RESEARCH REPORT
PORK QUALITY

Title: Prevention of Pinking and Off-Odor in Irradiated Pork Loin – **NPB #02-03**

Investigator: Dong U. Ahn,

Institution: Iowa State University

Date Received: April 30, 2003

Abstract: The lipid oxidation, color, volatiles, and sensory evaluation of double-packaged pork loin were determined to establish a modified packaging method to improve the quality of irradiated pork loin. Vacuum-packaged irradiated samples produced large amounts of sulfur-volatiles (dimethyl sulfide and dimethyl disulfide) responsible for irradiation off-odor during storage, whereas lipid oxidation was promoted under aerobic conditions. Exposing irradiated pork to aerobic conditions for 1 to 3 d during the 10-d storage was effective in controlling both lipid oxidation and irradiation off-odor regardless of packaging sequence (double-packaging model). Sensory panelists recognized irradiation odor from all irradiated meat regardless of packaging methods, but double packaging significantly reduced the intensity of irradiation odor. The production of carbon monoxide-heme pigments responsible for the increased redness by irradiation was not effectively controlled by double packaging alone. This indicated that double packaging was effective in controlling off-odor but was not good enough to control color changes in irradiated pork.

Introduction: Consumers and regulatory agencies are well aware the dangers of *E. coli*, *Salmonella*, and *Listeria* to human health. Irradiation provides the best method to control these pathogens in raw meat. The quality changes in irradiated meat, however, are also a concern for the meat industry and the consumer. Pink color (Millar et al., 1995; Nam and Ahn, 2002) and off-odor (Patterson and Stevenson, 1995; Ahn et al., 2001) produced by irradiation persist throughout storage period under vacuum conditions. The major volatile compounds responsible for off-odor in irradiated meats were sulfur compounds. Irradiation produced sulfur compounds via the radiolytic degradation of sulfur-containing amino acids, methionine and cysteine (Jo and Ahn, 2000; Ahn, 2002). The generation of a pink color defect and off-odor is a critical for the use of irradiation with pork because consumers associate the presence of a pink color with undercooked or contaminated and off-odor with the formation of undesirable chemical compounds via the radiolytic reaction.

The color and odor changes in irradiated meat are highly dependent upon packaging conditions. Under aerobic packaging conditions, most of sulfur compounds produced by irradiation disappeared and color returned to normal after a few days of storage in irradiated turkey breast (Nam and Ahn 2003). Lipid oxidation, however, significantly increased when meat was irradiated and stored in aerobic packaging conditions (Ahn et al., 2001).

Therefore, an appropriate use of aerobic and vacuum-packaging combinations (double packaging) can be effective in minimizing lipid oxidation and off-odor volatiles in irradiated pork loin during storage and may also affect the pink color in irradiated pork. Two double packaging strategies are devised: In model #1, pork loin is doubly packaged in aerobic and vacuum bag, irradiated, and then the outer vacuum bag is removed after a few days of storage. In model #2, loin is aerobically packaged, irradiated, and then vacuum-packaged again after a few days of storage.

Objectives: To determine the effectiveness of double packaging conditions on lipid oxidation, volatiles, and color of irradiated pork loin during the refrigerated storage.

Procedures:

Sample preparation: Pork loin (*Longissimus dorsi*) muscles from 8 different animals were purchased from a local packing plant and trimmed of all surface fat. The lean muscles were sliced into 2 cm-thick steaks and packaged in 1) oxygen-permeable bags (polyethylene, 4x6, 2 mil, Associated Bag Company, Milwaukee, WI), 2) oxygen-impermeable vacuum bags (nylon/polyethylene, 9.3 mL O_2/m^2/24 h at 0 °C; Koch, Kansas City, MO), or 3) doubly packaged: pork loins were individually packaged in oxygen-permeable bags at first and then number of aerobically packaged loins were vacuum-packaged in an oxygen-impermeable bag (double packaging model #1) or pork loins were individually packaged in oxygen-permeable bags, irradiated, and then vacuum-packaged in an oxygen-impermeable bag after few days (double packaging model #2).

The packaged meat samples were irradiated at 2.5 kGy using a Linear Accelerator (Circe IIIR; Thomson CSF Linac, Saint-Aubin, France) with 10 MeV of energy, 10.2 kW of power level, and 88.9 kGy/min of average dose rate. For double packaging model #1, the outer vacuum bags were removed after 3 d (V3/A7), 5 d (V5/A5), 7 d (V7/A3), or 9 d (V9/A1) of 4 °C storage. For double packaging model #2, aerobically packaged and irradiated loins were vacuum-packaged at 1 d (A1/V9), 3 d (A3/V7), 5 d (A5/V5), or 7 d (A7/V3) of storage. Nonirradiated vacuum-, irradiated aerobically, and irradiated vacuum-packaged samples were prepared as control or standard. Lipid oxidation, color, gas, oxidation-reduction potential, and volatiles of the samples were determined after 0 d and 10 d of storage. Sensory evaluation was conducted at 10 d.

