Effects of irradiation on properties of cured ham

by

Terry Andrew Houser

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Terry Andrew Houser

has met the thesis requirements of Iowa State University

Signatures have been redacted for privacy
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CHAPTER 1. INTRODUCTION

Contamination of ready-to-eat meat products by *Listeria monocytogenes* and other pathogens has resulted in human illness and recalls of millions of pounds of ready-to-eat meat products. Although irradiation has been approved for use in fresh and frozen meat and poultry products to destroy pathogenic bacteria, it has not been approved for use in ready-to-eat meat products. Irradiation is effective in destroying *Listeria monocytogenes* and would be ideal to use for retail ready-to-eat meats due to their relatively small size of half a kilogram or less. In addition, the use of irradiated meats in the manufacture of cured meat products has not been reported. Concerns regarding changes in quality characteristics need to be addressed before processors will embrace this technology.

Our objectives are to investigate irradiation effects on cured color development and stability, oxidative stability, sensory odor, and residual nitrite level when applied at different steps in the production process of a cured meat product. We hypothesized that irradiation applied to raw ham muscles will have minimal effect on quality characteristics of subsequently cooked cured ham. In contrast, we expected that irradiation after pre-blending would have negative effects on cured color development. We theorized that free radicals produced in the irradiation process would limit the ability of nitric oxide to bind with the heme iron located in the myoglobin molecule. Changes in instrumental CIE L* (lightness), a* (redness), and b* (yellowness) color scores would be evidence of
this. It is also known that nitrite is responsible for preventing lipid oxidation, therefore we hypothesized that lipid oxidation will be higher in pre-blended product exposed to irradiation. We do not expect color or oxidation changes in cooked product because the denaturing process of heating is thought to stabilize the nitric oxide attachment of the iron portion of the myoglobin molecule.

**Thesis Organization**

This thesis is organized into four chapters including a general introduction, general literature review, a complete manuscript, and general conclusions. The manuscript was prepared using the *Journal of Food Science Style Guide* and was co-authored by Dr. Joseph G. Sebranek, and Dr. Steven Lonergan.
CHAPTER 2. LITERATURE REVIEW

Introduction to Irradiation

Irradiation, according to Gove (1981), is “the application of X-rays, radium rays or other radiation.” Radiation is the physical phenomena in which energy travels through space or matter (Olson 1995). This energy can be applied to a material to preserve or sterilize it. The most useful form of radiation for preservation and sterilization is ionizing radiation. Ionizing radiation is radiation containing energy levels high enough to eject electrons from their orbitals (Olson 1995). The breaking of these chemical bonds is known as radiolysis (World Health Organization 1994). When applied to bacterium, radiolysis destroys bacterium DNA, which prevents the bacterium from replicating. Radiolysis causes production of free radicals and a linear relationship exists between free radicals and radiation dose level. Free radical production can be estimated for irradiation when applied to water (Fig. 1). This gives an idea of the products that might be expected when meat is irradiated since lean muscle is 72% water (Romans and others 1985).

The three types of radiation sources capable of ionization are gamma rays, x-rays, and accelerated electrons (Olson 1995). Gamma rays are photons produced by radioactive isotopes of cobalt-60 or cesium-137, which have energy levels between 1-2 million electron volts (MeV). Since photons have no mass or charge they are capable of deep penetration. X-rays are also photons of 1-2
MeV energy level that are produced by collisions of accelerated electrons with heavy metals such as tungsten. The final form of radiation sources to be discussed is accelerated electrons, which have energy levels of 5-10 MeV. Accelerated electrons have mass and charge, and therefore, are not capable of penetrating as completely as gamma or x-rays. This occurs as the product absorbs energy from the electron, slowing it down (Olson 1995).

\[
\begin{align*}
H_2O + \text{Irradiation} & \rightarrow H_2O + e^- \\
H_2O^+ + H_2O & \rightarrow H_3O^+ + \cdot OH \\
e^- + \text{aq} & \rightarrow e^-_{\text{aq}} \\
e^-_{\text{aq}} + H^+ & \rightarrow H\cdot \\
e^-_{\text{aq}} + O_2 & \rightarrow O_2\cdot \\
2O_2\cdot & \rightarrow 2H^+ \rightarrow H_2O_2 + O_2
\end{align*}
\]

Proportions of products of \(H_2O + \text{Irradiation}\) →

\[
0.3 \cdot OH + 0.3 e^-_{\text{aq}} + 0.05 H\cdot + 0.04 H_2 + 0.07 H_2O_2 / \mu \text{mol J}^{-1}
\]

Figure 1. Irradiation Interactions with Water (Modified from Swallow 1991)

The international unit (IU) of radiation dose level is the Gray (Gy), which is equal to 1 joule of energy per kilogram of food. Food products are commonly irradiated with doses of well over 1000 Grays, thus kilo Gray (kGy) is the commonly used term. Radiation dose may be classified into three categories: low dose (<1 kGy), medium dose (1-10 kGy), and high dose (>10 kGy). Low-
dose irradiation is mainly used for disinfestations of insects and higher forms of life from vegetables. Medium-dose irradiation is generally used for pasteurization and shelf life extension of various food products. High-dose irradiation is generally used for sterilization purposes mainly for herbs and spices (Olson 1995). Irradiated foods must bear the radura symbol (Fig. 2) unless the word "Irradiated" is part of the product name. In addition, all labels of irradiated foods must bear a statement such as "Treated with radiation" or "Treated by irradiation" (FDA 1998).

Figure 2. Radura Symbol (FDA 1998)

History of Meat Irradiation

Although irradiation of food is considered a new technology by much of the general public, it has been widely researched for its microbiological-inhibiting properties (Huhtanen and others 1989; Grant and Patterson 1991; Clavero and others 1994; Gürsel and Gürakan 1997). X-rays were the first form of irradiation available for food irradiation research. In 1921, a U.S. patent was issued for use
of x-rays for treatment of *Trichinella spirilis* in meat products. However, the use of x-rays was not widely adopted then or since as it is an inefficient process. World War II was the catalyst for the use of radiation for preserving food items as new technology proliferated, not for peaceful use, but for military means. The first electron accelerators were constructed from Klystron tubes developed for use in radar systems. In addition, the atomic age made available large quantities of radioisotopes to be used in gamma radiation facilities as a by-product of atomic weapon production (Goresline 1982).

In 1953, President Eisenhower started the landmark "Atoms for Peace" policy. This policy encouraged the development of technologies, which would utilize radiation for peaceful purposes (Goresline 1982). The "Atoms for Peace" policy resulted in a significant amount of food irradiation research to be conducted. Much of this early work centered itself around sterilization of food for use by American soldiers. In 1965, prompted by ongoing research, the U.S. Army office of the Surgeon General declared products with doses below 56 kGy safe for human consumption (Olson 1995).

A decade and a half later, in 1981, the World Health Organization concluded "irradiation of any food commodity up to an overall average dose of 10 kGy presents no toxicological hazard; hence toxicological testing of foods so treated is no longer required," (WHO 1981). However, it wasn't until 1999 that the United States Department of Agriculture (USDA) approved the use of irradiation for fresh red meats and poultry. The USDA final rule, implemented February 22,
2000, limits the use of irradiation of fresh red meat and poultry to an overall absorbed dose of 4.5 kGy and frozen red meat and poultry to an overall average absorbed dose of 7.0 kGy (USDA 1999). The U.S. Food and Drug Administration (FDA) has also approved irradiation for microbial disinfestations of dehydrated enzyme preparations, spices, and herbs as well as maturation or sprouting of fresh foods (FDA 1998). Currently, irradiation is not approved for ready-to-eat cured or uncured meat products in the U.S. This is because food irradiation was classified under the Food Additives Amendment of the Food Drug and Cosmetics Act as an ingredient, not a processing technique. This required exhaustive research to be conducted through animal feeding trials to conclude that irradiation is safe. Since irradiation is, in reality, a process and not an ingredient, it has been hard to prove its safety under normal testing protocols (Sapp 1995). Regulatory constraints as well as consumer advocacy groups will continue to hinder the advancement of irradiation technologies in future years. The need for a safer food supply may justify changes in regulatory policy.

**Justification for Irradiation of Ready-to-Eat Meat Products**

As of 1989, a zero tolerance policy has been in effect with regard to *L. monocytogenes* in ready-to-eat meat products. The policy states that any product testing positive for *L. monocytogenes* will be classified as adulterated. Once a product is found adulterated, the USDA Food Safety Inspection Service (FSIS) will request that the product be recalled (USDA 1989). As a result,
millions of pounds of ready-to-eat meat products have been recalled since the regulations inception. Thermal processing has been shown to kill *L. monocytogenes*, which has a thermal D-value at 145° F of 2.56 min (Wilson 1988). However, post thermal-process contamination has been linked to the recalls of ready-to-eat meats. A 1992 Australian study detected the presence of *L. monocytogenes* in 78 out of 175 various randomly selected commercially available ready-to-eat meat products (Grau and Vanderlinde 1992). Another study found *L. monocytogenes* in exudate of 7.5% of various ready-to-eat meat product samples tested (Wang and Muriana 1994). These researchers concluded that post-thermal process contamination prior to packaging was the cause, which could occur as a result of poor sanitation or cross contamination from employees as *Listeria* is found throughout the environment (Prescott and others 1996).

Irradiation has been shown as an effective method for controlling *L. monocytogenes* in both fresh and cured meat products. Research conducted by Huhtanen and others (1989) yielded an average D-value for mechanically deboned chicken of 0.45 kGy with a range of 0.27 to 0.77 kGy. Additionally, Fu and others (1995a) found that a dose of 1.8 kGy decreased *L. monocytogenes* by almost 6 log of colony forming units per gram (CFU / g) for irradiated cured ham. However, irradiation should not be considered the only solution for *L. monocytogenes* control. Gürsel and Gürakan (1997) concluded that *L. monocytogenes* was able to grow in minced chicken breast meat even after a 2.5
kGy dose. In this study minced chicken breast meat was inoculated with $10^4$ cells per gram of *L. monocytogenes*, irradiated at 2.5 kGy, and stored for 15 days at $4^\circ C$. It was found that *L. monocytogenes* cells were able to repair themselves after 11 days of storage after receiving irradiation treatment. This would lead one to conclude that proper food handling procedures such as the mandatory Hazard Analysis and Critical Control Point (HACCP) system in conjunction with irradiation are necessary to yield a microbiologically safe product (USDA 1996).

