EVALUATING QUALITY AND PALATABILITY CHARACTERISTICS OF BEEF SUBPRIMALS TREATED WITH LOW-DOSE IRRADIATION

A Thesis

by

JOHN LAWRENCE ARNOLD

Submitted to the Office of Graduate Studies of
Texas A&M University
in partial fulfillment of the requirements for the degree of

MASTER OF SCIENCE

December 2011

Major Subject: Animal Science

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Approved by:

Co-Chairs of Committee,	Jeffrey W. Savell
	Kerri B. Harris
Committee Members,	Rhonda K. Miller
	Davey B. Griffin
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ABSTRACT

Evaluating Quality and Palatability Characteristics of Beef Subprimals Treated with Low-Dose Irradiation. (December 2011)

John Lawrence Arnold, B.S., Texas A&M University

Co-Chairs of Advisory Committee: Dr. Jeffrey W. Savell
Dr. Kerri B. Harris

This study was conducted to evaluate the impact of low-dose irradiation on beef quality and sensory attributes. Beef top rounds (n=10), bottom round flats (n=10), and knuckles (n=18) were collected from a commercial meat processing facility. Paired subprimals were randomly assigned to treated (irradiated) and control (non-irradiated) groups. The treated group was irradiated with a surface dose of 1-1.5 kGy. Following treatment, subprimals were fabricated into thirds and randomly assigned to one of three aging days (0, 14, or 21). After the aging period, subprimal pieces were trimmed, cut into 2.54 cm steaks, and the resulting trimmings were ground to produce 0.113 kg patties. Steaks and patties were randomly assigned to one of two shelf-life days (2 or 4). During retail display, L*, a*, and b* measurements were taken for raw steak and patty color (0, 2, and 4 day). Steaks and patties from all treatments were evaluated by a trained sensory panel for flavor, basic taste, mouthfeel, after-taste, and texture attributes. Steaks and patties were cooked on open-faced grills, and used for cooked color analysis. Samples from across treatments were used for thiobarbituric acid reactive substances (TBARS) analysis. Differences in raw steak and patty color were seen among samples.

No differences were evident between cooked steak samples; however, cooked patty color differences were observed. Further, numerous palatability attributes were impacted by treatment. Additionally, differences in TBARS values were seen. These results suggest that if chilled subprimals or carcasses were treated with low-dose e-beam irradiation, quality and palatability characteristics could be negatively impacted.

DEDICATION

I dedicate this thesis to my grandpa, John Dwight Pentecost. You have provided me with constant love and support, and I am very grateful. Thank you for encouraging me to be the best that I can be. You have truly inspired me, and I am blessed to have you in my life.

ACKNOWLEDGEMENTS

First, I thank Dr. Jeff Savell, for providing me the opportunity to attend graduate school in meat science. I have been given numerous opportunities that I would not have had otherwise. Next, I thank Dr. Kerri Harris for her continuous support and encouragement that helped to guide me through this project and my graduate career. She was instrumental in the success of this project. Next, I appreciate Dr. Rhonda Miller for her unwavering support, patience, and guidance. Finally, I thank Dr. Davey Griffin for being a member of my committee and giving me numerous opportunities while here at Texas A&M University.

Much thanks goes to the staff of the Electron Beam Center at Texas A&M University. Their continued patience and guidance provided me with a unique learning experience. This project would have not been possible without their help.

I also thank the numerous graduate and undergraduate students who assisted with this project. Without the help of Ashley Haneklaus, Miles Guelker, Carson Ulbrich, Cody Labus, Lindsey Mehall, Gatlan Gray, Adria Greyson, Jacob Lemmons, Melanie Moore, Russell McKeith, Haley Grimes, Kayla Nelson, Leslie Frenzel, Amanda Smith, Amanda Harbison, Julianne Riley, Maggie Albrecht, and Jenny Bohac, I would not have been able to complete this project.

Last, but not least, I thank my wonderful family for their love and support throughout my time at Texas A&M University. To my parents, Donn and Gwen, I thank you both for molding me into the person that I am today. I wouldn't be here without your love and support. To my sister, Kara, thank you for your continuous encouragement. You helped to push me through all the tough times.

This project was funded by The Beef Checkoff.

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CHAPTER I

INTRODUCTION

The meat industry is constantly searching for microbial interventions or processing aids to help reduce pathogens, thereby reducing the probability of a foodborne disease outbreak and subsequent economic losses associated with outbreaks. It is estimated that each year approximately 48 million Americans get sick, 128,000 are hospitalized, and 3,000 die of foodborne diseases (Centers for Disease Control and Prevention, 2011). Food safety issues among the beef industry are frequent, affect the health of numerous individuals, and cost the United States billions of dollars.

Numerous interventions have been developed to help minimize microbiological contamination on beef products. Although, food has been safely irradiated in the United States for more than thirty years, there is limited application of irradiation to fresh beef. Research has been conducted to assure consumers that the use of food irradiation, according to governmental regulations, is safe and does not increase human exposure to radiation. Energy used in this process is not strong enough to cause food to become radioactive (Food Safety and Inspection Service, 1999)

Food irradiation is the process of treating food with radiant energy to eliminate microorganisms to promote food safety and reduce spoilage (Food Safety and Inspection Service, 1999). Electron beam (e-beam) irradiation is a stream of high-energy electrons.

This thesis follows the style of *Meat Science*.

These electrons are produced by an electron generator and expelled from an electron gun. E-beam irradiation, unlike gamma-ray irradiation, is unique because the electron generator can be turned-off between uses to minimize associated workplace dangers. No radioactive material is involved with e-beam use, although some concrete shielding is necessary to protect workers. However, due to the non-radioactive nature of the e-beam, facilities containing this equipment are much less extensive than those containing radioactive irradiation technologies (Centers for Disease Control and Prevention, 2005). The accelerated electrons generated from e-beam irradiation reduce microorganism levels by damaging the nucleic acid contained in the microbial DNA. Commonly, electron energy can interact with adjacent molecules within the microorganism, such as water, which does further damage to the genetic material (Pillai, 2004).

Monitoring the amount of irradiation applied to a food product is important to ensure that the use of irradiation as a food safety intervention is in compliance with United States Department of Agriculture's Food Safety and Inspection Service (USDA-FSIS) regulations. The amount of energy transferred to the product being irradiated is measured in a unit called a Gray (Gy) (Centers for Disease Control and Prevention, 2005). Adjusting the speed at which the product passes under the e-beam controls the dose applied to the irradiated product (Pillai, 2004).

Irradiation has been found to be very successful in the reduction and elimination of food microorganisms. The use of low-dose irradiation has been found to reduce the presence of *Escherichia coli* O157:H7, which is a prominent pathogen found on beef cuts and trimmings (Fu, Sebranek, & Murano, 1995). Success shown by low-dose irradiation sparked the beef industry to submit a petition to the USDA-FSIS to approve low-dose carcass irradiation as a processing aid (American Meat Institute, 2005).

Many beef quality and sensory attributes might be altered when using low-dose irradiation. In the event that the use of low-dose irradiation is used as a processing aid, more information is needed to allow the beef industry to better understand the consequences associated with low-dose irradiation. The objectives of this study were to determine the impact of low-dose carcass irradiation on the quality characteristics of beef subprimals and trimmings and to determine the impact of low-dose irradiation on palatability characteristics of steaks and ground beef produced from treated subprimals and trimmings.

CHAPTER II

REVIEW OF LITERATURE

2.1. Lipid oxidation

Lipid oxidation is a major cause of quality deterioration in meat products, due to unfavorable changes in meat flavor, color, and texture (Kanner, 1994). The reduction of oxygen produces several compounds, better known as free radicals, which play an important role in the oxidation of meat products. Superoxide anion radical, perhydroxyl radical, hydrogen peroxide, and hydroxyl radical are examples of free radicals that are by-products of lipid oxidation. Free radicals have unpaired electrons that make them very unstable and highly reactive and are capable of oxidizing lipids and proteins leading to cell death and tissue damage (Morrissey, Sheehy, Galvin, Kerry, & Buckley, 1998). Lipid oxidation goes through a free radical chain reaction involving three stages: initiation, propagation, and termination.

During the initiation stage, a hydrocarbon loses a hydrogen to form a fatty acyl radical. Unsaturated and polyunsaturated fatty acids are more vulnerable to this step due to the presence of double bonds (Morrissey et al., 1998). The initiation reaction is sparked by radicals or other transition metal-oxygen complexes such as iron. Each initiation process yields two free radicals that contribute in the chain reaction mechanism. The propagation stage begins when the fatty acyl radical reacts with oxygen at the fatty acids double bond to form a peroxyl radical, which propagates the fatty acid oxidation chain reaction. Lipid hydroperoxide is produced during the propagation of the chain reaction. This compound will continue to react with transition metals, iron and copper, to form peroxyl and alkoxyl radicals (Morrissey et al., 1998). The final stage of lipid oxidation is termination. During the termination phase, two radicals interact and form less reactive by-products such as aldehydes, alcohols, and hydrocarbons. When there are no radicals available to interact with oxygen lipid oxidation ceases (Morrissey et al., 1998).

Lipid oxidation occurs in meat in both triacylglycerols and phospholipids. The configuration and number of double bonds in the fatty acids are directly related to the rate of oxidation in the meat system. As the number of double bonds increases the rate of lipid oxidation increases. Oxygen reacts with the double bond in fatty acids to form peroxide linkages (Morrissey et al., 1998). In the production of ground beef, meat trimmings are ground, which disrupts the tissue layers and exposes the phospholipid layer to oxygen resulting in an increased rate of oxidation (Pearson, Love, & Shorland, 1977).

Thiobarbituric acid-reactive substances (TBARS) can be measured to indicate the extent of lipid peroxidation in raw meat (Raharjo, Sofos, & Schmidt, 1993). Thiobarbituric acid (TBA) reacts with malonaldehyde (MDA) which is a secondary product from lipid peroxidation. This reaction results in the formation of red color that can be detected spectrophotometrically.

Numerous studies have been conducted to compare the TBARS values of irradiated and non-irradiated meat products. Chen et al. (2007) performed an experiment that assessed the changes in beef quality with different gamma irradiation doses and storage times. Beef *M. semitendinosus* were fabricated into four pieces. One piece was utilized as the control (0.0 kGy) and the other three pieces were aerobically packaged individually and irradiated with a ^{60}Co source to levels of 1.13, 2.09, and 3.17 kGy. TBARS values were measured in triplicate following the method described by Buege and Aust (1978). TBARS values were reported as 1 μg of malondialdehyde per gram. Following irradiation, the muscle pieces were removed from packaging and used to determine TBARS values. Non-irradiated control samples exhibited significantly lower ($P<0.05$) initial TBARS values (4.47 μg/g) than irradiated samples (6.17, 6.55, and 7.35 μg/g at doses of 1.13, 2.09, and 3.17 kGy, respectively) that were aerobically packaged. For day 0, TBARS values increased as the dose of irradiation increased. TBARS values of all the samples increased after 10 days of storage, however the values were lower ($P<0.05$) for irradiated samples than control samples.

