (Liu & Chen 2001). The bands lower than 450 nm were not utilized due to the anomalies and distortions.

Fig. 2 plots the relative intensity ratios of $R_1 = A_{485 \text{ nm}}/A_{560 \text{ nm}}$ and $R_2 = A_{635 \text{ nm}}/A_{560 \text{ nm}}$ versus irradiation dosage level, linking the variations in the amount of MetMb (485 nm), OxyMb (560 nm), and SulfMb (635 nm) for individual meat, respectively. Generally, both the R_1 and R_2 values decrease with the increase of irradiation dose. It suggests that, with irradiation treatment, MetMb and SulfMb are likely reduced to OxyMb and DeoxyMb (Voet & Voet, 1995). The relative increase and accumulation of OxyMb species might be responsible for the meat redness. However, Fig. 2 shows the anomalies of both the R_1 and R_2 values for meats irradiated at lower dosages (0.18 and 0.46 kGy), likely due to the sample variations and the unaccounted contribution from DeoxyMb species. Detailed studies are necessary to examine the effect of lower irradiation dose on the structure of meats.

Table 1 compares the L^* , a^* , and b^* color indexes for irradiated chicken breast meats by irradiation dose. With the increase in irradiation dose, a^* (redness) value increased and b^* (yellowness) value decreased, while L^*

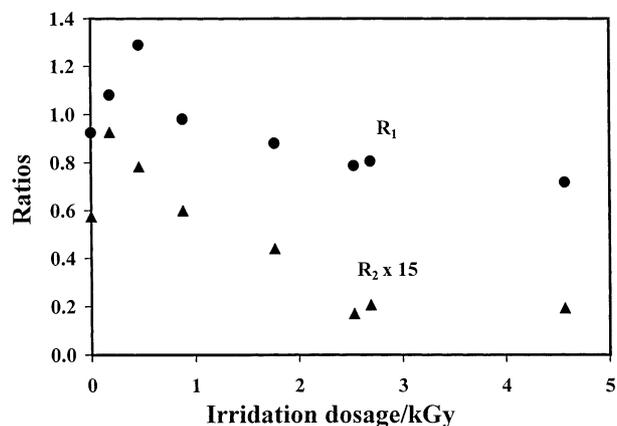


Fig. 2. Plot of the intensity ratios of $R_1 = A_{485 \text{ nm}}/A_{560 \text{ nm}}$ (circle) and $R_2 = A_{635 \text{ nm}}/A_{560 \text{ nm}}$ (triangle) in the second derivative spectra versus irradiation dosage. R_2 values were multiplied by 15 to fit the y -axis scale.

(lightness) value showed no significant variation. E^* , the fraction of redness relative to those of yellowness and lightness, increased clearly as dose increased, as did the total color changes (ΔE). Linear regression analysis using SAS demonstrated that the increase in a^* , E^* and ΔE and the decrease in b^* as a function of dose were

Table 1
Color characteristics of chicken breast meats immediately after irradiation

Dose (kGy)	0	0.18	0.46	0.88	1.77	2.69	2.53	4.57	LSD ^a
<i>a</i> *	6.7	7.0	6.5	6.6	8.1	9.8	8.6	9.9	1.4
<i>b</i> *	16.0	15.3	14.9	13.6	14.1	14.4	13.4	12.4	1.8
<i>L</i> *	50.7	51.5	52.0	52.1	50.3	49.0	49.9	49.9	2.4
ΔE	3.6	3.8	4.4	4.5	4.4	5.6	4.5	5.7	1.4
<i>E</i> *	0.56	0.60	0.57	0.63	0.74	0.90	0.83	1.01	0.14

^a Least significant difference (LSD) at *P* < 0.05.