In addition to the improved control of *L. monocytogenes*, irradiation does not seem to interfere with the antibotulinal efficacy of nitrite. Szczawinski and others (1989) concluded that irradiation doses up to 9 kGy did not change inhibition of *Clostridium botulinum* spores in meat products containing 100 mg/kg to 200 mg/kg nitrite prior to cooking.

Irradiation has also has been shown to control spoilage organisms. A dose-dependent shelf-life extension was found when using medium-dose irradiation on a ground beef media. Lefebvre and others (1992) reported a 4-day shelf-life extension after irradiation at 1.0 kGy, 10-day extension with a dose of 2.5 kGy, and a 15-day extension with a 5.0 kGy absorbed dose for ground beef when stored at 4.0°C. The end of shelf life for the ground beef was determined when the bacterial CFU exceeded $10^7$ CFU/g. Irradiation has also been shown effective in extending the shelf life of whole-muscle meat products. Grant and Patterson (1991) irradiated fresh pork chops in a modified-atmosphere package...
at 1.75 kGy, which extended shelf life of the chops by 4 days compared with the control.

**Consumer acceptance**

The consumer's knowledge of irradiation processing is very limited, even though much scientific work has landed in the public eye (Bruhn 1995). Shin and others (1992) determined that consumers would pay more for a food product if they were guaranteed it to be free of *Salmonella* or *Trichinella spirilis*. Although this study did not take into account consumer views of irradiation, it is clear that both organisms can be killed with irradiation and should guarantee the product to be safe (Brake and others 1985; Clavero and others 1994).

When consumers are faced with the decision to purchase irradiated products, it seems the amount of education regarding the irradiation of food products is the limiting factor. Resurreccion and others (1995) reported that of 446 participants in a mail survey, 32.6% believed irradiated foods contain radioactivity. Another 48.7% of the participants were unsure whether or not the possibility existed for irradiated foods to contain radioactivity. This study also showed that only 45% of the participants would buy food which was irradiated, and then only if properly labeled.

However, if consumers are exposed to accurate educational information, it has been reported that purchasing of irradiated products will increase. Hashim and others (1995) found that participants in this study who would purchase
irradiated poultry products increased from 59.5% to 83.3% for boneless skinless chicken breasts and 61.9% to 85.7% for chicken thighs after viewing an educational slide program. Education of the consumer in the last few years may be the reason irradiation is finding some success. It is estimated that, by the end of the year 2000, there were 1,500 supermarkets in the U.S. carrying at least some irradiated meat products (Lipsky 2000).

**Meat Curing and Curing Ingredients**

The process of meat curing started as a preservative method at the early beginning of our civilization. The ancient Egyptians are credited with the first recorded use of salting and drying as a means of preserving meat (Pearson and Tauber 1984). Salt was added at very high concentrations to reduce water activity, which inhibited microbial growth and extended the usefulness of the product (Hedrick and others 1994). This preservation technique allowed early man to hold meat over from times of plenty to times of need. Although the basic ingredients of meat curing (salt and cure) have changed little in the last few thousand years, the reason for curing meats has changed. Modern inventions, such as refrigeration, vacuum packaging, and modern sanitation practices, have made meat curing no longer a necessity but a function of variety and convenience (Pearson and Tauber 1984).

Sodium chloride (salt) and sodium nitrite (cure) are absolutely necessary for a majority of cured characteristics including color, texture, flavor, and storage
stability (Sebranek and Fox 1985). The primary function of salt is to decrease water activity, increase protein solubility, and impart certain flavor characteristics. However, if salt alone is used to preserve meat products, it imparts a brown color and a harsh taste due to its prooxidant behavior. Sodium nitrite counteracts this oxidation process by terminating the lipid oxidation sequence, preventing warmed-over flavor which has been described as a rancid or stale flavor (Aberle and others 2001), and preventing destruction of heme pigments by salt (Sakata and Nagata 1992). Sodium nitrite is also responsible for cured meat color, flavor, and anti-microbial properties, which make it one of the most unique molecules involved in the total meat system (Cho and Bratzler 1970; Brown and others 1974; Pearson and Tauber 1984).

Although salt and nitrite are necessary ingredients, alkaline phosphates, reductants such as ascorbates and erythorbates, sweeteners, and water all play major roles in the meat curing process. Alkaline phosphates are incorporated in many curing mixtures to increase pH (Prusa and Kregel 1985), therefore increasing water-binding potential, which is an important economic and quality factor in processed meat products. Reducing agents such as sodium ascorbate and sodium erythorbate are added to curing solutions to catalyze cured color development (Lee and Shimaoka 1984). Added sugar and sweeteners such as dextrose and corn syrup solids soften the hardening effects of salt and form browning products upon heating which accentuate the flavor of cured meat.
products. Finally, water is added to cured meat systems as a mode of transport in which the other non-meat ingredients are carried.

**Oxidation in Meat Systems**

Oxidation is the process of taking electrons away from a molecule, which gives that molecule a more positive net charge. Oxidation in meat systems may occur by electron transfer, hydrogen abstraction, or exchange of free electrons (McMillan 1996). Oxidative processes in meat systems may affect unsaturated fatty acids, amino acids in proteins, heme groups in pigments, and conjugated double bonds in vitamins. Factors affecting oxidative processes in muscle foods include inherent muscle properties, storage and processing to cause pigment or lipid degradation, metal ions, pH, enzymes, salts, heating, freezing, light exposure, and exposure to air or oxygen (McMillan 1996).

Oxidation of fatty acids is given the term lipid oxidation or oxidative rancidity. Lipid oxidation is one of the main factors limiting the quality and acceptability of meats and meat products (Morrissey and others 1998). This acceptability is dependent upon the extent in which oxidative rancidity has occurred (Gray 1978). Fortunately, all muscle foods have inherent antioxidant properties, which can be classified as lipid, cytosolic, and enzymic antioxidant systems. The functionality of these three systems is dependent on animal species, muscle type, and diet. Lipid and cytosolic antioxidant systems primarily scavenge free radicals and chelate free metal ions. The amounts of lipid and
cytosolic antioxidant activity are dependent upon diet and anatomical location as a result of muscle fiber type. In addition, antioxidant enzymes catalyze conversion of highly reactant oxidation species to less reactive products. Furthermore, added antioxidants such as nitrites, ascorbates, and polyphosphates can be added to control lipid oxidation caused by increased oxygen exposure as a result of grinding or chopping which are commonly performed in the production of meat products. Nitrite inhibits lipid oxidation by stabilizing lipid membranes, chelating free iron, and stabilizing the iron heme complex. Ascorbates have the ability to regenerate α-Tocopherol, which can scavenge free radicals when incorporated into muscle. Finally, polyphosphates function as chelators of prooxidant metals which are active lipid oxidation catalysts (Kanner 1994; Decker and Mei 1996; Morrissey and others 1998).

Lipid oxidation of an unsaturated fatty acid occurs in three phases; initiation, propagation, and termination (Fig. 3). Initiation occurs when a hydrogen atom (H) is eliminated from an unsaturated fatty acid (RH) by bonding with oxygen (O₂) or other catalysts. The propagation step results from the formation of a fatty acyl radical (R•) which reacts with oxygen, forming a peroxy radical (ROO•). It is in the propagation step that a chain reaction is set off, further oxidizing remaining unsaturated fatty acids when more radicals are produced (Morrissey and others 1998). Propagation is completed in the termination step when oxygen becomes unavailable to bind with the fatty acyl radical.
Initiation

$$ RH + O_2 \rightarrow R^\cdot + \cdot OH $$

Propagation

$$ R^\cdot + O_2 \rightarrow ROO^\cdot $$
$$ ROO^\cdot + RH \rightarrow ROOH + R^\cdot $$

Termination

$$ R^\cdot + R^\cdot \rightarrow RR $$
$$ R^\cdot + ROO^\cdot \rightarrow ROOR $$
$$ ROO^\cdot + ROO^\cdot \rightarrow ROOR + O_2 $$

Figure 3. Mechanism for Lipid Oxidation (Gray 1978)

Nitrite added to cured meats has an important antioxidant effect upon lipid oxidation (Shahidi and others 1991). It has been proposed that nitrite and its products have the ability to stabilize the iron heme complex (Killday 1988), effectively preventing heme iron from reacting with unsaturated fatty acids. This is important as iron (Fe$^{2+}$ and Fe$^{3+}$) can react with lipid hydroperoxides (ROOH) found in the propagation step to form peroxyl radicals (ROO•) and alkoxyl radicals (RO•) that readily react with oxygen (Morrissey and others 1998). Another proposed mechanism for nitrite and its products that prevent lipid oxidation is the stabilization of double bonds at which free radicals can attack. Erduran and Hotchkiss (1995) proposed that dinitrogen trioxide (N$_2$O$_3$), a product of nitrite
(2NaNO₂ + 2 H⁺ → N₂O₃ + H₂O + 2 Na⁺) addition, substantially inhibited but did not completely block volatile oxidation products from the fatty acid triolein.

Lipid oxidation in meat systems is most commonly measured using the 2-thiobarbituric acid test (TBA) or slightly modified versions of this method. The TBA test was developed by Tarladgis and others (1960) and measures the mg of malonaldehyde per 1000 g of product in the test sample. Malonaldehyde is a dicarbonyl product resulting from the oxidation of unsaturated fatty acids. A correlation coefficient of 0.89 has been found between detection of rancid samples by sensory taste panel and TBA number. Furthermore, a threshold range of 0.5 to 1.0 has been reported for detection of off-odor in fresh ground pork ham (Tarladgis and others 1960).