Kim et al. (2002b) conducted a study that compared the changes of lipid oxidation in irradiated meat from different animal species and the effects of packaging and storage time on lipid oxidation. Beef loins were collected, cut into 3 cm thick steaks, and individually packaged in either polyethylene oxygen-permeable or vacuum bags. The packaged product was irradiated at 0.0 or 3.0 kGy using a Linear Accelerator. TBARS values were measured by the modified method of Buege and Aust (1978) and expressed as mg of malondialdehyde per kg of sample. Animal species, irradiation dose, storage time, and packaging methods significantly impacted the TBARS values of meat. Irradiation increased the TBARS values in beef that was aerobically packaged. TBARS values on day 7 were significantly higher than those on day 0. With the implementation of vacuum packaging, no differences in TBARS values between day 0 and day 7 existed. Additionally, vacuum-packaged product showed lower TBARS values than aerobically packaged samples on day 7.

An experiment was performed by Fu et al. (1995) to evaluate the effects of low and medium dose irradiation on the quality characteristics of beef steaks and ground beef. Beef ribeye rolls were collected from a commercial processor and cut into 2.5 cm thick steaks. Additionally, ground beef was purchased from the retail sector and separated into 25 g portions to be used as experimental units. Samples were divided into five groups, assigned to different irradiation processing treatments, and irradiated using a Linear Accelerator. Low or high dose rates were produced by changing the power level and conveyor speed. Doses used were 0.6 kGy and 1.5 kGy, both at low and high dose rates. Non-irradiated samples were used as controls. The same method was used for the irradiation of ground beef, except the doses were 0.8 kGy and 2.0 kGy, with both low and high dose rates. All treatment combinations for steaks and patties were evaluated immediately after irradiation (day 0). Selected samples were also stored for 7 days to simulate consumer storage. Lipid oxidation was measured using the method of Tarladgis et al. (1960). For steaks, thiobarbituric acid (TBARS) values increased after 7 days of storage for all samples, with aerobic packaging producing more lipid oxidation than vacuum packaging. TBARS values for ground beef were greater than 2.0 mg/kg at day 0 and there was no significant difference ($P>0.05$) in values between treatment groups. Irradiated samples exhibited higher TBARS values than control samples after 7 or 9 days storage.

2.2. Meat color

Meat color is a result of the concentration of pigments, their chemical states, and the light-scattering properties of the meat (McDougall, 1983). Hemoglobin and myoglobin are the two main pigments in meat. Hemoglobin, a pigment in blood and is used to transport oxygen from the lungs to the muscles. Myoglobin stores oxygen and is the pigment in muscle. In muscle tissue, 80 to 90 percent of the total pigment is composed of myoglobin. Myoglobin consists of a globular protein portion and a nonprotein portion called a heme ring. The heme component of the myoglobin is important because the color of the meat is moderately dependent on the oxidative state of the iron molecule within the heme ring.

The reaction of myoglobin with certain compounds results in color changes in meat. Iron associated with myoglobin can become oxidized. When the iron is oxidized (ferric state) it cannot interact with specific molecules of interest, including oxygen. When the iron is in its reduced state (ferrous state) it will combine with molecules such as oxygen. When this occurs, the reduced pigment reacts with oxygen and forms a pigment called oxymyoglobin. This pigment is responsible for the bright cherry red color in meat. The deoxymyoglobin pigment, characterized by a dark purple color, is produced when the myoglobin is deprived of oxygen. Lastly, metmyoglobin is the oxidized form of myoglobin. The chemical state of the iron is changed from ferrous to ferric. This pigment produces the brown color present in meat products that have oxidized (Forrest, Aberle, Hedrick, Judge, & Merkel, 1975).

Irradiating fresh beef at doses sufficient to reduce pathogen load may result in quick development of brown, green, or in some cases, bright red pigments (Millar, Moss, & Stevenson, 1996; Tappel, 1957). At lower doses of irradiation, color changes occur which are a result of the myoglobin concentration, the state of the myoglobin before irradiation, the proximate conditions of the myoglobin, and the temperature and atmosphere during irradiation (Brewer, 2004). It is believed that improved shelf-life can be obtained from the treatment of low-dose irradiation if the reaction between color and irradiation can be minimized (Thayer, 1993).

Numerous studies have been conducted to better understand the impact of irradiation on the color of meat. Arthur et al. (2005) performed an experiment to evaluate the impact of electron beam irradiation on beef quality. The study was developed to simulate the effect of applying electron beam irradiation to chilled beef carcasses. Flank steaks were collected from a commercial processor, vacuum packaged, and transported to the irradiation facility. Flank steaks were assigned randomly to one of five different treatments. The surface fat on the external side of the flanks was trimmed to different thicknesses to give five different treatment penetrations. Treatments were 75% muscle penetration, 50% muscle penetration, 25% muscle penetration, 10% muscle penetration, and 0% penetration (control). Samples were irradiated with a Dynamitron at a dosage of 1.0 kGy. Portions of the flank steaks were removed for cooking and the remaining portion was cut in half horizontally to expose fresh surfaces and was allowed to convert from deoxymyoglobin to myoglobin. Next, Hunter colorimeter measurements were taken in duplicate, 30 minutes and 2 hours after cutting. It was discovered that

Hunter color values were affected (*P*<0.05) by treatment penetration. However, the impact on L* and b* were not linear. The effects of treatment penetration on a* values were generally linear and had a dose-related pattern.

Within the same study, quality characteristics for irradiated ground beef were evaluated. Boneless chuck short ribs were fabricated into 2 cm thick strips, vacuum packaged, and transported to the irradiation facility. A portion of the trimmed short ribs was uniformly irradiated and the remaining sample was left untreated to serve as the control. Different blends of ground beef were produced using the irradiated and non-irradiated meat strips. Batches included 100%, 50%, 25%, 10%, 5%, and 0% treated short rib components. The different ground beef formulations were formed into 113.4 g patties, blast frozen, and packaged in aerobic packaging material. Patty color was evaluated after 20 and 40 days of frozen storage. At each frozen storage time, Hunter colorimeter measurements were taken in duplicate for four randomly selected patties of each treatment after 18 hours of thawing. The proportion of irradiated trim did not affect any color measurements of the ground beef patties (*P*>0.05).

Another study conducted by Kim et al. (2002a) tried to identify changes in color values in irradiated meats from different animal species. The L*, a*, and b* values of different species were compared to determine the impact that irradiation, packaging, and storage time had on meat quality. Beef loins were collected, cut into 3 cm thick steaks, and individually packaged in either polyethylene oxygen-permeable or vacuum bags. The packaged product was irradiated at 0.0 or 3.0 kGy using a Linear Accelerator. Samples were stored for 7 days and evaluated for color on day 0 and day 7. Color values were measured on the surface of the meat samples using a LabScan colorimeter. An average value from two random locations on each sample surface was used for analysis. It was found that L* values of irradiated beef decreased significantly after 7 days of storage and treated beef had lower L* values than non-irradiated after 7 days of storage. Additionally, L* values were not affected by irradiation in vacuum packaged product. At storage day 0, irradiation decreased a* values in both aerobic and anaerobic packaging systems. Irradiation caused b* values in beef to decrease at storage day 0 in aerobic packaging. Overall, the color change exhibited in beef products by irradiation was more apparent in aerobic packaging than in vacuum packaging and L*, a*, and b* values of beef were generally affected by both irradiation and storage day.

An experiment was performed by Millar et al. (2000) evaluating the effect of ionizing radiation on the color of meat. M. *longissimus dorsi* samples were collected from beef carcasses. Samples were cut into steaks, placed in polystyrene trays, and wrapped in oxygen permeable film. Ten samples were irradiated using a ^{60}Co source to an estimated dose of 5.0 kGy. Following treatment, sample color was evaluated using a Monolight spectrophotometer. Color evaluation was repeated on days 2, 3, 4, 5, 6, and 7. After day 7 color measurements were taken, the overwrap film was removed, a 1 cm thick slice was removed from the exterior surface, the overwrap film was replaced, and the color of the freshly cut slice was taken to obtain a color measurement representative of the internal pigment state. It was discovered that for the exterior surface, the L* values for the control samples were significantly higher than the irradiated samples on day 1. Additionally, L* values for treated beef increased with storage time with a statistically significant (*P*<0.05) linear slope. The a* values for the external surface of treated beef were significantly (*P*<0.001) lower than control samples on each day of storage. The a* values for irradiated beef did not change significantly during storage, however the a* values for the control samples showed a significant (*P*<0.05) linear decrease with storage time. The b* values for the external surface of treated beef were significantly lower than control samples on days 1, 2, 4, 5, 6, and 7 of storage.

When looking at the results for the internal color measurements, the L* values for freshly cut beef samples were higher than the exterior surface. For the freshly cut surface, the L* values for both the control and treated beef samples were significantly higher than their respective exterior surfaces. No significant a* differences were seen on the freshly cut samples due to irradiation. Lastly, b* values for the freshly cut surface of the control samples were not significantly different from the irradiated samples.

2.3. Sensory evaluation

Arthur et al. (2005) performed an experiment to evaluate the impact of electron beam irradiation on the sensory attributes of beef. The study simulated the effect of applying electron beam irradiation to chilled beef carcasses. Flank steaks were collected from a commercial processor, vacuum packaged, and transported to the irradiation facility. Flank steaks were assigned randomly to one of five different treatments. The fat on the external side of the flanks was trimmed to different thicknesses to give five different treatment penetrations. Treatments were 75% muscle penetration, 50% muscle penetration, 25% muscle penetration, 10% muscle penetration, and 0% penetration (control). Samples were irradiated with a Dynamitron at a dosage of 1.0 kGy. Following treatment, flank steaks were stored for an additional 12 to 14 days and then cooked and evaluated for sensory attributes. A section was obtained from the center of the flank steak and then cut into cubes. The cubes were stir-fried at 177 °C for 5.5 minutes. Samples were evaluated by a 10-member trained descriptive attribute sensory panel for six attributes: beef aroma intensity, off-aroma, tenderness, juiciness, beef flavor intensity, and off-flavor (8 = extremely intense, none, extremely tender, extremely juicy, extremely intense, and none, respectively; and 1 = none, intense, extremely tough, extremely dry, none, and extremely intense, respectively). Following cooking, panelists evaluated three cubes. It was determined that none of the flank steak sensory attributes were impacted ($P<0.05$) by any treatment.

Additionally, quality characteristics for irradiated ground beef were evaluated. Boneless chuck short ribs were fabricated into 2 cm thick strips, vacuum packaged, and transported to the irradiation facility. A portion of the trimmed short ribs was uniformly irradiated and the remaining sample was left untreated to serve as the control. Different blends of ground beef were produced using the irradiated and non-irradiated meat strips. Batches were created by utilizing different proportions of treated meat in the final formulations. Batches included 100%, 50%, 25%, 10%, 5%, and 0% treated short rib components. The different ground beef formulations were formed into 113.4 g patties, blast frozen, and packaged in aerobic packaging material. Ground beef patties were evaluated after 20 and 40 days of frozen storage. Patties were thawed and cooked on grills for 3.75 minutes at a grill temperature of approximately 177 °C. Cooked samples were cut into 12 wedges and panelists were served two wedges for analysis. Samples were evaluated by a 10-member trained descriptive attribute sensory panel for the same six attributes that were evaluated for steaks.

It was discovered that all patty sensory attributes were affected ($P<0.05$) by proportion of irradiated trim. For ground beef aroma intensity and beef flavor intensity, the 100% irradiated treatment batch received less favorable ratings. This makes it apparent that the trained panel was capable of detecting an aroma and flavor that could be attributed to treatment. Panelists did not detect a difference between the control (0%) and either of the 5% or 10% treatment batches. Off-flavor ratings were lowest ($P<0.05$) for the 100% irradiated samples. Both the 100% and 50% treated samples had more ($P<0.05$) off-flavor and off-aroma than did all the other treatment batches. It was found that tenderness and juiciness ratings were lowest ($P<0.05$) for the 100% samples, but differences between other treatment groups were not linear or dose related.