2-Thiobarbituric acid-reactive substances (TBARS): Lipid oxidation was determined by a TBARS method (Ahn et al., 1998). Minced sample (5 g) was placed in a 50-mL test tube and homogenized with 15 mL of deionized distilled water (DDW) using a Brinkman Polytron (Type PT 10/35; Brinkman Instrument, Inc., Westbury, NY) for 15 s at high speed. The meat homogenate (1 mL) was transferred to a disposable test tube (13×100 mm), and 50 μL butylated hydroxytoluene (7.2% in ethanol) and 2 mL thiobarbituric acid/trichloroacetic acid [20 mM TBA and 15% (w/v) TCA] solution were added. The mixture was vortexed and then incubated in a 90 °C water bath for 15 min. After cooling,

the samples were vortexed and centrifuged at 3,000×g for 15 min. The absorbance of the resulting upper layer was read at 531 nm against a blank (1 mL DDW + 2 mL TBA/TCA). The amounts of TBARS were expressed as mg of malonedialdehyde (MDA) per kg of meat.

Color measurement: CIE color values were measured on the sample surface using a LabScan colorimeter (Hunter Associated Labs, Inc., Reston, VA) that had been calibrated against black and white reference tiles covered with the same packaging materials as used for samples. The CIE L*- (lightness), a*- (redness), and b*- (yellowness) values were obtained by an illuminant A (light source). Random readings from both top and bottom locations on a sample surface was used for statistical analysis.

Oxidation-reduction potential (ORP): A pH/ion meter (Accumet 25; Fisher Scientific, Fair Lawn, NJ) was used to measure ORP. A platinum electrode filled with an electrolyte solution (4 M KCl saturated with AgCl) was tightly inserted into the center of the block of meat sample. To minimize the effect of air, the smallest pore was made in sample by a cutter before inserting the electrode. A temperature-reading sensor was also inserted to compensate for the effect of temperature. ORP readings (mV) were recorded at exactly 2 min after inserting the electrode into a sample.

Gas Compounds: The method of Nam and Ahn (2002) was modified to detect gases in meat samples. Minced meat sample (10 g) was placed in a 24-mL screw-cap glass vial with a Teflon*fluorocarbon resin/silicone septum (I-Chem Co., New Castle, DE). The vial was microwaved at 1.55 kW for 10 s to release gas compounds from the meat. After 5 min of cooling in room temperature, the headspace (200 μL) was withdrawn using an airtight syringe and injected into a split inlet (9:1) of a GC (HP 6890, Hewlett Packard Co., Wilmington, DE). A Carboxen-1006 Plot column (30 m x 0.32 mm i.d.; Supelco, Bellefonte, PA) was used and a oven temperature was programmed (initial temperature, 80°C; increased to 120°C at 20°C/min). He was the carrier gas at a constant flow of 1.8 mL/min. FID connected to a nickel catalyst (Hewlett Packard Co.) was used for detector and the temperatures of inlet, detector and nickel catalyst were set at 130, 280 and 375°C, respectively. Detector air and H_2 flows were 400 and 35 mL/min, respectively. The compounds detected were identified using standard gases (CO; Aldrich, Milwaukee, WI; CH_4 and CO_2; Praxair, Danbury, CT). An integrated peak area was converted to a concentration (ppm) in the headspace (14 mL) of 10 g meat from the concentration of CO_2 in air (330 ppm).

Volatiles: A dynamic headspace analysis was performed using a Solatek 72 Multimatrix-Vial Autosampler/Sample Concentrator 3100 (Tekmar-Dohrmann, Cincinnati, OH) connected to a GC6890/MS5973 (Hewlett-Packard Co., Wilmington, DE) according to the method of Ahn et al. (2001). Minced sample (3 g) was placed in a 40-mL vial, He (40 psi) was flushed for 3 s, and a Teflon*fluorocarbon resin/silicone septum (I-Chem Co., New Castle, DE) was capped airtight. The maximum waiting time in a loading tray (4°C) was less than 2 h to minimize oxidative changes before analysis. The meat sample was purged with He (40 mL/min) for 14 min at 40°C. Volatiles were trapped using a Tenax/charcoal/silica column (Tekmar-Dohrmann) and desorbed for 2 min at 225°C, focused in a cryofocusing module (–80°C), and then thermally desorbed into a column for 60 s at 225°C. An HP-624 column (7.5 m, 0.25 mm i.d., 1.4 μm nominal), an HP-1 column (52.5 m, 0.25 mm i.d., 0.25μm nominal), and an HP-Wax