Irradiation and Lipid Oxidation

There are conflicting reports in regards to irradiation-induced oxidation in meat products. This contradiction is dependent upon packaging environment, and whether or not the product is cooked or cured. Lefebvre and others (1994) reported that peroxide values of ground beef, aerobically packaged and irradiated from 1-5 kGy, were 9-12 times higher than controls at day 0. Peroxides are the primary products of fat oxidation upon ionizing radiation in the presence of oxygen and can be used as indicators of the extent of lipid oxidation. Luchsinger and others (1996) found that aerobically-packaged pork chops had higher TBA values following 1.5 and 2.5 kGy irradiation doses depending on
storage time (P<0.05 at 14 days for 1.5 kGy and P<0.05 at 7 days for 2.5 kGy). However, TBA values for anaerobically packaged products, such as ground pork irradiated at 1 kGy, showed no difference (P>0.05) when compared with controls (Ehioba and others 1987). These data agree with Luchsinger and others (1996), in which vacuum-packaged pork chops irradiated from 1.5 to 2.5 kGy exhibited no change (P>0.05) in TBA values when compared with controls. This conflicts with Zhao and Sebranek (1996) in which anaerobically packaged pork chops had significantly higher TBA values at day 1 and 2 wks of storage after irradiation at a dose of 1 kGy compared with nonirradiated control. However, TBA values for both irradiated and non-irradiated controls were well below the 1.0 mg/kg threshold.

Oxidation of cooked uncured meat products has been shown to increase as a result of exposure to oxygen. This is due in part by the production of free heme iron and enhanced oxygen contact with membrane lipids due to the cooking process (Ahn and others 1993, 1998). Suppressed oxidation in cooked meat products has been reported in previous research involving high dose irradiation at 48 kGy (Chang and others 1961; Green and Watts 1966). One explanation for this phenomenon was that malonaldehyde may have undergone secondary reactions at these high radiation doses resulting in a lower TBA value and disguising the amount of rancidity found in irradiated products. This, however, is not the case according to Green and Watts (1966), who demonstrated that irradiated product had three times less oxygen uptake than
control, thereby showing an antioxidant effect. It was hypothesized that irradiation produced an antioxidant compound unknown to the authors.

There have been mixed results regarding antioxidant benefits of medium-dose irradiation (1-10 kGy). Shahidi and others (1991) reported that homogenized vacuum-packaged cooked pork irradiated at 5 and 10 kGy had lower TBA values than non-irradiated control. However, Ahn and others (1998; 1999) found that irradiation did not seem to impact cooked meat oxidation nearly as much as did oxygen availability in cooked ground pork patties and sausages. Pork sausages irradiated in anaerobic environment had higher TBARS values only on day 0 for treatments with 2.5 kGy and 4.5 kGy compared with nonirradiated control and showed no difference in TBARS values after day 0 for any irradiation dose and storage date up to 8 days. This was not the case in regard to the aerobically packaged products where TBARS values increased significantly for all treatments as storage time increased, regardless of irradiation dose.

It is known that nitrite addition to meat prevents lipid oxidation (Shahidi and others 1991). This also seems to be the case with irradiated cured meats. Shahidi and others (1991) found lower TBA values for cooked, pork homogenate cured with 156 mg/kg nitrite over all storage days (0-21 days) and irradiation doses of 0, 5, and 10 kGy compared with uncured irradiated pork homogenate. Fu and others (1995a) found no difference between TBA values of irradiated cured ham slices subjected to doses of 0, 0.9, and 1.8 kGy over a storage period
of 9 days. This work agrees with Shahidi and others (1991) in which no increase in TBA values were reported for cooked, cured pork homogenate irradiated under anaerobic conditions at 0, 5, and 10 kGy over a 21 day storage period. In fact, these researchers found that irradiation at 5 and 10 kGy actually improved lipid stability over the 21 day storage period compared with the nonirradiated control. However, Terrell and others (1981a) found a significant increase in TBA values for anaerobically packaged frankfurters exposed to irradiation dose levels of 8-32 kGy compared with nonirradiated control. It must be realized that all of the aforementioned studies had a limited time frame when comparing oxidative stability. It is not uncommon to find cured ready-to-eat meat products with shelf life of over 90 days. Therefore, it would seem necessary to study oxidative changes over a longer period of time to find out if irradiation is viable for cured, ready-to-eat meat products.

**Fresh Meat Color**

Gove (1981) defines color as “any of manifold phenomena of light or of visual sensation or perception that enables one to differentiate objects even though the objects may appear otherwise identical.” This is a very accurate description of color in the context of meat if one recognizes that, except for color, it would be hard to distinguish between two different cuts of meat given that they were the same size and chemical composition. It should come as no surprise that color is one of the most important characteristics consumers rely on to
determine the freshness of a cut of meat. The consumer's perception is psychological in which a negative or positive reaction is directly related to the meat cuts desirability based upon color (Hiner 1954). Therefore, it is no surprise that research involving meat color has been very extensive.

The basis of our understanding of meat color starts with the myoglobin molecule. Myoglobin is a globular heme protein consisting of 140-160 amino acid residues, depending upon species of animal. The myoglobin molecule contains 90-95% of the total iron found in the muscle cell. It is this iron, contained within the myoglobin molecule, that is responsible for the majority of fresh meat color. The heme iron is held within the myoglobin molecule by an attachment to the proximal histidine at the 5th ligand of iron. The sixth ligand of iron determines the meat pigment oxidation state (Renerre 1999).

Fresh meat pigment is most commonly found in one of three forms: myoglobin, oxymyoglobin, and metmyoglobin. Myoglobin is the unoxygenated pigment found when the iron atom is in a reduced state (Fe$^{2+}$). The occupant of the sixth ligand is a water molecule. The color of myoglobin is purple and is most often associated in the meat industry with fresh, vacuum-packaged meat products. Consumers at a grocery store meat counter would be most familiar with the pigment known as oxymyoglobin. Oxymyoglobin imparts the characteristic bloom or cherry-red pigment found when the myoglobin molecule has been oxygenated at the sixth ligand. Finally, the metmyoglobin pigment is found when the iron molecule has been oxidized from the Fe$^{2+}$ charge to the Fe$^{3+}$
charge. The occupant of the sixth ligand is either a water molecule or a hydroxyl molecule. Most consumers use the color imparted by the pigment as a means to determine if meat lacks freshness, as the meat turns brown with age.

The three pigments of fresh meat color are constantly being interconverted in fresh, postmortem muscle (Fig. 4). Fresh postmortem muscle has inherent reducing abilities such as metmyoglobin reductase, that allow the reformation of myoglobin from metmyoglobin in the presence of oxygen (Faustman and others 1996). The process of oxygenation, which causes the bloom effect in fresh meat, is dynamic in that oxygen constantly associates and disassociates from the heme complex. This constant change results in eventual depletion of reducing agents causing increased oxidation to the metmyoglobin form (Fox 1966).

![Figure 4. Fresh Meat Pigments (Modified from Pearson and Tauber 1984)](image-url)
Meat color is affected by many different factors that can be separated into intrinsic and extrinsic variables, all of which contribute to the oxidative stability of the heme complex. Intrinsic factors affecting fresh meat color include pH, muscle metabolic rate, species, and age. Extrinsic factors include temperature, oxygen availability, lighting, and surface microbial growth (Renerre 1999).

Measurement of changes in meat color are most commonly achieved by the use of CIE (Commission International d’Eclairage) L*, a*, b* values. L* values are useful in determining change in lightness with a value of 0 equal to black and 100 equal to perfect white. A positive a* value indicates redness whereas a negative a* value represents greenness. The a* value is most commonly used for meat products to see treatment effects regarding an increase or decrease in redness. The b* value measures the degree of yellowness with a positive value whereas a negative value would yield the degree of blueness. Several combinations of these variables such as hue angle ($\tan^{-1} \frac{b}{a}$) or saturation index $(a^2 + b^2)^{1/2}$ may be used to determine color changes over treatment time. In addition to the L*a*b* values, reflectance spectra may be used to indicate color changes. Reflectance spectra utilizes an x and y-axis representing wavelength in nanometers and % reflectance. Reflectance spectra and reflectance ratios derived at specific wavelengths can be useful in determining pigment content and extent of color fading (Hunt and others 1991).
Irradiation Effects on Fresh Meat Color

Of the previously mentioned factors listed, irradiated fresh meat color seems to be impacted the most by packaging environment, species, and irradiation dose levels. Nanke and others (1998) reported no difference in L* values for anaerobically packaged pork, beef, and turkey at irradiation doses of 0 -10.5 kGy. On the other hand, a* and b* values seem to be dependent upon species and anaerobic packaging environments. Fu and others (1995a) reported that a* values increased for anaerobically packaged pork with an irradiation dose of 2.0 kGy. Additional research conducted by Luchsinger and others (1996) and Nanke and others (1998) has confirmed this increase in redness. Nanke and others (1998) described the same effect for turkey a* values up to a 4.5 kGy dose above which no increase in redness was observed. However, beef a* values generally change in an opposite fashion. Nanke and others (1998) observed a decline in beef a* values with up to a 4.5 kGy dose. With regard to b* values, anaerobically packaged pork and turkey have shown increases with increasing radiation dose (Luchsinger and others 1996; Nanke and others 1998). In contrast, beef b* values showed no change until irradiation dose levels reached 10.5 kGy (Nanke and others 1998).