A study was conducted by Murano et al. (1998) to explore the effect of irradiation atmosphere, irradiation temperature, storage atmosphere, and storage time on the sensory characteristics of ground beef patties. Additionally, their impact on shelf-life of raw ground beef patties was determined. Fresh ground beef was collected and 100 g patties were formed. Ground beef patties were divided into three different batches and each batch was divided into three groups according to packaging treatment. The first batch was packaged by placing patties onto polyfoam trays and covering them with polyolefin stretch, oxygen permeable overwrap film. The second batch was paged under vacuum by placing each sample in a high barrier polyethylene pouch. Lastly, the third batch was packaged under oxygen permeable overwrap followed by inserting the sample inside a polyethylene pouch and packaging it under vacuum. Samples were irradiated at a target dose of 2.0 kGy by electron beam. Following treatment, the third batch was removed from the polyethylene pouch. Following treatment, patties were cooked by grilling from the frozen state until an internal temperature of 74 °C was reached. Sensory evaluation was conducted to determine how cooked ground beef patty flavor, texture, juiciness, and aftertaste varied over six irradiated samples and to a non-irradiated control.

It was found that after one day the samples irradiated under anaerobic packaging conditions demonstrated increased juiciness, while those irradiated under vacuum but stored under air received higher tenderness scores. Also, both control and treated patties evaluated after 7 days of storage showed no differences for all attributes.

Lefebvre et al. (1994) performed an experiment that tried to determine an optimal radiation dose of treatment in order to extend shelf-life without impacting product qualities. Three batches of ground beef were purchased from the retail sector. Samples were packaged in polyethylene bags and irradiated at doses of 0.0, 1.0, 2.5, and 5.0 kGy by a UC-15 irradiator. Samples were stored for up to 22 days after treatment. A group of 10 non-expert panelists examined the sensory properties of irradiated beef samples. Odor, color, texture, and flavor of cooked samples were evaluated. Beef samples were fried for 4 to 5 minutes and warmed in a microwave oven before serving. The panel was asked to score the differences or similarities between the control, the irradiated, and the fresh reference beef samples. The reference sample was given a value of 5. Any score that fell between 5 and 9 indicated a preference for the sample and a score that fell between 1 and 5 indicated a sample less appreciated.

On day 0, control samples produced a score of 4.6, 1.0 kGy samples scored a 4.3, 2.5 kGy samples received a score of 3.9, and the 5.0 kGy samples scored a 3.5. Additionally, the flavor of the cooked reference samples obtained scores of nearly 5 throughout the evaluation process. It is apparent that the application of irradiation imparted unfavorable flavors to the beef samples. The lower the dose of irradiation, the better the scores were. In contrast, lower doses of irradiation caused the product to acquire an undesirable flavor due to spoilage. The difference in texture between treated samples and control samples were not significant, and remained stable throughout the project.

CHAPTER III

MATERIALS AND METHODS

3.1. Dosimetry trials

Subprimals used for dosimetry trials complied with Institutional Meat Purchase Specifications (IMPS) as described by USDA (2010). Beef round, top (inside), untrimmed (IMPS # 168), beef round, outside round (flat) (IMPS # 171B), and beef round, sirloin tip (knuckle), peeled (IMPS # 167A) were purchased from a local wholesaler. Subprimals were irradiated at the National Center for Electron Beam Research, Texas A&M University, College Station, Texas.

Dosimetry trials were conducted in three phases. In the first phase, the surface dose was measured to determine the speed at which the subprimals should be exposed to the electron beam to produce an average surface dose of 1.0-1.5 kGy. On each subprimal, nine Kodak BioMax (Eastman Kodak Company, Rochester, NY) alanine dosimeter strips were placed on the external surface (Figure 1) and wrapped with Saran Wrap (S. C. Johnson, Racine, WI). The subprimals were irradiated with a single overhead electron beam expelled from a 10-MeV linear accelerator (Titan Corp., San Diego, CA). Following treatment, the dosimeter strips were removed, the subprimals were flipped, nine more dosimeter strips were placed on the opposite surface, and the subprimals were wrapped with Saran Wrap. Following treatment, the dosimeters were analyzed for dose with an e-scan alanine dosimeter reader (Bruker BioSpin Corp.,

Figure 1
Surface dosimeters

Billerica, MA). This process was repeated until the desired dose, 1.0-1.5 kGy, was obtained and the speeds were recorded for each of the three subprimals.

In the second phase, the internal dose was measured to understand the penetration characteristics of the irradiation. On each subprimal, nine locations evenly spaced across the surface of the subprimals were identified, and a knife was used to pierce a hole toward the center of the subprimal at a 45° angle (Figure 2) to prevent the dosimeters from overlapping. Next, three alanine pellet dosimeters (Far West Technology, Inc., Goleta, CA) were separated approximately 1.27 cm apart and wrapped in Glad Cling Wrap (The Glad Products Co., Oakland, CA)(Figure 3). This process was repeated until sufficient dosimeter packets were made. The dosimeter packets were inserted into the nine holes, leaving the most proximal dosimeter pellet flush with the surface of the cut. The subprimals were treated with a single overhead electron beam expelled from a 10-MeV linear accelerator. The dosimeter packets were removed, the subprimals were flipped, nine more holes were cut, and dosimeter packets were inserted into the opposite side. Following treatment, the dosimeter pellets were removed from the Cling Wrap and their identity (proximal, intermediate, and distal) was maintained. The dosimeters were analyzed for dose with a dosimeter reader and their corresponding values were recorded. Following the second phase, it was found that the dose of irradiation was still increasing at the most internal dosimeter.

The third phase was conducted to elaborate on the second phase and to better understand the penetration of irradiation into the subprimals. On each subprimal, the thickest point was identified and two holes were cut toward the center of the subprimal

Figure 2
Subprimal preparation for internal dosimeters

Figure 3
Pellet dosimeters in wrapping for internal dose measurement

at a 45° angle. Next, eight alanine pellet dosimeters were separated in a straight line with approximately 1.27 cm separation and individually heat sealed in a plastic bag (Figure 4). The dosimeter packets were inserted into the two holes leaving the most proximal dosimeter pellet on the surface of the cut. The subprimals were passed through a single overhead electron beam expelled from a 10-MeV linear accelerator. The two dosimeter packets were removed from the subprimals, taken out of the plastic bag, and analyzed for dose with a dosimeter reader.

3.2. Carcass selection

A total of nine carcasses were selected from one commercial beef processor. Carcasses were selected to exhibit the following characteristics: USDA Select (USDA, 1997), USDA Yield Grade 2 (USDA, 1997), "A" maturity (USDA, 1997), have an appropriate hot carcass weight (317.5 to 408.2 kg), and be free of any other defects including bruises, calloused eye, blood splash, dark cutter, or major fat tears. Individual carcass data can be found in Table 1. Carcasses that qualified for selection were appropriately identified.

3.3. Subprimal collection

Subprimals collected for this study complied with Institutional Meat Purchase Specifications (IMPS) as described by USDA (2010). Beef round, top (inside), untrimmed (IMPS # 168, n=10), beef round, outside round (flat) (IMPS # 171B, n=10), and beef round, sirloin tip (knuckle) (IMPS # 167, n=18) were identified and tagged on

Figure 4
Pellet dosimeters bagged for internal dose measurement

Table 1. Carcass data collected on each beef carcass selected for this study

Animal #	Fat thickness (cm)	Ribeye area (cm^2)	Carcass weight (kg)	USDA Yield grade[a]	Marbling score[b]
1	0.5	83.9	405.1	2.6	370
2	0.5	89.0	344.1	2.0	370
3	1.0	96.1	359.3	2.1	380
4	0.8	90.3	335.7	2.2	370
5	1.0	98.7	375.1	2.1	350
6	0.5	93.6	370.1	2.0	330
7	0.5	83.9	319.1	2.0	350
8	0.5	98.7	365.1	2.0	360
9	1.0	99.4	359.5	2.0	340

[a] USDA (1997)

[b] Slight 0-90 = 300-390

the exterior of the carcass to assure identification integrity through fabrication. Following fabrication, subprimals were vacuum packaged and transported to Rosenthal Meat Science and Technology Center, Texas A&M University, College Station, TX via insulated containers. Upon arrival, subprimals were stored for 2 days under refrigerated conditions (2-4 °C) until treatment.

3.4. Subprimal treatment

Subprimals from each side (right/left) of the carcass were randomly divided into a control group (non-irradiated) and a treated group (irradiated). The subprimals designated for irradiation were treated at the National Center for Electron Beam Research, Texas A&M University, College Station, TX. Three Kodak BioMax alanine dosimeter strips were placed on the fat surface of each subprimal at a level that was considered to be thick, thin, and intermediate; and the cuts were wrapped in Saran Wrap (Figure 5). Bottom rounds were passed through an electron beam expelled from a 10-MeV linear accelerator at 0.24 meters per second (MPS), top rounds were treated at 0.23 MPS, and knuckles were treated at 0.24 MPS. Following treatment, the dosimeter strips were removed and analyzed for absorbance to ensure the target surface dose (1.0-1.5 kGy) was achieved.

3.5. Fabrication

Subprimals (irradiated and non-irradiated) were initially cut into three equal parts. The inside rounds were cut into thirds to produce cranial, intermediate, and caudal

Figure 5
Dosimeter strip placement for final treatment

portions (Figure 6). The bottom round flats were cut into thirds to generate proximal, intermediate, and distal portions (Figure 7), and the knuckles were fabricated into thirds to produce lateral, intermediate, and medial portions (Figure 8). Next, the subprimal pieces were randomly assigned by the cutting personnel to three aging days (0, 14, or 21). The pieces not designated for day 0 were vacuum-packaged and stored in the absence of light for either 14 or 21 days under refrigerated conditions (2-4 °C). Following the designated storage times, the subprimal pieces were trimmed of all external fat, trimmings were produced by removing approximately 1.27 cm of exposed surface lean, and 2.54 cm steaks were cut. After the appropriate numbers of steaks were cut, the remaining lean portion was combined with the lean trim. The trimmings were coarse ground through a 0.95 cm plate and hand-mixed, fine ground through a 0.3175 cm plate and hand-mixed, and formed into 0.113 kg ground beef patties. Additionally, 0.113 kg ground beef samples were collected from each batch of ground beef and vacuum-packaged for fat analysis. The steaks and patties were placed in foam trays and PVC overwrapped. Following packaging, the steaks and patties were placed under continuous fluorescent lighting (Sylvania F40N, Danvers, MA) ($\bar{x}$ = 2378.64 lux) in a cooler for 2 or 4 days to simulate retail display.