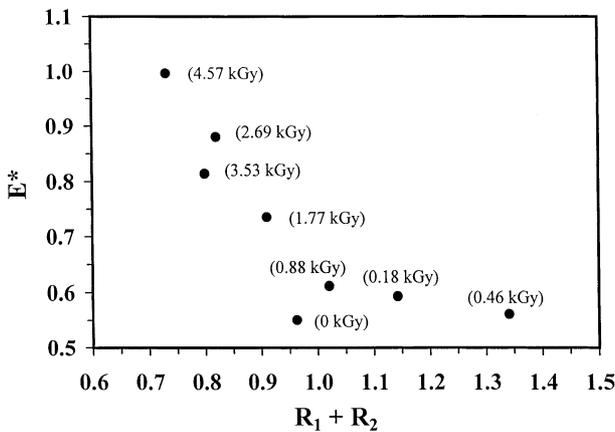


Fig. 3. Relationship between the combined *R*₁ and *R*₂ values and color index *E** in various irradiated meats. Numbers in parentheses indicate the actual irradiation dosage.

significant (*P* < 0.05). The changes in *a**, *b**, *E**, and ΔE revealed that chicken breast meats increased in redness, and decreased in yellowness, as dose increased.

There appears to be a relationship between the combined *R*₁ and *R*₂ values (calculated by the addition of *R*₁ and *R*₂ for each meat spectrum) and the corresponding color index *E** (shown in Fig. 3) for various meats at different irradiation levels. This indicates that the combination of *R*₁ and *R*₂ generally increases with the decrease in meat color, suggesting that irradiation process can enhance meat color as a result of production of OxyMb components.

4.2. Storage effect

During nonfrozen storage, raw meats undergo several changes that can affect their quality attributes (Kinsman et al., 1994; Lawrie, 1985; Price & Schweigert, 1987). These changes are reflected through color, tenderness, flavor, and juiciness of the meats. Among them, color is one of the primary sensory factors.

In a similar procedure to that described above, the intensities for the bands due to MetMb, OxyMb, and SulfMb components were estimated from the second derivative of visible reflectance spectra of irradiated

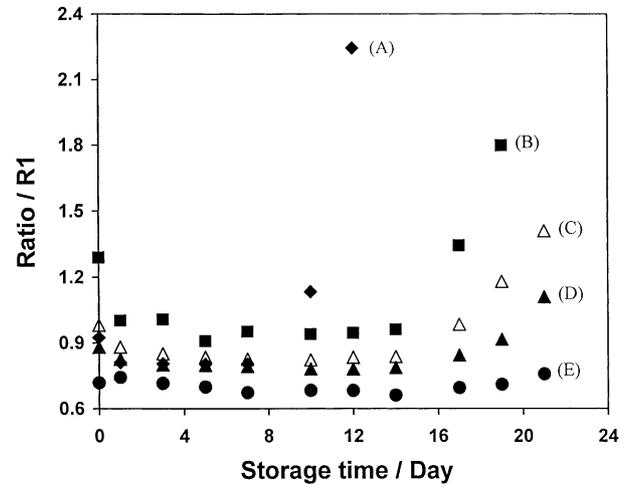


Fig. 4. Plot of the intensity ratio of *R*₁ = *A*_{485 nm}/*A*_{560 nm} in the second derivative spectra versus storage time, for the meats at the irradiation dosage of 0 kGy (A); 0.46 kGy (B); 0.88 kGy (C); 1.77 kGy (D); 4.57 kGy (E).

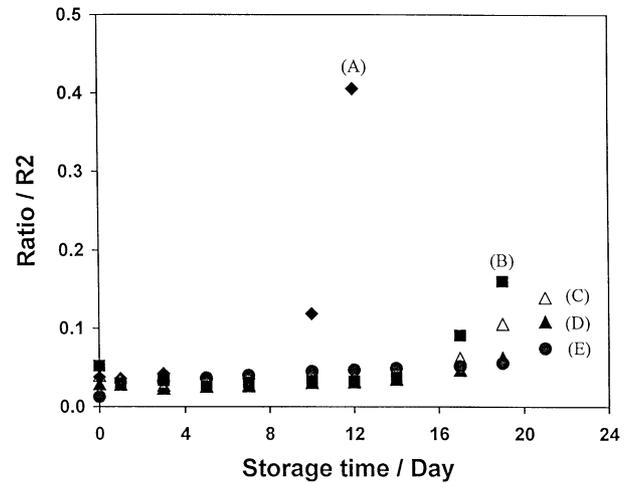


Fig. 5. Plot of the intensity ratio of *R*₂ = *A*_{635 nm}/*A*_{560 nm} in the second derivative spectra vs. storage time, for the meats at the irradiation dosage of 0 kGy (A); 0.46 kGy (B); 0.88 kGy (C); 1.77 kGy (D); 4.57 kGy (E).