Aerobically packaged meat seems to react much differently with regards to species. Luchsinger and others (1996) reported no change in L* values for aerobically packaged pork when irradiated. This research agrees with Nanke and others (1999) in which no change in L* value was observed in aerobically
packaged pork and turkey irradiated at doses from 0-10.5 kGy. While anaerobic packaging increased pork a* values in irradiated samples, a decrease in a* values has been observed over storage time for irradiated pork in an aerobic packaging environment (Luchsinger and others 1996; Nanke and others 1999; Millar and others 2000). This is also the case for beef. Nanke and others (1999) reported lower a* values as irradiation dose level increased from 0-10.5 kGy. These data agree with Miller and others (2000) in which a* values were lower (P<0.001) for beef irradiated at 5 kGy regardless of storage day. Aerobically packaged turkey, on the other hand, exhibited no change (P>0.05) for either a* or b* values regardless of irradiation doses of 0-10.5 kGy (Nanke and others 1999). Most research agrees that b* values decrease in aerobically packaged beef with the application of irradiation. Nanke and others (1999) reported lower b* values for all doses of 1.5-10.5 kGy compared with nonirradiated control. This agrees with Millar and others (2000) who found consistently lower b* values for aerobically packaged beef irradiated at 5 kGy compared to nonirradiated control. Research conducted using pork has revealed some inconsistencies with regard to irradiation effects on b* values. Luchsinger and others (1996) reported an increase in b* values for irradiated, aerobically packaged pork for doses of 1.5 and 2.5 kGy over a 14 day storage period. This contradicts Nanke and others (1999) in which pork b* values decreased (P<0.05) with irradiation doses from 1.5-10.5 kGy. However, both studies are in general agreement with Millar and
others (2000) in which $b^*$ values were shown to decrease initially for day 1 but showed an increase over nonirradiated control at days 6 and 7.

**Cured Meat Color**

The characteristic pink color of cured meat is important in the eye of the consumer, much like the characteristic bright red oxymyoglobin pigment is in fresh meat. Cured meat color is widely known to be the result of the addition of nitrite to the meat formula. It is believed that, originally, nitrite was probably first added accidentally to the curing process by addition of contaminated salt (Hedrick and others 1994). Like fresh meat, cured meat color is a result of the oxidation state and occupant of the sixth ligand of the heme iron complex. Nitric oxide (NO), formed as a product of nitrite addition, binds to the sixth ligand position of myoglobin. Upon denaturation of the myoglobin protein, the characteristic cured meat pigment known as nitrosohemochrome is formed (Killday and others 1988).

Prior to the attachment of nitric oxide to the myoglobin molecule, the nitric oxide must be produced from nitrite ($\text{NO}_2^-$). The process of nitric oxide production can occur from many different chemical pathways, however only three mechanisms of importance will be discussed (Fig. 5). The first of these pathways involves the conversion of nitrous acid ($\text{HNO}_2$) to nitric oxide (NO), nitric acid ($\text{HNO}_3$), and water ($\text{H}_2\text{O}$). The second method results from the reduction of nitrite by endogenous reductants found in the muscle tissue. The third and final
method results from reduction of nitrite by means of added reducing agents such as ascorbate and erythorbate.

The last two pathways yield the majority of nitric oxide production in cured meat products, due to the strong acid environment required for the reaction with nitrous acid (Sebranek and Fox 1985). Although it is hard to quantify the extent at which endogenous reductants affect nitric oxide production, it is beneficial to add additional reducing agents such as sodium ascorbate and sodium erythorbate. Lee and Shimaoka (1984) determined that added erythorbate decreased residual levels of nitrite in bologna-style sausages. This decreased residual nitrite content would indicate that more nitrite was converted to nitric oxide to be used for cured color development. This conclusion agrees with previous work of Brown and others (1974) in which added ascorbate was shown to decrease residual nitrite and increase cured color development in nitrite-cured hams.

1. \( \text{HNO}_2 \rightarrow \text{HNO}_3 + \text{NO} + \text{H}_2\text{O} \)
2. \( \text{NO}_2^- + \text{Endogenous reductants} \rightarrow \text{NO} \)
3. \( \text{NO}_2^- + \text{Ascorbate or Erythorbate} \rightarrow \text{NO} \)

Figure 5. Generation of Nitric Oxide (Sebranek and Fox 1985)
The process of nitric oxide production is dependent upon several factors including pH, temperature, and time. The pH is a factor in nitric oxide production realizing a lower pH would increase the conversion of nitrous acid to nitric oxide. A shift in pH is especially important if alkaline phosphates are used in commercial meat curing solutions. Prusa and Kregel (1985) and Ahn and Maurer (1989) concluded that added phosphate effectively increased pH, decreasing nitric oxide production determined by evidence of a higher residual nitrite concentration in finished poultry products. Acton and Dick (1977) implicated the importance of temperature for the development of cured color in the production of fermented sausages. It was determined that nitric oxide heme pigment conversion increased (P<0.05) with increasing temperature increments (0-38°C) over the fermentation period. It must be noted that this effect was also dependent on an increasingly acidified environment from 5.9 to 4.8 pH. Furthermore, time is an important factor because all chemical reactions are rate dependent. Lee and Cassens (1976) reported that at minimum, a 2 hour period was necessary for 90% of nitrite to be converted to nitric oxide and to bind with myoglobin, yielding nitrosomyoglobin.

As nitric oxide is produced in the postmortem muscle from the addition of nitrite, oxidation state of the myoglobin molecule may also change from the myoglobin (Fe$^{2+}$) state to the oxidized metmyoglobin (Fe$^{3+}$) form (Fig. 6). Once the metmyoglobin pigment is formed, nitric oxide can then attach at the sixth ligand position of the heme complex yielding nitrosyl metmyoglobin. The next
step in the process results from the autoreduction of the heme complex to form nitrosyl myoglobin radical cation. The nitrosyl myoglobin radical is then further reduced at the protein portion of the molecule to form nitrosyl myoglobin. The completion of the curing reaction involves the denaturation of the nitrosyl myoglobin protein, in which the heme complex becomes detached. This process of denaturation occurs primarily as a result of thermal processing in cured meat production. The resulting pigment formed from protein denaturation is the characteristic pink nitrosohemochrome pigment (Killday and others 1988).

Although the nitrosohemochrome pigment is more stable than the nitrosyl myoglobin pigment, both are susceptible to oxidation in the presence of light and oxygen. Walsh and Rose (1956) reported that the oxidative stability of nitric oxide myoglobin was impacted by light and oxygen availability. It was suggested that oxygen reacted with nitrosyl myoglobin to form metmyoglobin and nitrite. It was noted that the rate of this oxidation process showed a marked increase in the presence of light. On the other hand, nitrosohemochrome does not seem to be as impacted by oxygen alone. Homsey (1957) showed that the process of cured meat pigment fading occurred as a result of the exposure to light in the presence of oxygen and not by oxygen alone. This is the principle reason that most cured meats are packaged under vacuum in the absence of oxygen if the intention is to display the product under lighted retail display conditions.
Irradiation Effects upon Cured Meat Color

It is known that cured meat color is directly related to the content of nitrite added to the curing brine. Sebranek and others (1977) reported a decrease in consumer panel appeal regarding cured color for frankfurters formulated with decreasing amounts of nitrite (156 mg/kg to 0 mg/kg). Research by Terrell and others (1982) also showed that nitrite was necessary to develop desirable internal cured color regardless of specie (beef, turkey, and chicken) for frankfurters. However, the limited amount of research conducted on cured meat color regarding the effect of irradiation has produced mixed results. The majority
of research has indicated that nitrite is essential in maintaining cured color both from sensory and analytical measurement standpoints. Terrell and others (1981a) studied the effect of irradiation dose level on color characteristics of frankfurters cured with various combinations of quantities of nitrite and nitrate ranging from 0-100 mg/kg. It was found that franks cured with 100 mg/kg nitrite had more desirable external, internal, and cured color sensory ratings than franks formulated without nitrite regardless of irradiation dose (0-32 kGy).

The ability of nitrite to protect cured color has also been affirmed by the use of L*a*b* values. Shahidi and others (1991) reported no effect of irradiation dose level on L*a*b* values for cooked, cured pork homogenate. This same study also showed a significant decrease in a* values and an increase in b* values for pork homogenate formulated without nitrite. However, Byun and others (1999) proposed that irradiating pork loin without nitrite at 5 and 10 kGy could attain cured color. These researchers reported equivalent a* values for uncured pork resulting in comparable color characteristics to nitrite-cured pork. This latest research on irradiation for cured meat seems to refute all previous research to date concerning the essential role of nitrite in cured meat systems as it relates to color.

Measurement of residual nitrite has been useful in studying the effect of added ingredients upon cured color development. Irradiation has been linked to decreasing residual nitrite and decreasing internal and external color in cured and cooked pork products (Terrell and others 1981b). Szczawinski and others
(1989) studied the destruction of residual nitrite by irradiation, not for its effect upon color, but for its effect upon *Clostridium botulinum* inhibition. It was found that irradiation up to 9 kGy destroyed 23-34% of residual nitrite compared with control. It has been suggested that this residual nitrite may be converted to nitrate. In theory, oxidation products formed in the irradiation process including hydroxyl radicals could react with residual nitrite to form nitrate ($\text{NO}_2^- + \cdot\text{OH} \rightarrow \text{NO}_3^- + \text{H}^+$). Draudt and Deatherage (1956) indicated that nitrite and nitrate were oxidation products of nitric oxide as a result of the application of radiation on nitrosochrome pigment. However, this study did not indicate irradiation dose that was used. In addition, Shults and others (1977) found very low concentrations of nitrite in corn beef briskets that were formulated with 25-150 mg/kg nitrite and irradiated at 25-45 kGy. These same researchers also found nitrate in corned beef in which only nitrite was added. This would lead one to conclude that nitrate may be formed upon irradiation as a result of residual nitrite reacting with oxidation products. However, it is not known whether nitrate could be converted to nitrite by breaking of chemical bonds resulting from the irradiation process. Even if nitrate could be converted to nitrite during the irradiation process it would be too late to react with the myoglobin protein to form cured meat pigment as it would already be denatured in most cases. This may be the case as Shults and others (1977) reported lower sensory color scores for corned beef formulated with nitrate alone and irradiated at 25-45 kGy compared with irradiated nitrite-cured beef.
Sensory Odor Characteristics of Irradiated Meats

Color and oxidative stability are important factors that influence consumer perception of meat products. However, the consumer’s sense of smell must also find a product pleasing in order for repeat purchasing to occur.