3.6. Trained sensory panel

Following storage, the steaks and patties were evaluated by an expert trained panel for sensory and shelf-life characteristics. Flavor and texture descriptive sensory evaluation was conducted at the Texas A&M University Sensory Testing Facility. For

Figure 6
Inside round portions

Figure 7
Bottom round portions

Figure 8
Knuckle portions

sensory determinations, steaks were cooked to an internal temperature of 70 °C and patties were cooked to an internal temperature of 75 °C on a Hamilton Beach Portafolio Indoor/Outdoor Grill (Hamilton Beach/Proctor-Silex, Inc., Southern Pines, NC). Internal temperatures were monitored by a copper-constantan thermocouple (Omega Engineering, Stanford, CT) inserted into the geometric center of each steak and a probe was inserted into the geometric center of each patty. Once the internal temperature reached 35 °C for steaks and 37 °C for patties, they were flipped and cooked until the final internal temperature for steaks was 70 °C and patties were 75 °C. Following cooking, the steaks were cut into 1.27 cm cubes and the patties were cut into 1/8 patty wedges and served warm (within 5 minutes post-cooking) to each of the five trained flavor and texture descriptive attribute sensory panelists. Three cubes and two wedges were served to each panelist for evaluation.

The panel was trained as defined by AMSA (1995) and Meilgaard et al. (2007). Flavor, basic tastes, mouthfeels, and after-tastes were defined by Bhumlratana et al. (2011), and texture attributes were determined during ballot development sessions. Panelists were provided samples of beef from treatments during training and ballot development sessions. After attributes for the ballot were defined, training sessions were conducted. During training sessions, panelists were provided samples similar to those for the study. Following training, the study was initiated after panelists could consistently and accurately identify sensory attributes (AMSA, 1995). Each panelist was seated in individual booths equipped with red theater gel lights. Samples were served in a random order and identified using three-digit codes. Unsalted saltine crackers, fat-free ricotta cheese, and double distilled, deionized water was served to the panelists between samples to cleanse the palate. The panelists evaluated each sample using a 15-point universal scale with 0 = none and 15 = extremely intense for defined attributes (Meilgaard, Civille, & Carr, 2007).

Panelists were asked to evaluate steak samples for beefy, brown/roasted, bloody/serumy, fat-like (Fat), metallic, cardboard, painty, fishy, liver-like, putrid, umami, overall sweet (Osweet), sour milk (Smilk), sweet, sour, salty, bitter, and aftertaste. Panelists scored these attributers from 0 (none) to 15 (extremely intense).

Additionally, panelists evaluated for juiciness (0 = extremely dry; 15 = extremely juicy), muscle fiber tenderness (MFT) (0 = extremely tough; 15 = extremely tender), connective tissue amount (CTA) (0 = none; 15 = extremely high), and overall tenderness (Otend) (0 = extremely tough; 15 = extremely tender). Overall tenderness was the average of connective tissue amount and muscle fiber tenderness except when connective tissue amount was a 7 or 8. If this occurred, then overall tenderness was the same as muscle fiber tenderness.

Patty samples were evaluated for beefy, brown/roasted, bloody/serumy, fat-like, metallic, cardboard, painty, fishy, liver-like, putrid, umami, overall sweet (Osweet), sour milk (Smilk), sweet, sour, salty, bitter, and aftertaste. Panelist scored these attributers from 0 (none) to 15 (extremely intense).

Further, juiciness (0 = extremely dry; 15 = extremely juicy), springiness (0 = none; 15 = extremely springy), and hardness (0 = extremely soft; 15 = extremely hard) were also evaluated as texture attributes. Two sessions were conducted with eight samples evaluated per session where samples were represented across treatments. A 20 min break was given between sessions and samples were served a minimum of four minutes apart.

3.7. Color analysis

During retail refrigerated storage, color measurements were taken on PVC-packaged steaks and patties on days 0, 2, and 4. Three different readings were randomly taken from the surface of each patty and steak. After steaks and patties were cooked for sensory analysis, cooked steak cubes and patty slices were analyzed for cooked color measurements. Three color measurements were taken from the internal portion of three random cubes from the steaks and three random wedges from the patties. Color was measured using a Minolta Colorimeter (CR-300, Minolta Co., Ramsey, NJ) which was calibrated with a white tile daily to ensure consistency among days. Each reading consisted of L*, a*, and b* color space values.

3.8. TBARS analysis

Lipid oxidation was evaluated using a modified TBA (2-thiobarbituric acid) method defined by Wang et al. (2002). TCA (trichloroacetic acid) extraction solution was prepared by mixing 7.5% trichloroacetic acid, 0.1% EDTA (ethylenediaminetetraacetic acid), and 0.1% propyl gallate into double distilled water. 80 mM TBA (thiobarbituric acid) solution was produced by mixing 1.15 g TBA into 100 mL double distilled water. TEP (tetraethoxypropane) solution was prepared by adding 240 µL of tetraethoxypropane to 1 L of double distilled water.

Standards were produced by diluting 1 mM TEP solution to 80 nM and combining different concentrations (0, 2, 4, 6, 8, 10, 20, and 30 mg/kg) of 80 nM TEP solution and TCA extraction solution. After the standards were made, samples were prepared for extraction. Samples were minced, weighed, and 5 g of each sample were placed in a 50 mL centrifuge tube and 15 mL TCA extraction solution was added. The samples were homogenized for 20-30 s using a Polytron homogenizer (PT 10-35 GT, Kinematica, Bohemia, NY). Following homogenization, tubes were placed in a Jouan centrifuge (C 412, Jouan Inc., Winchester, VA) and centrifuged at 1,500 *g* for 15 min. The samples were filtered through No. 4 Whatman paper and 125 µL of the resulting extract was loaded in triplicate into a 96-well Nunclon Surface microplate (Nalge Nunc International, Rochester, NY). After the samples were loaded, 125 µL of TBA solution was dispensed into each well of the microplate using a pipette. The microplate was then incubated for 130 min at 40 °C. After incubation, absorbance was read at 532 nm on a microplate reader (Epoch Microplate Spectrophotometer, BioTek, Winooski, VT).

3.9. Fat analysis

Ground beef samples (0.113 kg) were collected for each batch produced during fabrication. Fat and moisture analysis was conducted by snap-freezing the sample in liquid nitrogen and pulverizing it in a Waring blender. Approximately 3 g of powdered sample was weighed into a pre-dried filter-paper thimble and used to determine the fat and moisture content of the ground beef by the oven drying and ether extraction procedures (AOAC, 1990) in duplicate.

3.10. Statistical analysis

Data were analyzed by analysis of variance programs using SAS PROC GLM (SAS Institute, Cary, NC) with an α of $P<0.05$. The model included main effects of treatment, subprimal, age day, and shelf-life day. Two-, three-, and four-way interactions were included in the full model. If the interactions were not significant ($P>0.05$), they were pooled into the error term and the final model was calculated. The p-diff function at $P<0.05$ was used to separate least squares means when significant differences occurred.

CHAPTER IV

RESULTS AND DISCUSSION

4.1. Raw color

Least squares means for bottom round steak L* color space values for age day and shelf day are shown in table 2. Mean bottom round steak L* color space values were significantly different (*P*<0.05) for age day and shelf day. Bottom round age day 0 steaks produced the lowest (44.39) mean L* value compared to age day 14 (46.24) and age day 21 (46.07), which did not differ (*P*>0.05) from each other. Additionally, shelf day 0 (46.99) bottom round steaks had an elevated L* color space value compared to shelf day 2 (45.11) steaks. In table 3, least squares means for bottom round steak a* and b* color space values for age day and treatment × shelf day are exhibited. Mean a* and b* color space values for bottom round steaks were highest (*P*<0.05) for age day 14 (19.08 and 8.76, respectively), lowest (*P*<0.05) for age day 21 (16.05 and 7.64, respectively), and age day 0 (18.04 and 8.10, respectively) mean a* and b* values differed (*P*<0.05) from the other two age days. Control and treated bottom round steak a* color space values decreased (*P*<0.05) as shelf day increased. Treated shelf day 0 (20.77) bottom round steaks produced lower a* values than control shelf day 0 (22.42) steaks originally, but the difference between treated and control steaks for shelf day 2 and 4 was not significant (*P*>0.05). Mean b* color space values were highest (*P*<0.05) for control shelf day 0 (8.97) bottom round steaks compared to the other

Table 2. Least squares means ± SEM[a] for bottom round steak L* color space values for age day and shelf day main effects

	L*
Age Day	
0	44.39b ± 0.32
14	46.24a ± 0.31
21	46.07a ± 0.32
P>F	<0.0001
Shelf Day	
0	46.99a ± 0.28
2	45.10b ± 0.28
4	44.60b ± 0.40
P>F	<0.0001

[a,b] Means within a column lacking a common letter differ ($P<0.05$)

[a] SEM = Standard error of the least squares means

Table 3. Least squares means ± SEM[a] for bottom round steak a* and b* color space values for age day main effect and treatment × shelf day interaction

	a*	b*
Age Day		
0	18.04b ± 0.26	8.10b ± 0.14
14	19.08a ± 0.26	8.76a ± 0.14
21	16.05c ± 0.26	7.64c ± 0.14
P>F	<0.0001	<0.0001
Treatment × Shelf Day		
Control 0	22.42a ± 0.33	8.97a ± 0.18
Control 2	17.99c ± 0.32	8.24b ± 0.18
Control 4	13.59d ± 0.46	8.19bc ± 0.25
Treated 0	20.77b ± 0.32	7.60c ± 0.18
Treated 2	17.60c ± 0.32	8.06bc ± 0.18
Treated 4	13.97d ± 0.46	7.93bc ± 0.25
P>F	0.0256	0.0021

[a-d] Means within a column lacking a common letter differ ($P<0.05$)

[a] SEM = Standard error of the least squares means

combinations. Additionally, control shelf day 4 (8.19), treated shelf day 0 (7.60), treated shelf day 2 (8.06), and treated shelf day 4 (7.93) mean b* values did not differ (*P*>0.05).

In table 4, least squares means for top round steak L* and a* color space values for shelf day and treatment × age day are presented. Mean L* color space values for shelf day 2 (46.65) did not differ (*P*>0.05) from shelf day 4 (46.62), but both were different (*P*<0.05) than shelf day 0 (48.51) top round steaks. Additionally, mean a* color space values for top round steaks decreased significantly (*P*<0.05) as shelf day increased. Control age day 14 (49.25) top round steaks produced an elevated (*P*<0.05) mean L* color space value compared to control age day 0 (46.55) and 21 (46.75) steaks, which did not differ from each other. Treated age day 14 (47.84) and 21 (47.77) top round steaks exhibited higher (*P*<0.05) mean L* color space values compared to treated age day 0 (45.42) top round steaks. Mean a* color space values were highest (*P*<0.05) for control age day 14 (21.39) top round steaks and were lowest (*P*<0.05) for control age day 21 (17.43) top round steaks. Mean a* color space values did not differ (P>0.05) for treated age day 0 (18.20), 14 (18.60), and 21 (18.44) top round steaks. Least squares means for top round steak b* color space values for treatment × age day and treatment × shelf day are presented in table 5. Mean b* color space values for top round steaks were highest (*P*<0.05) for control age day 14 (10.29), lowest (*P*<0.05) for control age day 21 (8.20), and both differed (*P*<0.05) from control age day 0 (9.47) steaks. Treated age day 14 (8.97) top round steaks produced an elevated (*P*<0.05) mean b* color space value compared to treated age day 0 (8.43) and treated age day 21 (8.60) steaks. Additionally, control shelf day 0 (10.13) top round steaks exhibited the highest mean b* color space

Table 4. Least squares means ± SEM[a] for top round steak L* and a* color space values for shelf day main effect and treatment × age day interaction

	L*	a*
Shelf Day		
0	48.51a ± 0.28	23.42a ± 0.26
2	46.65b ± 0.28	18.64b ± 0.26
4	46.62b ± 0.40	14.89c ± 0.36
P>F	<0.0001	<0.0001
Treatment × Age Day		
Control 0	46.55cd ± 0.45	19.83b ± 0.41
Control 14	49.25a ± 0.45	21.39a ± 0.41
Control 21	46.75bc ± 0.45	17.43d ± 0.41
Treated 0	45.42d ± 0.45	18.20cd ± 0.41
Treated 14	47.84b ± 0.45	18.60c ± 0.41
Treated 21	47.77bc ± 0.45	18.44cd ± 0.41
P>F	0.0111	<0.0001

[a-d] Means within a column lacking a common letter differ ($P<0.05$)

[a] SEM = Standard error of the least squares means

Table 5. Least squares means ± SEM[a] for top round steak b* color space values for treatment × age day and treatment × shelf day interactions

	b*
Treatment × Age Day	
Control 0	9.47b ± 0.18
Control 14	10.29a ± 0.18
Control 21	8.20d ± 0.18
Treated 0	8.43d ± 0.18
Treated 14	8.97c ± 0.18
Treated 21	8.60cd ± 0.18
P>F	<0.0001
Treatment × Shelf Day	
Control 0	10.13a ± 0.16
Control 2	9.12b ± 0.16
Control 4	8.71bc ± 0.22
Treated 0	8.71bc ± 0.16
Treated 2	8.77bc ± 0.16
Treated 4	8.52c ± 0.22
P>F	0.0007

[a-d]Means within a column lacking a common letter differ ($P<0.05$)

[a]SEM = Standard error of the least squares means

value and control shelf day 4 (8.71), treated shelf day 0 (8.71), treated shelf day 2 (8.77), and treated shelf day 4 (8.52) steak mean b* values did not differ (*P*>0.05).