chicken meats stored at 0 °C from Day 1 to Day 21. Then the relative intensity ratios of *R*₁ = *A*_{485 nm}/*A*_{560 nm} and *R*₂ = *A*_{635 nm}/*A*_{560 nm} were determined. Relationships between the relative intensity ratios of *R*₁ and *R*₂ versus storage time are plotted in Figs. 4 and 5, respectively. Notably, the trend of both *R*₁ and *R*₂ values strongly depends on the irradiation levels of meats. It indicates that an increase in either *R*₁ or *R*₂ of irradiated meats can be delayed 7–12 days compared with that in raw meats as the storage progresses. The result suggests that the production of MetMb and SulfMb components can be delayed as a result of irradiation. In other words, OxyMb maintains the steady-state, which, in turn, benefits the color appearance of meats in the storage period. Hence, the irradiation process not only enhances

Table 2
Color characteristics of chicken breast meats stored at 0 °C and 10 days after irradiation

Dose (kGy)	0	0.18	0.46	0.88	1.77	2.69	2.53	4.57	LSD ^a
<i>a</i> *	5.7	7.6	7.9	7.9	8.6	9.2	8.7	10.2	1.5
<i>b</i> *	16.1	16.4	16.0	16.0	15.3	15.9	15.1	14.7	1.7
<i>L</i> *	51.3	51.9	50.8	51.8	50.1	49.5	50.8	47.5	3.1
ΔE	3.0	4.5	4.0	4.8	4.6	5.8	5.6	7.1	1.9
<i>E</i> *	0.46	0.62	0.66	0.67	0.74	0.78	0.76	0.94	0.16

^a Least significant difference (LSD) at $P < 0.05$.

Table 3
Color characteristics of chicken breast meats stored at 0 °C and 20 days after irradiation

Dose (kGy)	0	0.18	0.46	0.88	1.77	2.69	2.53	4.57	LSD ^a
<i>a</i> *	8.4	8.5	6.5	7.5	7.8	9.5	8.0	9.7	1.5
<i>b</i> *	15.4	15.5	16.3	15.7	15.3	15.9	15.0	16.0	1.7
<i>L</i> *	49.7	50.7	51.9	51.3	53.1	49.3	52.3	50.0	2.6
ΔE	2.8	3.7	4.2	4.4	4.4	3.5	3.5	3.0	2.8
<i>E</i> *	0.72	0.72	0.53	0.64	0.65	0.79	0.69	0.80	0.13

^a Least significant difference (LSD) at $P < 0.05$.

the meat color, but also preserves color by slowing the accumulation of undesirable pigments.

Table 2 presents the color characteristics of the same chicken breasts stored in 0 °C on the 10th day after the irradiation. As irradiation dosage increased, *a**, *E** and ΔE values increased, while irradiation dose had no consistent effect on *b** and *L* values. The linear increase in *a**, *E** and ΔE were significant ($P < 0.05$) when analyzed using the linear regression model. Compared with Day 0 values as shown in Table 1, *a**, *b**, *L**, ΔE and *E** values show no significant changes. However, after 20 days of storage, the effect of irradiation dosages on *a**, *b**, ΔE and *E** largely disappears (Table 3). The results are in agreement with the results in Figs. 4 and 5.

5. Conclusions

This work has demonstrated the potential of visible spectroscopy and HunterLab measurement in studying the changes of meat structure and associated color characteristics. Relative intensity ratios of $R_1 = A_{485 \text{ nm}} / A_{560 \text{ nm}}$ and $R_2 = A_{635 \text{ nm}} / A_{560 \text{ nm}}$, which are related to absorbances of the visible bands at 485 nm (metmyoglobin), 560 nm (oxymyoglobin), and 635 nm (sulphyoglobin), decrease with the increase of irradiation dose. Meanwhile, values of R_1 and R_2 increase with the storage and the increments are dose-dependent. The results suggest that the relative amount of OxyMb species in irradiated meats begins to decompose 7–12 days later than raw meats. Furthermore, the magnitude of R_1

and R_2 values is found to be correlated with the relative amount of redness in meats.

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