Odor panel scores involving uncured irradiated meats have yielded mixed results. Heath and others (1990) concluded that electron beam irradiation (1-3 kGy) produced detectable odor in raw chicken thighs. These same researchers discovered that once the product was cooked, the off-odor could be detected in the 2 and 3 kGy treatments but not in the 1 kGy treatment group. Chicken breast meat was also analyzed at the same dose levels and found to be less likely to form off-odors. It was hypothesized that since the thighs had skin attached at the time of irradiation that increased oxidation and off-odors occurred due to a greater amount of fat contained in the skin.

This research agrees with Fu and others (1995b) in which beef steaks irradiated at 0.6 and 1.5 kGy had consistently higher (though not significant P>0.05) off-odor scores than control regardless of packaging atmosphere. Fu et al., (1995a) also found irradiation to produce off-odors. Off-odor scores increased significantly for irradiated injected and non-injected pork chops as irradiation dose increased from 0.0 to 2.0 kGy.

In contrast, Fu and others (1995b) indicated that there was no off-odor difference between aerobically packaged ground beef irradiated at doses from 0-2.0 kGy. This research agrees with findings by Zhao and Sebranek (1996) in
which no differences in off-odor were detected for anaerobically packaged pork chops at doses of 0.0 to 1.0 kGy.

Cured meat products share the same inconsistencies regarding whether or not irradiation causes off-odors. Shults and others (1977) found that off-odor in cooked corned beef increased as measured by 21-member sensory panel after irradiation at 25 kGy. Terrell and others (1981a; 1981b) studied irradiation effects on quality attributes in frankfurters. Both studies concluded that irradiation increased off-odor development as irradiation dosage increased from 0.0 to 8.0 kGy. However, Fu and others (1995a) reported no increase in off-odor development due to irradiation doses from 0.0 to 1.8 kGy for anaerobically packaged cured ham slices.

**Summary**

Irradiation is a viable method to control *Listeria monocytogenes* and other pathogenic organisms as a result of post-thermal process contamination in ready-to-eat cured meat products. However, research conducted to evaluate quality changes occurring over an extended shelf life for cured meats treated with radiation has not been undertaken. In addition, research focusing on quality attributes of cured-color stability in cooked cured meats formulated with radiation-treated raw meats and pre-blended meats has not been extensively studied. Therefore, the objective of this research is to determine the fate of residual nitrite,
cured meat color, oxidative stability and sensory odor scores in ready-to-eat ham as affected by irradiation at various processing steps.

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CHAPTER 3. EFFECTS OF IRRADIATION ON PROPERTIES OF CURED HAM

A paper to be submitted to the Journal of Food Science

Terry A. Houser, Joseph G. Sebranek, and Steven Lonergan

Abstract

The quality characteristics of cured ham, manufactured with the application of ionizing radiation (4.5 kGy) to fresh uncured ham (raw), fresh cured ham (pre-blend), cured cooked ham (cooked), and non-irradiated control were compared during a 90-120 day storage period. Irradiation processing increased lipid oxidation (TBA) for all treatments. The pre-blend treatment showed significantly lower L* values compared with control regardless of storage period. All treatments except for cooked ham had lower b* values over the storage period. No changes in residual nitrite concentrations were observed for any irradiation treatments for day 0 compared with day 90. The cooked ham treatment had higher off-odor scores than all other treatments on day 0.

Keywords: Irradiation, nitrite, color, oxidation, ham.

Introduction

Increasing concern over pathogenic, microbial contamination of red meat and poultry products has prompted the USDA to approve medium dose (1-10 kGy) irradiation for some food applications. As of February 22, 2000, fresh red
meats may be irradiated up to 4.5 kGy and frozen red meats may be irradiated to 7.0 kGy (USDA 1999). Although thermal processing is the current method of choice for *L. monocytogenes* destruction by the meat industry (Wilson 1988), post-heating contamination resulting in food-borne illness has been cause for great concern in ready-to-eat (RTE) processed meats (Grau and Vanderlinde 1992; Wang and Muriana 1994). Medium-dose irradiation (1-10 kGy) is not approved for use in processed meats at this time, even though it has been proven to reduce or eliminate pathogens such as *L. monocytogenes* in pre-packaged RTE meats (Fu and others 1995; Gürsel and Gurakan 1997). An average D-value for *L. monocytogenes* of 0.45 kGy has been determined using mechanically deboned chicken meat (Huhtanen and others 1989). Therefore, a 5-log reduction of *L. monocytogenes* should be achieved with an average absorbed dose of 2.5 kGy. Furthermore, irradiation treatment of RTE meats coupled with the mandatory HACCP (USDA 1996) program would produce a microbiologically safe product conforming to USDA's zero tolerance policy for *L. monocytogenes* (USDA 1989).

Although irradiation can reduce or eliminate microbial pathogens, it may also produce some undesirable quality effects in RTE meats. Most of the research performed with RTE meats reporting quality losses has been done with high-dose irradiation (>10 kGy). Kamerei and others (1981) reported that irradiation at 32 kGy altered the cured color of ham to a brown color (radiation-induced fading). This agrees with Terrell and others (1981a), who found
significantly (P<0.05) less desirable internal, external, and cured color for irradiated (32 kGy) frankfurters compared with non-irradiated control. Studies involving medium-dose irradiation (1-10 kGy) have not been conclusive. Shahidi and others (1991) reported that irradiated (4.2 kGy) ground pork loin, cured with 156 ppm sodium nitrite and 550 ppm sodium ascorbate exhibited decreased (P<0.05) Hunter a (redness) values, and increased (P<0.05) b (yellowness) values over a 21-day storage period. On the other hand, commercially formulated vacuum-packaged irradiated hams (1.8 kGy) exhibited no difference (P>0.05) for pH, Hunter L, a, and b values over a 9-day storage period (Fu and others 1995) this study also reported no change (P>0.05) in sensory panel scores for color and odor of hams measured after irradiation on day 0.

Shahidi and others (1991) reported that TBA values decreased (P<0.05) in cured ground pork compared with non-irradiated control at days 7-21 of refrigerated storage. It was suggested that the antioxidant effect of nitrite may have been enhanced by the conversion of residual nitrite to nitric oxide facilitated by irradiation (4.2 kGy). This could be the case as Szczawinski and others (1989) found a dose-dependent decrease in residual nitrite content for cured, cooked, ground pork slurries treated by irradiation. For example, a 9 kGy dose reduced residual nitrite by 25-34% compared with non-irradiated control.

In previous studies involving cured meat, it has not been possible to clearly define the effect of irradiation on color stability, lipid oxidation and residual nitrite content, particularly during extended storage. Commercial hams, and RTE
meats in general, have a shelf life in excess of 60 days. Thus, the objective of this research was to determine the effect of medium-dose irradiation on selected properties of RTE cured ham. The investigation concentrated on cured color stability, lipid oxidation and residual nitrite over an extended storage period. Further, it is not clear whether irradiation for cured meats is best applied to unprocessed, pre-blended or cooked products. We hypothesized that irradiation will have minimal effects on treated raw meat trimmings to be used for cured meat processing. However, it is also hypothesized that radicals, formed during the irradiation process, will have a detrimental effect on the formation of nitric oxide in pre-blended meats. Thus, research was initiated to facilitate our understanding of potential advantages or disadvantages induced by irradiation treatment when applied at different steps in the production of cured meats.

**Materials and Methods**

Porcine semimembranosus and biceps femoris (ham) muscles were obtained from the Iowa State University Meat Laboratory (Ames, IA., U.S.A.). The ham was trimmed free of fat with a Townsend Model 7600 membrane skinner (Townsend Eng., Des Moines, IA., U.S.A.) and cut into three portions. These ham pieces were then mixed together and randomly assigned by weight to 4 different treatment groups, a control and irradiation at three different points in the ham production process. A Townsend Model 1450 injector (Townsend Eng., Des Moines, IA., U.S.A.) was used to pump all ham pieces to a target 125% of
initial green weight with curing brine. Final concentrations of curing ingredients in pumped products were 2.5% sodium chloride, 1.5% sugar, 0.35% sodium phosphate (100% tripolyphosphate), 550 ppm sodium erythorbate and 200 ppm sodium nitrite. Ham pieces were then macerated with a Stork Protecon Model PMT-41 macerator (Stork RMS-Protecon Inc., Gainesville, GA., U.S.A.). Next, the ham pieces were vacuum tumbled with an Inject Star Model VMS-77 vacuum tumbler (Globus Lab. Inc. Vienna, Austria) continuously for 2 hours. Curing brine was added to the tumbler to achieve desired 125% pump retention. Ham pieces were transferred to Cryovac CN590 cook-in bags (Cryovac Sealed Air Corp. Duncan, SC., U.S.A.), vacuum-packaged and placed into stainless steel ham molds. The cook-in bags had an O₂ transmission rate of 20 cc/m²/24hr at 1 atm, 22.8°C, and 0% relative humidity (RH). Hams were then transferred to an Alkar one-truck thermal processing oven (Alkar, Lodi, WI., U.S.A.). Cooking was conducted at 79.4°C with 100% RH for the entire process until an internal ham temperature of 70°C was reached. After thermal processing, hams were chilled for 12 hrs at 2-4°C. The whole hams were removed from molds and sliced to a 5mm thickness with a Hobart Model 1712 slicer (Hobart Corp., Troy, OH., U.S.A.). Slices were then placed into Cryovac B540 vacuum bags (Cryovac Sealed Air Corp., Duncan, SC., U.S.A.) and vacuum packaged with a Multivac Model A6800 vacuum packaging machine (Multivac Inc., Kansas City, MO., U.S.A.). Packaging film had an O₂ transmission rate of 3-6 cc/m²/24hr at 1 atm, 4.4°C, and 0% RH, and a water vapor transmission rate of 0.5-0.6 g/645 cm²/24
hr and 100% RH. Ham slices were stored at 2-4°C for the entire storage period of up to 120 days. The experiment was replicated 4 times on 2 separate production days.