Least squares means for knuckle steak L* color space values for age day and shelf day are shown in table 6. Mean knuckle steak L* color space values for age day 0 (44.75) did not differ (*P*>0.05) from age day 14 (44.86), but both were different (*P*<0.05) than age day 21 (47.84). Shelf day 0 (47.06) knuckle steaks produced an elevated (*P*<0.05) mean L* value compared to shelf day 2 (45.15) and 4 (45.25) steaks, which did not differ (*P*>0.05) from each other. In table 7, least squares means for knuckle steak a* color space values for shelf day and treatment × age day are presented. Mean knuckle steak a* color space values decreased (*P*<0.05) significantly as shelf day increased. Additionally, mean a* values for control age day 0 (18.58) knuckle steaks differed (*P*<0.05) from treated age day 0 (16.27) steaks. As age day increased, the difference (*P*>0.05) between treated and control knuckle steaks disappeared. Lastly, least squares means for knuckle steak b* values for treatment × shelf day are shown in table 8. Mean b* values for treated shelf day 0 (7.14) steaks were the lowest (*P*<0.05) when compared to the other combinations. Initially, the control shelf day 0 (8.59) steaks were different (*P*<0.05) than its treated counterpart, but as shelf day increased the difference (*P*>0.05) between treated shelf day 4 (7.27) and control shelf day 4 (7.55) steaks were not seen.

In table 9, least squares means for bottom round patty L* color space values for age day and shelf day are presented. The mean L* color space value for age day 14 (49.67) bottom round patties did not differ (*P*>0.05) from those patties for age day 21

Table 6. Least squares means ± SEM[a] for knuckle steak L* color space values for age day and shelf day main effects

	L*
Age Day	
0	44.75b ± 0.44
14	44.86b ± 0.44
21	47.84a ± 0.44
P>F	<0.0001
Shelf Day	
0	47.06a ± 0.40
2	45.15b ± 0.40
4	45.25b ± 0.56
P>F	0.0015

[a,b] Means within a column lacking a common letter differ ($P<0.05$)

[a] SEM = Standard error of the least squares means

Table 7. Least squares means ± SEM[a] for knuckle steak a* color space values for shelf day main effect and treatment × age day interaction

	a*
Shelf Day	
0	21.10a ± 0.23
2	17.81b ± 0.23
4	14.31c ± 0.32
P>F	<0.0001
Treatment × Age Day	
Control 0	18.58b ± 0.36
Control 14	20.09a ± 0.36
Control 21	17.42cd ± 0.36
Treated 0	16.27e ± 0.36
Treated 14	17.53c ± 0.36
Treated 21	16.55de ± 0.35
P>F	0.0352

[a-e] Means within a column lacking a common letter differ (*P*<0.05)

[a] SEM = Standard error of the least squares means

Table 8. Least squares means ± SEM[a] for knuckle steak b* color space values for treatment × shelf day interaction

	b*
Treatment × Shelf Day	
Control 0	8.59a ± 0.20
Control 2	8.17ab ± 0.20
Control 4	7.55bcd ± 0.28
Treated 0	7.14d ± 0.20
Treated 2	7.83bc ± 0.20
Treated 4	7.27cd ± 0.28
P>F	0.0083

[a-d] Means within a column lacking a common letter differ ($P<0.05$)

[a] SEM = Standard error of the least squares means

Table 9. Least squares means ± SEM[a] for bottom round patty L* color space values for age day and shelf day main effects

	L*
Age Day	
0	46.35b ± 0.26
14	49.67a ± 0.26
21	49.35a ± 0.26
P>F	<0.0001
Shelf Day	
0	49.68a ± 0.24
2	47.93b ± 0.24
4	47.76b ± 0.33
P>F	<0.0001

[a,b] Means within a column lacking a common letter differ ($P<0.05$)

[a] SEM = Standard error of the least squares means

(49.35), but both differed (*P*<0.05) from age day 0 (46.35) bottom round patties. Additionally, shelf day 0 (49.68) bottom round patties produced a higher (*P*<0.05) mean L* color space value compared to shelf day 2 (47.93) and shelf day 4 (47.76) patties, which did not differ (*P*>0.05). Least squares means for bottom round patty a* and b* color space values for age day and treatment × shelf day are shown in table 10. Mean a* color space values for age day 14 (17.55) bottom round patties were highest (*P*<0.05) compared to age day 0 (14.16) and 21 (14.54) bottom round patties. Age day 14 (9.90) bottom round patties produced the highest (*P*<0.05) b* color space values, age day 0 (7.55) bottom round patties exhibited the lowest b* color space values, and age day 21 (9.30) bottom round patties differed (*P*<0.05) from both. Initially, control shelf day 0 (24.15) bottom round patties produced elevated (*P*<0.05) mean a* color space values from treated shelf day 0 (20.84) bottom round patties, but when compared to treated and control shelf day 2 (14.92 and 14.13, respectively) and 4 (9.22 and 9.24, respectively) patties, mean a* color space values did not differ (*P*>0.05). Further, mean b* color space values for control shelf day 0 (10.82) bottom round patties were significantly (*P*<0.05) higher than treated shelf day 0 (8.28) patties, but as shelf day increased the differences between treated and control bottom round patties disappeared.

Least squares means for top round patty L* color space values for shelf day and treatment × age day are shown in table 11. Mean L* values for shelf day 0 (49.70) top round patties differed (*P*<0.05) from both shelf day 2 (47.37) and shelf day 4 (47.24) top round patties, which did not differ (*P*>0.05). Additionally, mean L* color space values for control age day 0 (46.82) top round patties differed from their treated age day 0

Table 10. Least squares means ± SEM[a] for bottom round patty a* and b* color space values for age day main effect and treatment × shelf day interaction

	a*	b*
Age Day		
0	14.16b ± 0.30	7.55c ± 0.10
14	17.55a ± 0.30	9.90a ± 0.10
21	14.54b ± 0.30	9.30b ± 0.10
P>F	<0.0001	<0.0001
Treatment × Shelf Day		
Control 0	24.15a ± 0.38	10.82a ± 0.13
Control 2	14.13c ± 0.38	8.28c ± 0.13
Control 4	9.24d ± 0.53	8.85b ± 0.18
Treated 0	20.84b ± 0.38	8.28c ± 0.13
Treated 2	14.92c ± 0.38	8.19c ± 0.13
Treated 4	9.22d ± 0.53	9.07b ± 0.18
P>F	<0.0001	<0.0001

[a-d] Means within a column lacking a common letter differ ($P<0.05$)

[a] SEM = Standard error of the least squares means

Table 11. Least squares means ± SEM[a] for top round patty L* color space values for shelf day main effect and treatment × age day interaction

	L*
Shelf Day	
0	49.70a ± 0.21
2	47.37b ± 0.21
4	47.24b ± 0.29
P>F	<0.0001
Treatment × Age Day	
Control 0	46.82b ± 0.33
Control 14	49.47a ± 0.33
Control 21	48.81a ± 0.33
Treated 0	45.03c ± 0.33
Treated 14	49.01a ± 0.33
Treated 21	49.49a ± 0.33
P>F	0.0008

[a-c] Means within a column lacking a common letter differ ($P<0.05$)

[a] SEM = Standard error of the least squares means

(45.03) counterparts, but as age day increased, differences (*P*>0.05) between control and treated patties were not seen. In table 12, least squares means for top round patty a* color space values for age day and treatment × shelf day are exhibited. Mean a* color space values were highest for age day 14 (18.79) top round patties, lowest for age day 0 (15.64) patties, and both differed (*P*<0.05) from age day 21 (16.56) patties. Further, mean a* color space values for control shelf day 0 (25.32) top round patties differed (*P*<0.05) from treated shelf day 0 (22.41) patties. However, when comparing control and treated shelf day 2 (16.49 and 16.69, respectively) top round patty mean a* color space values, no differences (*P*>0.05) were seen. Lastly, treated shelf day 4 (9.80) top round patties produced a significantly (*P*<0.05) lower mean a* color space value compared to control shelf day 4 patties. Least squares means for top round patty b* color space values for treatment × age day and treatment × shelf day are presented in table 13. The mean b* color space value for control age day 0 (8.13) top round patties was higher (*P*<0.05) than treated age day 0 (7.30) patties, control age day 14 (10.33) patties were higher (*P*<0.05) than treated age day 14 (9.65) patties, and there was no difference in control and treated age day 21 (9.58 and 9.39, respectively) top round patties. Initially, mean b* color space values for control shelf day 0 (11.30) top round patties differed (*P*<0.05) from treated shelf day 0 (9.14) patties, but as shelf day increased the differences (*P*>0.05) between control and treated top round patty mean b* color space values for shelf day 2 and 4 were not seen.