column (7.5 m, 0.250 mm i.d., 0.25 μm nominal) were connected. Ramped oven temperature was used to improve volatile separation. The initial oven temperature of 0°C was held for 1.5 min. After that, the oven temperature was increased to 15°C at 2.5°C per min, increased to 45°C at 5°C per min, increased to 110°C at 20°C per min, and then increased to 170°C at 10°C per min and held for 2.25 min at that temperature. Constant column pressure at 20.5 psi was maintained. The ionization potential of MS was 70 eV, and the scan range was 19.1 - 350 m/z. Identification of volatiles was achieved by the Wiley library (Hewlett-Packard Co.). The area of each peak was integrated using ChemStation^{TM} software (Hewlett-Packard Co.) and the total peak area (total ion counts x 10^4) was reported as an indicator of volatiles generated from the samples.

Sensory evaluation: A 12-member of sensory panelists evaluated the intensity of off-odor. Training sessions were conducted to familiarize panelists with the irradiation off-odor and rancid odor. Panelists were trained with meat samples irradiated at high dose and containing specific chemical compounds found in the volatiles of previous studies. 10 d-stored samples (3 g) were placed into a coded 40-mL sample vial and capped with a septum (I-Chem Co., New Castle, DE). The samples were incubated for 1 h at 30°C before serving. Four different samples with same packaging method were presented to each panelist in isolated booths at each separate session. Panelists were instructed to smell the samples in random and record the intensity of irradiation off-odor and rancid odor on a 15-cm line scale anchored from “not detectable” to “highly intense”.

Results:

A. Lipid oxidation

Irradiation increased TBARS values of pork loin, but vacuum condition prevented lipid oxidation by irradiation (Table 1). During the refrigerated storage, exposure time to aerobic conditions was the most critical factor on the development of lipid oxidation. The TBARS values of aerobically packaged pork loin were much higher than those of the vacuum-packaged meat and those of double packaged pork at Day 10 were proportional to the days under aerobic conditions. Double-packaged loins with model #2 (aerobically then vacuum-packaged) had lower TBARS than those with model #1 (vacuum- then aerobically packaged). However, the overall TBARS values at 10 d were not high and the differences by packaging methods were relatively small.

B. Color changes

Irradiation changed the color of raw pork loin to red (Table 2). The increase in redness (a-values) by irradiation was more distinct in vacuum-packaged pork loins than in aerobically packaged loins. This result indicates that packaging conditions are important in determining color changes of pork loin during the irradiation process. The increased redness in irradiated pork loin was very stable during the 10-d refrigerated storage irrespective to packaging methods. Double-packaged pork loins showed significantly lower a-values than vacuum-packaged ones after storage, but it was still higher than that of the nonirradiated vacuum-packaged control. Therefore, double packaging alone was not enough to control color changes in pork by irradiation. The L-values of pork loins was not much influenced but b-values showed a trend to increase by irradiation.

Irradiation decreased oxidation-reduction potential (ORP) of pork loin under vacuum-packaged conditions (Table 3). Irradiation provided pork loin with strongly reducing conditions, which enabled the conversion of ferric iron of heme pigment to a ferrous form. Swallow (1984) reported that hydrated electron, radiolyzed free radicals,

could be produced by irradiation and act as a very powerful reducing agent. But, the ORP values of irradiated pork loin increased at 10 d in contrast to the decrease in nonirradiated meat, showing that more oxidizing properties produced in irradiated meat during the storage. Irradiation produced a few gas compounds (Table 4) and carbon monoxide was a ligand of heme pigments in irradiated pork loin responsible for the redder color. The production of carbon monoxide was not much influenced by packaging conditions and storage, indicating that most of carbon monoxide produced was bound to the heme pigments in meat through the storage.

C. Off-odor volatiles

Many new volatile compounds were generated and a few volatiles already present in nonirradiated pork loins were increased by irradiation (Table 5). More than 3 times of total volatiles were produced in irradiated pork loin compared with the nonirradiated control. Sulfur (S)-containing volatiles along with 2-propanone and ethanol were predominant compounds in irradiated pork loin. The S-volatiles responsible for the characteristic irradiation off-odor were methanethiol, dimethyl sulfide, methylthio ethane, and dimethyl disulfide. The amounts of S-volatiles in irradiated pork loin were highly dependent upon packaging conditions. Higher amounts of S-volatiles were found in vacuum- or doubly packaged pork loin but not aerobically packaged ones at Day 0, showing that considerable amounts of S-compounds evaporated under aerobic conditions during irradiation and handling. The amounts of dimethyl sulfide and dimethyl disulfide in aerobically packaged pork loin were only 26% and 29% of the vacuum-packaged one, respectively, at Day 0. Lipid oxidation products were minimal in irradiated pork loin at 0 d and only aerobically packaged pork produced trivial amounts of hexanal.