Irradiation of ham samples took place at the Iowa State University Meat Laboratory Linear Accelerator Facility (LAF). Samples were irradiated by a CIRCE IIIR electron beam irradiator (Thomson CSF Linac., Saint Aubin, France) with an energy level of 10 MeV and a power level of 10 kw. Average dose rate for all treatments was 104.4 kGy / min and conveyor speed was set at 3.048 m/min in order to achieve required dose rate. All treatments except the control received an average absorbed irradiation dose of 4.5 kGy. Average absorbed doses were confirmed using 99% pure alanine dosimeters (Bruker Inst. Inc., Billerica, MA., U.S.A.) measured by a EMS 104 Electron Paramagnetic Resonance instrument (Bruker Analytische Messtechnik, Karlsruhe, Germany). Irradiation treatments were applied at three separate points in the sequence for the ham production process (Fig. 1). For treatment #1 (raw), meat was irradiated as a fresh uncured product just prior to injection. For treatment #2 (pre-blend), meat was irradiated as a fresh cured product after injection and maceration but prior to tumbling. Treatment #3 (cooked) was irradiated as a cooked, cured, and sliced product following completion of the heating process. Control samples received no irradiation treatment. All irradiation treatments were applied under anaerobic (vacuum-packaged) conditions.
Color measurements were conducted after 0, 15, 30, 60 and 90 days of storage, using a Hunterlab Labscan colorimeter (Hunter Associated Laboratories Inc., Reston, VA., U.S.A.). Day 0 represented the day that samples were sliced and vacuum-packaged. The Hunterlab colorimeter was standardized using a piece of packaging material over the white standard tile and all color measurements were performed on vacuum-packaged samples. Values for the white standard tile were $X=81.72$, $Y=86.80$, and $Z=91.46$. Illuminate A, $10^\circ$ standard observer, and a 4.445 cm viewing port area were used to calculate CIE values. CIE $L^*$ (lightness), $a^*$ (redness), and $b^*$ (yellowness) were measured simultaneously for all treatments (Hunt and others 1991). Color measurements were taken at 4 randomly selected areas for each treatment on the same slice throughout the 90-day storage period.

Lipid oxidation was measured by the modified 2-Thiobarbituric Acid (TBA) test (Zipser and Watts, 1962). TBA values were determined after 0, 15, 30, 60 and 90 days of storage with day 0 representing the day the samples were sliced and vacuum-packaged.

Residual nitrite level was measured in parts per million by the AOAC (1990a) method for all treatments following 7, 15, 30, 60 and 90 days of storage. Day 7 was chronologically 7 days after the product was sliced and vacuum-packaged.

Proximate composition was determined on all treatments for crude fat (ether extract method, AOAC 1990b), moisture (air oven drying method, AOAC
1990c) and crude protein (combustion method, AOAC 1993). All samples were analyzed in duplicate.

Purge loss was measured 120 days after slicing and vacuum packaging. Three samples per treatment were utilized. Samples were weighed in the package, then taken out of the package and wiped clean of excess moisture. Packaging material and sample were then reweighed and the difference calculated as a percent purge.

Cook yields for each of the sixteen ham groups produced were calculated using the pre-cook weight and post-cook weight 12 hrs after cooking was completed and just before slicing and packaging. Cook yields were expressed as percent finished product divided by the initial weight prior to cooking minus the weight of the cook-in bag.

Sensory odor evaluations were conducted for all treatments at 0, 15, 30, 60, and 90 days after processing. Each sample was warmed in a water bath while the vacuum package was still intact. Trained panelists (10-12) made up of Iowa State University students and staff were used for each session. Panelists were trained to distinguish between samples irradiated at 0 and 8 kGy using 0 kGy to represent no off odor and 8 kGy sample to represent distinct off odor. The 8 kGy sample was a cured, cooked, vacuum packaged ham slice. This permitted panelists to distinguish irradiation odor from normal ham odors. Panelists then evaluated samples using a line scale with graduations from 0-150 mm (Fig. 2), using 0 to represent no off-odor and 150 to represent intense off-
odor. Sample packages were opened by panelists after heating and immediately evaluated for odor.

This experiment was replicated 4 times over a 5-month period. Statistical analysis was performed for all measurements using the Statistical Analysis System (SAS 2000) mixed model procedure. The fixed effects were treatment and storage day. Random effects were replicate within treatment. Least squares means were used to determine level of significance at $P<0.05$.

Results and Discussion

There was no significant difference ($P>0.05$) in fat, moisture, or protein regardless of treatment (Table 1). There were no significant differences in cook yields manufactured for any treatment (Table 2). No differences ($P>0.05$) in purge loss percent were observed for any treatment (Table 3). These results indicate that hams were similar in chemical composition.

All treatments receiving irradiation processing had significantly higher ($P<0.05$) TBA values than non-irradiated control (Table 4). Although there were significant differences, all treatments were well below the threshold of oxidative rancidity of 0.5-1.0 as reported by Tarladgis and others (1960). In addition there were no differences ($P>0.05$) observed between treatments that were irradiated. No differences in TBA values were observed over the storage time within treatment (Table 5). This would indicate that nitrite was able to inhibit lipid oxidation over extended storage regardless of the application of irradiation at the
different ham production processing steps. This contradicts findings by Shahidi and others (1991) who reported increased TBA values for cooked cured pork homogenate over a 21-day storage period and a range of irradiation dosage (0-10 kGy). These researcher's findings may be the result of increased oxygen exposure to lipids as a result of homogenization in sample preparation. This would agree with Ahn (1998; 1999) who reported that irradiation (2.5-4.5 kGy) did not impact oxidation in cooked ground pork patties as much as oxygen availability. In addition, higher TBA values may have resulted in our experiment as a result of irradiation processing if the lipid fraction was higher in the manufactured hams, as fat content was very low (1.9-2.1 %).

The effect of irradiation treatment for color measurements taken by Hunterlab for CIE L* (lightness), a* (redness) and b* (yellowness) for cooked ham slices are reported in Table 6. The control and raw irradiated hams had significantly higher L* values than the pre-blend treatment group which would indicate that the pre-blend treatment was darker in appearance. This may be the result of decreased nitric oxide attachment to metmyoglobin prior to heating resulting in increased denatured metmyoglobin formation and decreased nitrosyl hemochrome formation. However, the pre-blend treatment was not significantly different (P>0.05) than the cooked treatment. There were no differences (P>0.05) in L* values between the cooked, raw, or control treatment. Which is consistent with findings of Fu and others (1995) who found no difference in Hunter L values for cooked ham irradiated at 0, 0.90, and 1.8 kGy. In addition,
Shahidi and others (1991) reported that Hunter L values did not change for cured cooked pork homogenate cured with 156 mg/kg nitrite and irradiated at 5 kGy compared with an untreated control. No significant differences were found between storage days for any treatment (Table 7).

CIE a* values for ham treatments showed no differences (P>0.05) as a result of treatment (Table 6) or storage day (Table 8). This would indicate that none of the treatments became less red as a result of irradiation treatment or storage period. This is consistent with findings by Fu and others (1995), who found no differences in Hunter a values as a result of irradiation treatment (0, 0.9, and 1.8 kGy) of cooked cured ham. This contradicts findings by Shahidi and others (1991) who found decreasing Hunter a values for cured cooked pork homogenate indicating a less red product regardless of irradiation dose over a 21 day storage period.

A significant interaction (P<0.05) was found between treatment and day for CIE b* values (Figure 3). All treatments except cooked treatment exhibited significantly (P<0.05) lower b* values over the 90-day storage period becoming less yellow. Whereas, cooked b* values did not decrease over storage period with the exception of day 60, which had lower b* values than day 0. Furthermore, b* values were not different between day 0 and day 90, and were significantly higher (P<0.05) than all other treatments at 90 days of storage which indicates the product was more yellow than all other treatments (Table 9). These findings agree with Fu and others (1995) who found no difference in b* values for...
irradiated (1.8 kGy) ham slices. This interaction would suggest that irradiation treatment after cooking has the ability to stabilize b* values over periods of extended storage.

Least squares means for residual nitrite content are listed in Table 10. A significant interaction was found between treatment and storage day and is illustrated in Figure 4. Irradiation treatment slowed the rate of depletion of residual nitrite content over the storage period compared with non-irradiated control. The control treatment had lower residual nitrite content on days 60 and 90 compared with day 7. The raw treatment exhibited no difference in residual nitrite content between day 7 and day 90. However, lower residual nitrite levels were shown between day 15 and day 60 and day 15 and day 90. The pre-blend treatment acted in much the same manner as the raw treatment with no differences in residual nitrite between day 7 and day 90. The pre-blend treatment also exhibited higher residual nitrite levels for day 7 compared with day 90. The cooked treatment showed no significant decrease in residual nitrite content over the storage period. The only difference found between treatments was the raw treatment had a higher residual nitrite content on day 15 compared with the cooked treatment on day 15. These results disagree with Szczawinski and others (1989), who reported a continued decrease in residual nitrite between days 7-28 days of storage for irradiated, cured (200 mg/kg) ground pork. This may be in part that Szczawinski and others (1989) stored their product at 30°C compared to 2-4°C. Increasing storage temperature has been reported to
increase the rate of residual nitrite depletion in cured minced pork (Gibson and others 1984). Shahidi and others (1991) and Byun and others (1999) suggested that irradiation might increase the reducing potential of added reducing agents. Our results suggest that this is not the case as lower residual nitrite content, which would indicate greater conversion of nitrite to nitric oxide were not found in the pre-blend treatment. In fact our results showed higher although not significantly different (P>0.05) residual nitrite contents for both treatments that received irradiation processing prior to cooking (raw and pre-blend treatments). This may indicate that free radicals produced in the irradiation process may use up the reducing ability of endogenous reductants native to the muscle tissue that are needed for the formation of nitric oxide from nitrite.