In table 14, least squares means for knuckle patty L* color space values for treatment, age day, and shelf day are shown. Control (47.90) knuckle patties produced a

Table 12. Least squares means ± SEM[a] for top round patty a* color space values for age day main effect and treatment × shelf day interaction

	a*
<u>Age Day</u>	
0	15.64c ± 0.28
14	18.79a ± 0.28
21	16.56b ± 0.28
P>F	<0.0001
<u>Treatment × Shelf Day</u>	
Control 0	25.32a ± 0.35
Control 2	16.49c ± 0.35
Control 4	11.29d ± 0.50
Treated 0	22.41b ± 0.35
Treated 2	16.69c ± 0.35
Treated 4	9.80e ± 0.50
P>F	<0.0001

[a-e] Means within a column lacking a common letter differ (*P*<0.05)

[a] SEM = Standard error of the least squares means

Table 13. Least squares means ± SEM[a] for top round patty b* color space values for treatment × age day and treatment × shelf day interactions

	b*
Treatment × Age Day	
Control 0	8.13c ± 0.12
Control 14	10.33a ± 0.12
Control 21	9.58b ± 0.12
Treated 0	7.30d ± 0.12
Treated 14	9.65b ± 0.12
Treated 21	9.39b ± 0.12
P>F	0.0164
Treatment × Shelf Day	
Control 0	11.30a ± 0.11
Control 2	8.51cd ± 0.11
Control 4	8.23d ± 0.15
Treated 0	9.14b ± 0.11
Treated 2	8.46cd ± 0.11
Treated 4	8.75c ± 0.15
P>F	<0.0001

[a-d] Means within a column lacking a common letter differ ($P<0.05$)

[a] SEM = Standard error of the least squares means

Table 14. Least squares means ± SEM[a] for knuckle patty L* color space values for treatment, age day, and shelf day main effects

	L*
Treatment	
Control	47.90a ± 0.26
Treated	46.44b ± 0.26
P>F	<0.0001
Age Day	
0	44.98c ± 0.30
14	47.30b ± 0.31
21	49.22a ± 0.30
P>F	<0.0001
Shelf Day	
0	49.09a ± 0.27
2	46.68b ± 0.27
4	45.74c ± 0.39
P>F	<0.0001

[a-c] Means within a column lacking a common letter differ (*P*<0.05)

[a] SEM = Standard error of the least squares means

higher (*P*<0.05) mean L* color space value than its treated (46.44) counterpart. Additionally, age day 0 (44.98) patties produced the lowest (*P*<0.05) mean L* color space value, age day 21 (49.22) patties expressed the highest mean L* color space value, and age day 14 (47.30) patties differed (*P*<0.05) from both. Further, mean L* color space values for knuckle patties significantly decreased (*P*<0.05) as shelf day increased. Least squares means for knuckle patty a* and b* color space values for age day and treatment × shelf day are presented in table 15. Mean a* color space values were higher for age day 14 (18.02) knuckle patties than age day 0 (15.51) and 21 (15.93) patties, which did not differ (*P*>0.05). Mean b* color space values for age day 14 (9.16) knuckle patties did not differ (*P*>0.05) from age day 21 (9.18) patties, but both differed (*P*<0.05) from age day 0 (7.35) patties. Further, the mean a* color space value for control shelf day 0 (24.22) knuckle patties differed (*P*<0.05) from treated shelf day 0 (21.85) patties, but as shelf day increased the mean a* values for treated and control patties were not different (*P*>0.05). Control shelf day 0 (10.46) knuckle patties expressed an elevated (*P*<0.05) mean b* color space value compared to treated shelf day 0 (8.67) patties. However, as shelf day increased, differences (*P*>0.05) between treated and control knuckle patties disappeared.

4.2. Cooked color

No cooked bottom round, top round, and knuckle steak color differences (*P*>0.05) were seen between treatment, shelf day, age day, treatment × shelf day, and treatment × age day.

Table 15. Least squares means ± SEM[a] for knuckle patty a* and b* color space values for age day main effect and treatment × shelf day interaction

	a*	b*
Age Day		
0	15.51b ± 0.25	7.35b ± 0.11
14	18.02a ± 0.26	9.16a ± 0.12
21	15.93b ± 0.26	9.18a ± 0.11
P>F	<0.0001	<0.0001
Treatment × Shelf Day		
Control 0	24.22a ± 0.32	10.46a ± 0.14
Control 2	15.68c ± 0.32	8.06c ± 0.14
Control 4	10.39d ± 0.46	7.80c ± 0.21
Treated 0	21.85b ± 0.33	8.67b ± 0.15
Treated 2	15.88c ± 0.33	8.11c ± 0.15
Treated 4	10.90d ± 0.45	8.29bc ± 0.20
P>F	<0.0001	<0.0001

[a-d] Means within a column lacking a common letter differ (*P*<0.05)

[a] SEM = Standard error of the least squares means

Least squares means for cooked bottom round patty L* color space values for age day are presented in table 16. Cooked bottom round patty mean L* color space values were significantly (*P*<0.05) different for age day. The mean cooked bottom round patty L* color space value for age day 21 (56.60) was higher (*P*<0.05) than age day 0 (54.78) but was similar to age day 14 (56.14). In table 17, least squares means for cooked bottom round patty a* color space values for treatment are exhibited. Mean a* color space values for cooked bottom round patties were significantly (*P*<0.05) different for treatment. Mean cooked bottom round a* color space values for the control (9.50) patties was higher (*P*<0.05) than the treated patties (8.45). Lastly, least squares means for cooked bottom round patty b* color space values for shelf day are shown in table 18. Significant (*P*<0.05) differences in mean b* color space values were seen for shelf day. Cooked shelf day 4 (9.86) bottom round patties produced elevated (*P*<0.05) a* values in comparison to shelf day 2 (9.37) patties.

No cooked top round patty L* color space value differences (*P*>0.05) were seen between treatment, shelf day, age day, treatment × age day, and treatment × shelf day. In table 19, least squares means for cooked top round patty a* color space values for age day are shown. Mean a* color space values for cooked top round patties were significantly (*P*<0.05) different for age day. The cooked top round patty age day 21 (8.30) mean a* value did not differ (*P*>0.05) from age day 14 (8.26), but both differed (*P*<0.05) from age day 0 (9.45). Least squares means for cooked top round patty b* color space values for treatment × age day are presented in table 20. Mean b* color space values for cooked top round patties differed (P<0.05) significantly for treatment ×

Table 16. Least squares means ± SEM[a] for cooked bottom round patty L* color space values for age day main effect

	L*
Age Day	
0	54.78b ± 0.49
14	56.14ab ± 0.49
21	56.60a ± 0.49
P>F	0.0288

[a,b]Means within a column lacking a common letter differ (*P*<0.05)

[a]SEM = Standard error of the least squares means

Table 17. Least squares means ± SEM[a] for cooked bottom round patty a* color space values for treatment main effect

	a*
<u>Treatment</u>	
Control	9.50a ± 0.21
Treated	8.45b ± 0.21
P>F	0.0007

[a,b] Means within a column lacking a common letter differ (*P*<0.05)

[a] SEM = Standard error of the least squares means

Table 18. Least squares means ± SEM[a] for cooked bottom round patty b* color space values for shelf day main effect

	b*
Shelf Day	
2	9.37b ± 0.14
4	9.86a ± 0.14
P>F	0.0165

[a,b] Means within a column lacking a common letter differ (*P*<0.05)

[a] SEM = Standard error of the least squares means

Table 19. Least squares means ± SEM[a] for cooked top round patty a* color space values for age day main effect

	a*
Age Day	
0	9.45a ± 0.20
14	8.26b ± 0.20
21	8.30b ± 0.20
P>F	<0.0001

[a,b] Means within a column lacking a common letter differ (*P*<0.05)

[a] SEM = Standard error of the least squares means

Table 20. Least squares means ± SEM[a] for cooked top round patty b* color space values for treatment × age day interaction

	b*
Treatment × Age Day	
Control 0	10.47ab ± 0.31
Control 14	10.03bc ± 0.31
Control 21	9.29c ± 0.31
Treated 0	9.67bc ± 0.31
Treated 14	9.49c ± 0.31
Treated 21	10.91a ± 0.31
P>F	0.0003

[a-c] Means within a column lacking a common letter differ ($P<0.05$)

[a] SEM = Standard error of the least squares means

age day. Treated age day 21 (10.91) cooked top round patties expressed the highest (P<0.05) mean b* value and did not differ from control age day 0 (10.47) cooked top round patties. Mean b* values for control age day 14 (10.03), control age day 21 (9.29), treated age day 0 (9.67), and treated age day 14 (9.49) did not differ (P>0.05).

No cooked knuckle patty L* color space value differences (*P*>0.05) were seen between treatment, shelf day, age day, treatment × age day, and treatment × shelf day for cooked knuckle patties. In table 21, least squares means for cooked knuckle patty a* color space values for age day are shown. Cooked knuckle patty mean a* values differed (P<0.05) significantly for age day. The cooked knuckle patty mean a* value for age day 0 (10.53) did not differ from age day 14 (10.18), but both differed (P<0.05) from age day 21 (8.98). Least squares means for cooked knuckle patty b* color space values for shelf day are presented in table 22. Mean cooked knuckle patty b* values were significantly (P<0.05) different. Shelf day 2 (9.45) cooked knuckle patties produced and elevated (P<0.05) mean b* value compared to shelf day 4 (8.96) cooked knuckle patties.

4.3. Sensory analysis

Least squares means of bottom round steak sensory characteristics for trained sensory evaluation for treatment, age day, and shelf day are shown in tables 23 and 24. Mean control bottom round steak sensory ratings for bloody (2.03) and umami (0.99) were higher (*P*<0.05) than their treated counterparts. Additionally, mean control bottom round steak sensory ratings for overall sweet (1.01), juiciness (11.37), and muscle fiber tenderness (11.88) were higher (*P*<0.05) than the treated bottom round steaks.

Table 21. Least squares means ± SEM[a] for cooked knuckle patty a* color space values for age day main effect

	a*
Age Day	
0	10.53a ± 0.33
14	10.18a ± 0.33
21	8.98b ± 0.33
P>F	0.0042

[a,b] Means within a column lacking a common letter differ (*P*<0.05)

[a] SEM = Standard error of the least squares means

Table 22. Least squares means ± SEM[a] for cooked knuckle patty b* color space values for shelf day main effect

	b*
Shelf Day	
2	9.45a ± 0.15
4	8.96b ± 0.16
P>F	0.0305

[a,b] Means within a column lacking a common letter differ ($P<0.05$)

[a] SEM = Standard error of the least squares means

Table 23. Least squares means of bottom round steak sensory characteristics for trained sensory evaluation for treatment, age day, and shelf day main effects

	Brown[b]	Bloody[b]	Fat[b]	Cardboard[b]	Liver[b]	Putrid[b]	Umami[b]
Treatment							
Control	1.10	2.03a	1.45	0.10b	0.13	0.04	0.99a
Treated	1.83	1.58b	1.32	0.38a	0.23	0.08	0.69b
P>F	0.3260	0.0115	0.1564	0.0188	0.1824	0.4205	0.0357
Age Day							
0	2.11a	1.76	1.53a	0.03b	0.03b	0.02b	0.97
14	2.11a	1.96	1.43ab	0.37a	0.28a	0.08ab	1.01
21	1.52b	1.69	1.20b	0.37a	0.23ab	0.12a	0.54
P>F	0.0339	0.5140	0.0439	0.0157	0.0269	0.0467	0.0505
Shelf Day							
2	1.95	1.78	1.40	0.13	0.22	0.05	0.94
4	1.88	1.83	1.37	0.35	0.14	0.06	0.74
P>F	0.7138	0.7547	0.7335	0.0655	0.3265	0.8225	0.1592
RMSE[a]	0.232	0.231	0.070	0.108	0.041	0.015	0.148

[a,b] Means within a column lacking a common letter differ (*P*<0.05)

[a] RMSE = Root Mean Square Error from Analysis of Variance

[b] 15 = extremely intense; 0 = none

Table 24. Least squares means of bottom round steak sensory characteristics for trained sensory evaluation for treatment, age day, and shelf day main effects