Least squares means for sensory odor panel values are listed in Table 11. A significant interaction was found between treatment and storage time, which is illustrated in Figure 5. The cooked treatment had significantly higher off-odor scores than all other treatments at day-0. However, the cooked treatment was not significantly different (P>0.05) than all other treatments at 30-90 days of storage. It must be noted that increased off-odor scores do not seem to be the result of rancid odors produced from the oxidation of lipids. Although TBA values were higher for all irradiated treatments only the cooked treatment had higher off odor scores compared with control. This contradicts Fu and others (1995), who found no sensory odor differences for ham slices irradiated up to 1.8 kGy. This is most likely due to a difference in irradiation dose level (1.8 kGy vs. 4.5 kGy).
Terrell and others (1981a, 1981b) have reported a dose dependent increase in off-odor scores for irradiated frankfurters (0-32 kGy).

Conclusions

Our results indicate that pork ham could be manufactured with the application of irradiation to raw, uncured ham, cured, uncooked ham and cured, cooked ham with minimal changes to lipid stability, proximate composition, purge loss, and cured color stability when irradiated at or below 4.5 kGy. Our experiments also show that residual nitrite depletion is stabilized by the application of irradiation over an extended storage period. Our results suggest that free radical production as a result of irradiation processing may negate the ability of endogenous as well as added reductants to convert nitrite to nitric oxide. However, it does not seem that this decrease in reducing ability has an impact on color stability initially, or over extended storage period, possibly due to the high concentration of nitrite (200 mg/kg) added in the curing process. We can also conclude that the application of irradiation to uncured, uncooked ham and cured, uncooked ham has no affect on sensory odor panel scores. However, increased off odor scores for the cured, cooked treatment compared with all other treatments including control indicate that irradiation processing has a detrimental affect upon odor acceptability from 0-30 days of storage when doses of 4.5 kGy are used.
References


Gürsel B. and Gürakan GC. 1997. Effects of gamma irradiation on the survival of Listeria monocytogenes and on its growth at refrigeration temperature in poultry and red meat. Poultry Sci 76:1661-1664


Control

Raw Trimmed Pork Semimembranous and Biceps Femoris

125% Pump of initial green weight. Salt 2.5%, Sugar 1.5%, Phosphate 0.35%, Sodium erythorbate 550 ppm, 200 ppm Sodium Nitrite Final content

Macerate

Vacuum tumble continuously for 2 hours

Place into cook-in bags and vacuum package

Cook in Smokehouse

Slice and Vacuum package

Storage for 90 days

L*a*b* Color after Day 0, 15, 30, 60, and 90

Residual Nitrite after Day 7, 15, 30, 60, and 90

TBA values after Day 0, 15, 30, 60, and 90

Sensory Odor after Day 0, 15, 30, 60, and 90

Figure 1. Outline of irradiation treatments
Odor Evaluation of Sliced Ham

Panelist ______
Date ________

Please evaluate the samples for any off odor by cutting open each bag and sniffing the product. Please write the sample number in the space provided and use a vertical line to mark your evaluation of each product.

Sample # ________

__________________________________________ Intense off odor

No off odor

Sample # ________

__________________________________________ Intense off odor

No off odor

Sample # ________

__________________________________________ Intense off odor

No off odor

Sample # ________

__________________________________________ Intense off odor

No off odor

Please add any additional comments about the products here:

Figure 2. Sensory Odor Evaluation Sheet
Table 1. Least squares means for fat, moisture, and protein of manufactured hams by irradiation treatment.

<table>
<thead>
<tr>
<th>Treatment</th>
<th>Fat (n=8)</th>
<th>Moisture (n=8)</th>
<th>Protein (n=8)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Control</td>
<td>2.08(±0.155)</td>
<td>74.62(±0.1639)</td>
<td>19.20(±0.1076)</td>
</tr>
<tr>
<td>Raw</td>
<td>1.95(±0.253)</td>
<td>75.21(±0.4214)</td>
<td>18.44(±0.2231)</td>
</tr>
<tr>
<td>Pre-blend</td>
<td>1.93(±0.144)</td>
<td>74.67(±0.2561)</td>
<td>19.35(±0.1954)</td>
</tr>
<tr>
<td>Cooked</td>
<td>1.94(±0.139)</td>
<td>74.15(±0.4554)</td>
<td>20.03(±0.5945)</td>
</tr>
<tr>
<td>S.E.M.</td>
<td>0.385</td>
<td>0.7404</td>
<td>0.7209</td>
</tr>
</tbody>
</table>

Means within the same column with different superscripts are significantly different (P<0.05).

Table 2. Least squares means for % cook yield of manufactured hams by irradiation treatment.

<table>
<thead>
<tr>
<th>Treatment</th>
<th>% Cook Yield (n=4)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Control</td>
<td>91.4(±0.829)</td>
</tr>
<tr>
<td>Raw</td>
<td>91.9(±1.53)</td>
</tr>
<tr>
<td>Pre-blend</td>
<td>93.3(±0.206)</td>
</tr>
<tr>
<td>Cooked</td>
<td>89.4(±2.40)</td>
</tr>
<tr>
<td>S.E.M.</td>
<td>2.10</td>
</tr>
</tbody>
</table>

Means within the same column with different superscripts are significantly different (P<0.05).
Table 3. Least squares means for % purge loss of manufactured hams by irradiation treatment at 120 days of storage.

<table>
<thead>
<tr>
<th>Treatment</th>
<th>% Purge loss (n=12)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Control</td>
<td>4.51 (±0.256)</td>
</tr>
<tr>
<td>Raw</td>
<td>4.55 (±0.141)</td>
</tr>
<tr>
<td>Pre-blend</td>
<td>3.99 (±0.333)</td>
</tr>
<tr>
<td>Cooked</td>
<td>4.29 (±0.261)</td>
</tr>
<tr>
<td>S.E.M.</td>
<td>0.306</td>
</tr>
</tbody>
</table>

*a-d* Means within the same column with different superscripts are significantly different (P<0.05).

Table 4. Least squares means for TBA values of manufactured hams by irradiation treatment.

<table>
<thead>
<tr>
<th>Treatment</th>
<th>TBA Value (n=40)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Control</td>
<td>0.0937 (±0.00247)</td>
</tr>
<tr>
<td>Raw</td>
<td>0.123 (±0.00442)</td>
</tr>
<tr>
<td>Pre-blend</td>
<td>0.131 (±0.00364)</td>
</tr>
<tr>
<td>Cooked</td>
<td>0.133 (±0.00303)</td>
</tr>
<tr>
<td>S.E.M.</td>
<td>0.00517</td>
</tr>
</tbody>
</table>

*a-d* Means within the same column with different superscripts are significantly different (P<0.05).
Table 5. Least squares means for TBA values of manufactured hams by irradiation treatment and storage period.

<table>
<thead>
<tr>
<th>Treatment</th>
<th>Day 0 (n=8)</th>
<th>Day 15 (n=8)</th>
<th>Day 30 (n=8)</th>
<th>Day 60 (n=8)</th>
<th>Day 90 (n=8)</th>
<th>S.E.M.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Control</td>
<td>0.0774(±0.00549)</td>
<td>0.110(±0.00491)</td>
<td>0.101(±0.00333)</td>
<td>0.0913(±0.00332)</td>
<td>0.0891(±0.00263)</td>
<td>0.0116</td>
</tr>
<tr>
<td>Raw</td>
<td>0.0974(±0.00239)(^a)</td>
<td>0.166(±0.0111)(^b)</td>
<td>0.115(±0.00448)(^a)</td>
<td>0.121(±0.00283)(^a)</td>
<td>0.114(±0.00360)(^a)</td>
<td>0.116</td>
</tr>
<tr>
<td>Pre-blend</td>
<td>0.119(±0.00898)</td>
<td>0.155(±0.00809)</td>
<td>0.118(±0.00120)</td>
<td>0.126(±0.00606)</td>
<td>0.139(±0.00651)</td>
<td>0.139(±0.00758)</td>
</tr>
<tr>
<td>Cooked</td>
<td>0.114(±0.00207)</td>
<td>0.151(±0.00531)</td>
<td>0.124(±0.00374)</td>
<td>0.137(±0.00595)</td>
<td>0.139(±0.00758)</td>
<td>0.0116</td>
</tr>
<tr>
<td>S.E.M.</td>
<td>0.114</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

\(^a\) Means within the same row with different superscripts are significantly different (P<0.05).
Table 6. Least squares means for CIE L* a* and b* values of manufactured hams by irradiation treatment.

<table>
<thead>
<tr>
<th>Treatment</th>
<th>L* (n=80)</th>
<th>a* (n=80)</th>
<th>b* (n=80)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Control</td>
<td>72.3(±0.207)a</td>
<td>16.0(±0.101)</td>
<td>11.1(±0.107)</td>
</tr>
<tr>
<td>Raw</td>
<td>72.2(±0.179)a</td>
<td>15.0(±0.112)</td>
<td>11.2(±0.0992)</td>
</tr>
<tr>
<td>Pre-blend</td>
<td>70.1(±0.208)b</td>
<td>16.3(±0.0993)</td>
<td>11.3(±0.0817)</td>
</tr>
<tr>
<td>Cooked</td>
<td>71.8(±0.134)ab</td>
<td>15.3(±0.0781)</td>
<td>12.1(±0.0552)</td>
</tr>
<tr>
<td>S.E.M.</td>
<td>0.656</td>
<td>0.460</td>
<td>0.312</td>
</tr>
</tbody>
</table>

Means within the same column with different superscripts are significantly different (P<0.05).
Table 7. Least squares means for CIE L* values of manufactured hams by irradiation treatment and storage period.

<table>
<thead>
<tr>
<th>Treatment</th>
<th>Day 0 (n=16)</th>
<th>Day 15 (n=16)</th>
<th>Day 30 (n=16)</th>
<th>Day 60 (n=16)</th>
<th>Day 90 (n=16)</th>
<th>S.E.M.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Control</td>
<td>72.2(±0.442)</td>
<td>72.0(±0.530)</td>
<td>72.7(±0.459)</td>
<td>71.6(±0.456)</td>
<td>72.8(±0.420)</td>
<td>0.516</td>
</tr>
<tr>
<td>Raw</td>
<td>72.3(±0.313)</td>
<td>72.3(±0.425)</td>
<td>72.5(±0.403)</td>
<td>71.3(±0.426)</td>
<td>72.5(±0.396)</td>
<td></td>
</tr>
<tr>
<td>Pre-blend</td>
<td>70.1(±0.476)</td>
<td>69.9(±0.526)</td>
<td>70.8(±0.482)</td>
<td>69.4(±0.435)</td>
<td>70.4(±0.373)</td>
<td></td>
</tr>
<tr>
<td>Cooked</td>
<td>71.8(±0.222)</td>
<td>71.6(±0.367)</td>
<td>72.2(±0.260)</td>
<td>71.2(±0.311)</td>
<td>72.1(±0.286)</td>
<td></td>
</tr>
</tbody>
</table>

S.E.M. 0.802

*a-d* Means within the same row with different superscripts are significantly different (P<0.05).
Table 8. Least squares means for CIE a* values of manufactured hams by irradiation treatment and storage period.

<table>
<thead>
<tr>
<th>Treatment</th>
<th>Day 0 (n=16)</th>
<th>Day 15 (n=16)</th>
<th>Day 30 (n=16)</th>
<th>Day 60 (n=16)</th>
<th>Day 90 (n=16)</th>
<th>S.E.M.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Control</td>
<td>16.2(±0.244)</td>
<td>16.1(±0.253)</td>
<td>16.1(±0.231)</td>
<td>15.8(±0.209)</td>
<td>15.9(±0.214)</td>
<td>0.227</td>
</tr>
<tr>
<td>Raw</td>
<td>15.1(±0.253)</td>
<td>15.0(±0.199)</td>
<td>15.0(±0.223)</td>
<td>15.0(±0.213)</td>
<td>15.0(±0.223)</td>
<td></td>
</tr>
<tr>
<td>Pre-blend</td>
<td>16.4(±0.241)</td>
<td>16.3(±0.213)</td>
<td>16.1(±0.243)</td>
<td>16.2(±0.216)</td>
<td>16.3(±0.217)</td>
<td></td>
</tr>
<tr>
<td>Cooked</td>
<td>15.0(±0.245)</td>
<td>15.6(±0.125)</td>
<td>15.5(±0.132)</td>
<td>15.4(±0.158)</td>
<td>15.3(±0.176)</td>
<td></td>
</tr>
<tr>
<td>S.E.M.</td>
<td>0.503</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

*a-d* Means within the same row with different superscripts are significantly different (P<0.05).
Figure 3. The effect of irradiation treatment and storage on CIE $b^*$ values
Table 9. Least squares means for CIE $b^*$ values of manufactured hams by irradiation treatment and storage period.

<table>
<thead>
<tr>
<th>Treatment</th>
<th>Day 0 (n=16)</th>
<th>Day 15 (n=16)</th>
<th>Day 30 (n=16)</th>
<th>Day 60 (n=16)</th>
<th>Day 90 (n=16)</th>
<th>S.E.M.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Control</td>
<td>12.0(±0.230)$^a$</td>
<td>11.4(±0.197)$^{ab}$</td>
<td>11.3(±0.190)$^b$</td>
<td>10.5(±0.177)$^c$</td>
<td>10.5(±0.170)$^{cw}$</td>
<td>0.191</td>
</tr>
<tr>
<td>Raw</td>
<td>12.1(±0.164)$^a$</td>
<td>11.5(±0.213)$^{ab}$</td>
<td>11.3(±0.165)$^b$</td>
<td>10.6(±0.197)$^c$</td>
<td>10.6(±0.133)$^{cw}$</td>
<td></td>
</tr>
<tr>
<td>Pre-blend</td>
<td>12.1(±0.136)$^a$</td>
<td>11.5(±0.123)$^{ab}$</td>
<td>11.2(±0.145)$^{bc}$</td>
<td>10.7(±0.108)$^c$</td>
<td>10.8(±0.119)$^{cw}$</td>
<td></td>
</tr>
<tr>
<td>Cooked</td>
<td>12.5(±0.124)$^a$</td>
<td>12.2(±0.113)$^{ab}$</td>
<td>12.1(±0.0863)$^{ab}$</td>
<td>11.7(±0.0764)$^b$</td>
<td>12.2(±0.129)$^{abx}$</td>
<td></td>
</tr>
<tr>
<td>S.E.M.</td>
<td>0.356</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

$^a$-$^d$ Means within the same row with different superscripts are significantly different (P<0.05).

$^w$-$^z$ Means within the same column with different superscripts are significantly different (P<0.05).
Table 10. Least squares means for residual nitrite content (mg/kg) of manufactured hams by irradiation treatment and storage period.

<table>
<thead>
<tr>
<th>Treatment</th>
<th>Day 7 (n=8)</th>
<th>Day 15 (n=8)</th>
<th>Day 30 (n=8)</th>
<th>Day 60 (n=8)</th>
<th>Day 90 (n=8)</th>
<th>S.E.M.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Control</td>
<td>14.8(±1.12)a</td>
<td>14.1(±0.921)awx</td>
<td>12.5(±0.853)ab</td>
<td>7.89(±0.515)bo</td>
<td>5.29(±0.495)c</td>
<td>1.52</td>
</tr>
<tr>
<td>Raw</td>
<td>13.8(±1.67)ab</td>
<td>18.9(±1.95)aw</td>
<td>14.2(±2.02)ab</td>
<td>11.1(±1.59)b</td>
<td>8.84(±0.995)b</td>
<td></td>
</tr>
<tr>
<td>Pre-blend</td>
<td>15.1(±1.05)ab</td>
<td>15.9(±0.950)awx</td>
<td>15.1(±0.325)ab</td>
<td>11.9(±0.881)ab</td>
<td>9.85(±0.240)b</td>
<td></td>
</tr>
<tr>
<td>Cooked</td>
<td>9.32(±1.40)</td>
<td>8.60(±0.909)x</td>
<td>9.17(±1.63)</td>
<td>7.73(±0.744)</td>
<td>6.17(±0.634)</td>
<td></td>
</tr>
</tbody>
</table>

S.E.M. 2.50

\(^a-d^\) Means within the same row with different superscripts are significantly different (P<0.05).

\(^w-z^\) Means within the same column with different superscripts are significantly different (P<0.05).
Figure 4. The effect of irradiation treatment and storage on residual nitrite content
Table 11. Least squares means for sensory off-odor values of manufactured hams by irradiation treatment and storage period.

<table>
<thead>
<tr>
<th>Treatment</th>
<th>Day 0 (n=4)</th>
<th>Day 15 (n=4)</th>
<th>Day 30 (n=4)</th>
<th>Day 60 (n=4)</th>
<th>Day 90 (n=4)</th>
<th>S.E.M.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Control</td>
<td>50.1(±3.03)w</td>
<td>46.0(±4.61)w</td>
<td>55.8(±8.38)</td>
<td>32.8(±2.49)</td>
<td>36.5(±1.89)</td>
<td>5.88</td>
</tr>
<tr>
<td>Raw</td>
<td>56.9(±4.00)w</td>
<td>44.4(±5.44)w</td>
<td>49.4(±5.80)</td>
<td>46.4(±3.31)</td>
<td>41.2(±4.45)</td>
<td></td>
</tr>
<tr>
<td>Pre-blend</td>
<td>58.2(±3.42)w</td>
<td>60.6(±3.64) wx</td>
<td>50.2(±3.42)</td>
<td>50.4(±4.59)</td>
<td>43.3(±2.29)</td>
<td></td>
</tr>
<tr>
<td>Cooked</td>
<td>83.5(±6.21)ax</td>
<td>71.9(±3.90) abx</td>
<td>65.5(±1.49) ab</td>
<td>52.8(±1.94)b</td>
<td>51.3(±1.44)b</td>
<td></td>
</tr>
</tbody>
</table>

S.E.M. 8.31

^a-d^ Means within the same row with different superscripts are significantly different (P<0.05).

^w-z^ Means within the same column with different superscripts are significantly different (P<0.05).
Figure 5. The effect of irradiation treatment and storage on sensory odor scores
CHAPTER 4. GENERAL CONCLUSIONS

Applying ionizing radiation at selected processing steps yielded few practical changes in quality characteristics for cooked cured ham. Although TBA values increased statistically for all irradiated treatments they were all well below the 0.5-1.0-threshold range and therefore have no practical significance. The slight changes in L* values have no effect on cured color fading, since cured color fading is usually marked by decreasing a* (redness) and increasing b* (yellowness) values. We would therefore conclude that radiation-induced fading does not occur by applying medium dose irradiation up to 4.5 kGy at these selected steps in the ham production process. We can also conclude that irradiation does not seem to affect the level of residual nitrite in finished product that was treated at the raw or pre-blend stage. We had hypothesized that irradiation would destroy nitrite and decrease final cured color for the pre-blended treatment, both of which did not happen at doses used. Our results also indicated that if raw ham pieces treated with irradiation up to a dose of 4.5 kGy, most likely for shelf-life extension purposes (export markets), were to be used in manufacture of RTE hams, no adverse quality changes would result.

Increased off-odor sensory panel scores are the only commercially practical significant changes found in our experiment. When irradiation is approved for RTE meats it will most often be applied to a product similar to our cooked treatment, which is already cooked, packaged, and ready for retail distribution as a means of pathogen control. Our results indicated that off-odor
would decrease to a level similar to controls over time for the cooked treatment but were offensive to panelists from 0-15 days of storage. Therefore, irradiation dose level should be further investigated as to its role in off-odor development before commercial application of irradiation to RTE meats can occur.
ACKNOWLEDGEMENTS

I would like to thank my family for encouraging me to get an education. I would especially like to thank my father as he always reassured me that I could attain any goal I set my mind to.

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