	Osweet[b]	Smilk[b]	Sour[b]	Bitter[b]	Juiciness[c]	MFT[d]
Treatment						
Control	1.01a	0.46	1.43	1.20	11.37a	11.88a
Treated	0.79b	0.25	1.45	1.34	10.40b	11.07b
P>F	0.0283	0.0819	0.8762	0.0866	0.0003	0.0074
Age Day						
0	0.90	0.12b	1.17b	1.12b	10.73	11.25
14	1.04	0.44a	1.49a	1.28ab	10.91	11.38
21	0.77	0.50a	1.65a	1.41a	11.02	11.79
P>F	0.1943	0.0371	0.0018	0.0478	0.6532	0.3788
Shelf Day						
2	1.03a	0.25	1.31b	1.15b	10.88	11.44
4	0.77b	0.46	1.57a	1.39a	10.89	11.51
P>F	0.0141	0.0890	0.0115	0.0084	0.9630	0.8258
RMSE[a]	0.079	0.109	0.070	0.057	0.443	0.653

[a,b] Means within a column lacking a common letter differ ($P<0.05$)

[a] RMSE = Root Mean Square Error from Analysis of Variance

[b] 15 = extremely intense; 0 = none

[c] 15 = extremely juicy; 0 = extremely dry

[d] 15 = extremely tender; 0 = extremely tough

Further, mean brown sensory ratings for age day 0 (2.11) did not differ (*P*>0.05) from age day 14 (2.11), but both differed (*P*<0.05) from age day 21 (1.52). Mean fat-like sensory ratings for age day 0 (1.53) differed (*P*<0.05) from age day 21 (1.20), but age day 14 (1.43) ratings did not differ (*P*>0.05) from both. Mean cardboard sensory ratings were lowest for age day 0 (0.03) and highest for age days 14 (0.37) and 21 (0.37). Mean liver-like sensory ratings for age day 0 (0.03) differed (*P*<0.05) from age day 14 (0.28), but age day 21 (0.23) ratings were similar to both. Additionally, mean putrid sensory ratings were highest for age day 21 (0.12) and lowest for age day 0 (0.02). Mean sour milk and sour sensory ratings were lowest for age day 0 (0.12 and 1.17, respectively) and highest for age days 14 (0.44 and 1.49, respectively) and 21 (0.50 and 1.65, respectively). Lastly, age day 0 (1.12) had the lowest bitter sensory ratings compared to age day 21 (1.41) steaks.

Mean overall sweet sensory ratings for shelf day 2 steaks (1.03) differed (*P*<0.05) from shelf day 4 steaks (0.77). Also, mean sour and bitter sensory ratings for shelf day 2 (1.31 and 1.15, respectively) steaks differed (*P*<0.05) from shelf day 4 (1.57 and 1.39, respectively) steaks.

Least squares means of top round steak sensory characteristics for trained sensory evaluation for treatment, age day, and shelf day are presented in table 25. Mean control top round steak sensory ratings for fat-like (1.25) and juiciness (10.59) were higher than their treated counterparts. Additionally, mean cardboard sensory ratings were higher for treated (0.39) steaks compared to control (0.17) steaks. Umami and sweet sensory ratings for age day 0 (0.70 and 0.70, respectively) and age day 21 (1.05

Table 25. Least squares means of top round steak sensory characteristics for trained sensory evaluation for treatment, age day, and shelf day main effects

	Fat[b]	Cardboard[b]	Umami[b]	Sweet[b]	Juiciness[c]
Treatment					
Control	1.25a	0.17b	0.77	0.74	10.59a
Treated	1.00b	0.39a	0.59	0.69	9.96b
P>F	0.0046	0.0352	0.1232	0.2573	0.0263
Age Day					
0	0.96	0.20	0.70a	0.70a	10.27
14	1.06	0.32	0.28b	0.57b	10.53
21	1.36	0.33	1.05a	0.87a	10.02
P>F	0.0560	0.5879	0.0177	0.0445	0.6971
Shelf Day					
2	1.17	0.23	0.71	0.77a	10.28
4	1.09	0.33	0.64	0.66b	10.26
P>F	0.3511	0.3470	0.5828	0.0426	0.9574
RMSE[a]	0.055	0.082	0.109	0.020	0.599

[a,b] Means within a column lacking a common letter differ ($P<0.05$)

[a] RMSE = Root Mean Square Error from Analysis of Variance

[b] 15 = extremely intense; 0 = none

[c] 15 = extremely juicy; 0 = extremely dry

and 0.87, respectively) steaks did not differ (*P*>0.05), but both differed (*P*<0.05) from age day 14 (0.28 and 0.57, respectively) steaks. Lastly, shelf day 2 (0.77) top round steaks had higher (*P*<0.05) mean sweet sensory ratings than the shelf day 4 (0.66) steaks.

In table 26, least squares means of knuckle steak sensory characteristics for trained sensory evaluation for treatment and age day are displayed. Mean control knuckle steak sensory ratings for juiciness (10.84), muscle fiber tenderness (12.49), connective tissue amount (12.90), and overall tenderness (12.16) all differed (P<0.05) from their treated counterparts. Further, shelf day 4 (0.85) knuckle steaks produced higher sweet sensory ratings than the shelf day 2 (0.58) steaks.

Least squares means of ground beef patty sensory characteristics for trained sensory evaluation for treatment, subprimal, age day, and shelf day are shown in tables 27 and 28. Mean control ground beef patty sensory ratings for beefy (5.83), brown (2.56), bloody (0.74), fat-like (1.89), sour milk (0.84), sour (1.83), and juiciness (9.17) all differed (*P*<0.05) from their treated counterparts. Mean control ground beef sensory ratings for cardboard (0.36), sweet (0.62), and hardness (5.64) were all lower than the treated ground beef patties. Further, top round and bottom round patties produced higher sour milk (0.85 and 0.79, respectively) and sour (1.88 and 1.74, respectively) sensory ratings compared to knuckle patties. Knuckle (0.71) patties received a higher mean sweet sensory rating compared to the top round (0.62) and bottom round (0.63) patties. Lastly, bottom round (1.29) patties were more bitter than top round (1.11) patties, and knuckle (1.21) patties did not differ (*P*>0.05) from the two.

Table 26. Least squares means of knuckle steak sensory characteristics for trained sensory evaluation for treatment and shelf day main effects

	Sweet[b]	Juiciness[c]	MFT[d]	CTA[e]	Otend[d]
Treatment					
Control	0.71	10.84a	12.49a	12.90a	12.16a
Treated	0.72	10.21b	11.68b	12.19b	11.37b
P>F	0.9246	0.0163	0.0256	0.0233	0.0310
Shelf Day					
2	0.58b	10.42	12.08	12.39	11.75
4	0.85a	10.64	12.09	12.70	11.78
P>F	0.0059	0.4286	0.9907	0.3457	0.9316
RSME[a]	0.051	0.452	0.883	0.656	0.918

[a,b] Means within a column lacking a common letter differ (*P*<0.05)

[a] RMSE = Root Mean Square Error from Analysis of Variance

[b] 15 = extremely intense; 0 = none

[c] 15 = extremely juicy; 0 = extremely dry

[d] 15 = extremely tender; 0 = extremely tough

[e] 15 = extremely high; 0 = none

Table 27. Least squares means of ground beef patty sensory characteristics for trained sensory evaluation for treatment, subprimal, age day, and shelf day main effects

	Beefy[b]	Brown[b]	Bloody[b]	Fat[b]	Metallic[b]	Cardboard[b]	Putrid[b]	Umami[b]
Treatment								
Control	5.83a	2.56a	0.74a	1.89a	1.36	0.36b	0.26	0.74
Treated	5.62b	2.39b	0.59b	1.70b	1.38	0.51a	0.24	0.61
P>F	0.0337	0.0161	0.0052	0.0007	0.5326	0.0131	0.8138	0.8262
Subprimal								
Top Round	5.66	2.44	0.63	1.74	1.37	0.39	0.30	0.65
Bottom Round	5.65	2.45	0.70	1.78	1.42	0.53	0.23	0.67
Knucle	5.86	2.53	0.69	1.86	1.32	0.39	0.23	0.69
P>F	0.1146	0.5228	0.6828	0.2114	0.1412	0.0782	0.5074	0.6143
Age Day								
0	6.17a	2.67a	0.72	1.91a	1.27b	0.39b	0.05	0.84a
14	5.75b	2.43b	0.68	1.75b	1.39a	0.35b	0.15	0.64b
21	5.25c	2.32b	0.61	1.72b	1.45a	0.57a	0.55	0.54b
P>F	<0.0001	0.0003	0.2329	0.0119	0.0053	0.0053	0.4667	<0.0001
Shelf Day								
2	5.97a	2.52	0.74a	1.82	1.35	0.41	0.13	0.74
4	5.47b	2.43	0.59b	1.76	1.39	0.46	0.38	0.60
P>F	<0.0001	0.1713	0.0077	0.2779	0.3986	0.3474	0.3547	0.0011
RMSE[a]	0.236	0.116	0.074	0.071	0.046	0.083	0.004	0.132

[a-c] Means within a column lacking a common letter differ ($P<0.05$)

[a] RMSE = Root Mean Square Error from Analysis of Variance

[b] 15 = extremely intense; 0 = none

Table 28. Least squares means of ground beef patty sensory characteristics for trained sensory evaluation for treatment, subprimal, age day, and shelf day main effects

	Osweet[b]	Smilk[b]	Sweet[b]	Sour[b]	Bitter[b]	Juiciness[c]	Hardness[d]
Treatment							
Control	0.68	0.84a	0.62b	1.83a	1.23	9.17a	5.64b
Treated	0.65	0.64b	0.69a	1.64b	1.18	8.64b	5.78a
P>F	0.4248	0.0070	0.0275	0.0016	0.2165	<0.0001	0.0481
Subprimal							
Top Round	0.66	0.85a	0.62b	1.88a	1.11b	8.98	5.75
Bottom Round	0.63	0.79a	0.63b	1.74a	1.29a	8.78	5.68
Knucle	0.69	0.59b	0.71a	1.58b	1.21ab	8.95	5.70
P>F	0.4934	0.0101	0.0163	0.0006	0.0056	0.4152	0.6529
Age Day							
0	0.80a	0.55b	0.75a	1.44c	1.12b	8.98	5.65
14	0.64b	0.76a	0.63b	1.72b	1.12b	8.78	5.69
21	0.55b	0.92a	0.59b	2.04a	1.38a	8.96	5.78
P>F	<0.0001	0.0006	0.0003	<0.0001	<0.0001	0.4007	0.1826
Shelf Day							
2	0.75a	0.59b	0.72a	1.54b	1.10b	8.98	5.67
4	0.58b	0.90a	0.59b	1.93a	1.31a	8.83	5.75
P>F	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	0.2719	0.2678
RMSE[a]	0.038	0.134	0.023	0.091	0.051	0.434	0.121

[a,b] Means within a column lacking a common letter differ (*P*<0.05)

[a] RMSE = Root Mean Square Error from Analysis of Variance

[b] 15 = extremely intense; 0 = none

[c] 15 = extremely juicy; 0 = extremely dry

[d] 15 = extremely hard; 0 = extremely soft

Mean beefy ratings for age day 0 (6.17), age day 14 (5.75), and age day 21 (5.25) patties all differed (*P*<0.05) from each other. Mean sensory ratings for brown, fat-like, umami, overall sweet, and sweet were all highest for age day 0 patties, and age day 14 and 21patty ratings did not differ (*P*>0.05). Mean sensory ratings for metallic and sour milk were lowest for age day 0 patties, and age day 14 and 21 patty mean scores did not differ (*P*<0.05). Mean sensory ratings for cardboard and bitter were both highest for age day 21, and age day 0 and 14 did not differ from each other. Lastly, mean sensory scores for sour were highest for age day 21 (2.04), lowest for age day 0 (1.44), and age day 14 (1.72) patty scores differed (*P*<0.05) from both.

Mean shelf day 2 ground beef sensory ratings for beefy (5.97), bloody (0.74), overall sweet (0.75), and sweet (0.72) differed (*P*<0.05) from their shelf day 4 counterparts. Additionally, mean sensory ratings for sour milk, sour, and bitter were all higher for shelf day 4 patties than shelf day 2 patties.

4.4. TBARS analysis

In table 29, least squares means for bottom round and knuckle steak TBARS values for shelf day and treatment × age day are presented. Bottom round and knuckle steak mean TBARS values for shelf day 2 (1.07 mg/kg and 0.35 mg/kg, respectively) were significantly lower (*P*<0.05) than shelf day 4 (2.06 mg/kg and 1.67 mg/kg, respectively). Additionally, significant differences (*P*<0.05) for bottom round and knuckle mean TBARS values for treatment × age day were seen. Bottom round and

Table 29. Least squares means ± SEM[a] for bottom round and knuckle steak TBARS values (mg/kg TEP) for shelf day main effect and treatment × age day interaction

	Bottom Round	Knuckle
Shelf Day		
2	1.07b ± 0.15	0.35b ± 0.13
4	2.06a ± 0.15	1.67a ± 0.13
P>F	<0.0001	<0.0001
Treatment × Age Day		
Control 0	0.00d ± 0.26	0.00c ± 0.23
Control 14	1.23c ± 0.26	1.50b ± 0.23
Control 21	3.81a ± 0.26	0.96b ± 0.23
Treated 0	0.00d ± 0.26	0.00c ± 0.23
Treated 14	2.52b ± 0.26	1.31b ± 0.23
Treated 21	1.83bc ± 0.26	2.29a ± 0.23
P>F	<0.0001	0.0042

[a-d] Means within a column lacking a common letter differ ($P<0.05$)

[a] SEM = Standard error of the least squares means

knuckle control age day 0 (0.00 mg/kg and 0.00 mg/kg, respectively) and treated age day 0 (0.00 mg/kg and 0.00 mg/kg, respectively) mean TBARS values did not differ ($P<0.05$). The mean TBARS value for bottom round control age day 21 (3.81 mg/kg) steaks were significantly ($P<0.05$) higher than the other combinations. For the knuckle steaks, the treated age day 21 (2.29 mg/kg) mean TBARS value was significantly ($P<0.05$) higher than the other treatment × age day combinations. Overall, the mean TBARS values for both treated and control increased as age day increased. However, the treated bottom round steaks showed a significant increase ($P<0.05$) between age day 0 (0.00 mg/kg) and age day 14 (2.52 mg/kg), but the mean TBARS value did not increase for age day 21. Additionally, control knuckle steaks exhibited a significant increase ($P<0.05$) in mean TBARS values between age day 0 (0.00 mg/kg) and age day 14 (1.50 mg/kg), but the mean TBARS value for age day 21 did not increase.

Least squares means for top round steak TBARS values for age day and treatment × shelf day are presented in table 30. For top round steaks, the mean TBARS value for age day 0 (0.00 mg/kg) was significantly lower ($P<0.05$) than age day 14 (1.15 mg/kg) and 21 (0.65 mg/kg). Treatment × shelf day differences were not statistically significant ($P>0.05$).

In table 31, least squares means for bottom round patty TBARS values for age day and shelf day are reported. Bottom round patty mean TBARS values were statistically different ($P<0.05$) for age day and shelf day. Mean TBARS values for age day 0 (2.64 mg/kg) did not differ from age day 14 (1.76 mg/kg), but both differed ($P<0.05$) from age day 21. Additionally, the mean TBARS value for shelf day 4 (5.04

Table 30. Least squares means ± SEM[a] for top round steak TBARS values (mg/kg TEP) for age day main effect and treatment × shelf day interaction

	Top Round
Age Day	
0	0.00b ± 0.17
14	1.15a ± 0.17
21	0.65a ± 0.17
P>F	0.0002
Treatment × Shelf Day	
Control 2	0.00 ± 0.20
Control 4	0.81 ± 0.20
Treated 2	0.00 ± 0.20
Treated 4	1.60 ± 0.20
P>F	0.0536

[a,b] Means within a column lacking a common letter differ ($P<0.05$)

[a] SEM = Standard error of the least squares means

Table 31. Least squares means ± SEM[a] for bottom round patty TBARS values (mg/kg TEP) for age day and shelf day main effects

	Bottom Round
Age Day	
0	2.64b ± 0.42
14	1.76b ± 0.42
21	7.16a ± 0.42
P>F	<0.0001
Shelf Day	
2	2.66b ± 0.34
4	5.04a ± 0.34
P>F	<0.0001

[a,b] Means within a column lacking a common letter differ ($P<0.05$)

[a] SEM = Standard error of the least squares means

mg/kg) was significantly higher (*P*<0.05) than the mean TBARS value for shelf day 2 (2.66 mg/kg).

Least squares means for top round patty TBARS values for treatment × age day and treatment × shelf day are displayed in table 32. Mean TBARS values for treatment × age day were significantly different (*P*<0.05). Control age day 0 top round patties produced the lowest (0.79 mg/kg) mean TBARS values compared to the other combinations. Additionally, treated age day 21top round patties exhibited the highest (5.52 mg/kg) mean TBARS values. Control top round patty mean TBARS values significantly (*P*<0.05) increased with each age day. However, the same trend was not seen with the treated top round patties. Treated age day 0 (3.81 mg/kg) and age day 14 (3.26 mg/kg) top round patty mean TBARS values did not differ (*P*>0.05), but the treated age day 21 (5.52 mg/kg) top round patty TBARS value was significantly higher (*P*<0.05).

Mean TBARS values for treatment × shelf day were (*P*<0.05) different. The control shelf day 0 (2.03 mg/kg) top round patty mean TBARS value did not differ (*P*>0.05) from the control shelf day 4 (2.65 mg/kg) top round mean TBARS value. The top round control shelf day 4 (2.65 mg/kg) patty mean TBARS value did not differ from the top round treated shelf day 2 (3.27 mg/kg) patty mean TBARS value. Lastly, treated shelf day 4 (5.12 mg/kg) top round patties produced the highest (*P*<0.05) mean TBARS value in comparison to the others.

In table 33, least squares means for knuckle patty TBARS values for age day and treatment × shelf day are presented. Mean knuckle patty TBARS values for age day

Table 32. Least squares means ± SEM[a] for top round patty TBARS values (mg/kg TEP) for treatment × age day and treatment × shelf day interactions

	Top Round
Treatment × Age Day	
Control 0	0.79e ± 0.37
Control 14	1.89d ± 0.37
Control 21	4.34b ± 0.37
Treated 0	3.81bc ± 0.37
Treated 14	3.26c ± 0.37
Treated 21	5.52a ± 0.37
P>F	0.0355
Treatment × Shelf Day	
Control 2	2.03c ± 0.30
Control 4	2.65bc ± 0.30
Treated 2	3.27b ± 0.30
Treated 4	5.12a ± 0.30
P>F	0.0483

[a-e] Means within a column lacking a common letter differ ($P<0.05$)

[a] SEM = Standard error of the least squares means

Table 33. Least squares means ± SEM[a] for knuckle patty TBARS values (mg/kg TEP) for age day main effect and treatment × shelf day interaction

	Knuckle
Age Day	
0	4.39b ± 0.29
14	2.80c ± 0.29
21	5.35a ± 0.29
P>F	<0.0001
Treatment × Shelf Day	
Control 2	3.44b ± 0.34
Control 4	2.96b ± 0.34
Treated 2	3.08b ± 0.34
Treated 4	7.25a ± 0.34
P>F	<0.0001

[a-c] Means within a column lacking a common letter differ ($P<0.05$)

[a] SEM = Standard error of the least squares means

were significantly (*P*<0.05) different. Knuckle age day 21 (5.35 mg/kg) patties produced the highest (*P*<0.05) mean TBARS value of the three aging days. Knuckle age day 14 (2.80 mg/kg) patties exhibited the lowest (*P*<0.05) mean TBARS value from the three aging days. The knuckle patty age day 0 (4.39 mg/kg) mean TBARS value fell between the other two aging days. Further, differences in knuckle patty mean TBARS values for treatment × shelf day were significantly (*P*<0.05) different. Treated shelf day 4 (7.25 mg/kg) knuckle patties produced an elevated (*P*<0.05) mean TBARS value in comparison to control shelf day 2 (3.44 mg/kg), control shelf day 4 (2.96 mg/kg), and treated shelf day 2 (3.08 mg/kg) knuckle patty mean TBARS values and they did not differ (*P*>0.05) from each other.

4.5. Fat analysis

Least squares means for bottom round, knuckle, and top round ground beef fat percentages for treatment and age day are displayed in table 34. Bottom round ground beef mean fat percentages for control (4.61%) and treated (3.94%) groups were significantly (*P*<0.05) different. Differences between mean fat percentages for treated and control groups for knuckle and top round ground beef did not differ (*P*>0.05). Bottom round ground beef mean fat percentages for age day 0 (4.60%) and 14 (4.95%) were higher (*P*<0.05) than age day 21 (3.26%). Knuckle ground beef mean fat percentages were significantly different (*P*<0.05). Age day 14 (4.78%) was the highest mean fat percentage and did not differ from age day 0 (4.12%), but differed (*P*<0.05) from age day 21 (3.82%). There was no difference in knuckle age day 0 (4.12%) and

Table 34. Least squares means ± SEM[a] for bottom round, knuckle, and top round ground beef fat percentages (%) for treatment and age day main effects

	Bottom Round	Knuckle	Top Round
Treatment			
Control	4.61a ± 0.16	4.32 ± 0.21	4.78 ± 0.17
Treated	3.94b ± 0.17	4.16 ± 0.21	4.33 ± 0.17
P>F	0.0066	0.5833	0.0540
Age Day			
0	4.60a ± 0.21	4.12ab ± 0.26	4.98a ± 0.20
14	4.95a ± 0.20	4.78a ± 0.26	4.41b ± 0.20
21	3.26b ± 0.21	3.82b ± 0.26	4.28b ± 0.20
P>F	<0.0001	0.0326	0.0407

[a,b] Means within a column lacking a common letter differ ($P<0.05$)

[a] SEM = Standard error of the least squares means

age day 21 (3.82%) mean fat percentages. Additionally, the top round mean fat percentage for age day 0 (4.98%) was significantly ($P<0.05$) higher than age day 14 (4.41%) and 21 (4.28%). Lastly, differences in bottom round, knuckle, and top round mean fat percentages were not statistically different ($P>0.05$) for shelf day 2 and 4. Although mean fat percentage differences were observed, they were not believed to be drastic enough to be a concern.

CHAPTER V

CONCLUSIONS

If the application of low-dose irradiation is approved for this purpose and beef processors wish to use it, there is not much information readily available to show how the quality factors such as flavor and color of the resultant products are impacted. With the findings from this study, data can be used to develop educational or outreach materials to minimize or control the impact of low-dose irradiation on quality and palatability factors. This will help ensure the beef industry benefits from the food safety aspects of low-dose irradiation without creating quality problems that could result in economic losses to the industry. Although the impact on food safety has been demonstrated, it is crucial to the industry that we fully understand the quality implications of this technology.

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