After 10 d of refrigerated storage, the volatiles profile of irradiated pork loin was highly dependent upon packaging conditions (Table 6 and 7). The greatest amounts of total volatiles were detected in vacuum-packaged pork loin because large amount of S-compounds still remained or increased under vacuum conditions during storage. Dimethyl sulfide was the most predominant volatile compound in vacuum- and a few double-packaged pork loins. Dimethyl disulfide also was found mainly in vacuum-packaged and double-packaged pork exposed to aerobic conditions for just a few days. Interestingly, carbon disulfide was found only in nonirradiated vacuum-packaged pork loin as a S-volatile compound. Using a double packaging model #1 (V7/A3), the amounts of dimethyl sulfide and dimethyl disulfide reduced could be reduced to 67% and 2% of the vacuum-packaged pork loin. If another double packaging concept (V5/A5) is used, larger proportions of S-volatiles could be reduced.

Under aerobic conditions, most S-compounds disappeared during the 10-d storage period. Therefore, aerobic packaging was more beneficial than vacuum packaging in reducing S-volatiles responsible for the characteristic irradiation off-odor. However, aerobically packaged pork loin had relatively greater amounts of lipid oxidation products. Although the amounts of lipid oxidation in aerobically packaged pork loins at 10-d were not very high, lipid oxidation in aerobically packaged meat can be accelerated greatly after cooking. Therefore, both irradiation off-odor and lipid oxidation should be considered simultaneously, and thus double packaging was more desirable for storing irradiated pork than aerobic packaging. Exposing irradiated raw meat to aerobic conditions for 1 to 3 d and vacuum conditions for the remaining storage period was effective enough to control both lipid oxidation and S-volatiles.

D. Sensory characteristics

The intensity of irradiation and rancid odor in irradiated pork loins packaged with double packaging model #1 (V7/A3) and #2 (A3/V7) were compared with those with aerobic and vacuum packaging (Table 7 and 8). Most panelists easily distinguished the characteristic irradiation odor. The intensity of irradiation off-odor in irradiated vacuum-packaged pork ranked the highest and aerobically packaged meat the lowest. Double-packaged meat produced intermediate off-odor intensity but was significantly lower than that of the vacuum packaged meat. The result of odor intensity in irradiated pork was very consistent with that of S-volatiles detected in the pork at 10 d (Table 6 or 7), showing that S-volatiles were responsible for the irradiation off-odor. Rancid odor produced by lipid oxidation was very weak and panelists could not differentiate the intensity of rancid odor among packaging treatments. In conclusion, double packaging methods (both model #1 and 32) were an excellent method for controlling off-odor volatiles and minimized sensory problems, but was not good enough to control color changes in irradiated pork.

E. Discussion

As have seen in many previous works, irradiation increased lipid oxidation of pork only when the meat was exposed to air during storage. The degree of lipid oxidation in double-packaged meat was somewhere in between aerobically packaged and vacuum packaged pork. However, the degree of lipid oxidation was too low to be considered as a major quality problem in raw pork even after irradiation. Irradiation increased the redness in pork and the red color intensity of irradiated meat was more intense in vacuum-packaged than aerobically packaged than in aerobically packaged loins. This means that packaging conditions are important for color of irradiated pork loin. The increased redness was very stable and, irradiated pork loins looked freshier than nonirradiated loins. Double-packaged pork loins showed lower a-values than vacuum-packaged ones after storage, but it was still higher than that of the nonirradiated vacuum-packaged control. Therefore, double packaging alone was not enough to lower red color of irradiated pork to the nonirradiated loins. Vacuum-packaged irradiated loins produced large amounts of sulfur-volatiles (dimethyl sulfide and dimethyl disulfide) responsible for irradiation off-odor during storage, whereas double packaged pork, which expose irradiated pork to aerobic conditions for 1 to 3 d during the 10-d storage, was effective in controlling both irradiation off-odor regardless of packaging sequence (double-packaging model). Sensory panelists recognized irradiation odor from all irradiated meat regardless of packaging methods, but double packaging significantly reduced the intensity of irradiation odor. This indicated that double packaging was effective in controlling off-odor but was not good enough to control lipid oxidation and color changes in irradiated pork. Although not used, the addition of antioxidants may be helpful in improving the color and oxidative stability of double-packaged irradiated raw pork.

Table 1. TBARS values of irradiated raw pork loin with different packaging conditions during the refrigerated storage

	Nonir	Irradiated						
Storage	Vacuum	Aerobic	V3/A7[1]	V5/A5[1]	V7/A3[1]	V9/A1[1]	Vacuum	SEM
	---------- (mg MDA/kg meat) ----------							
0 day	0.12^{cy}	0.23^{ay}	0.21^{ay}	0.21^{az}	0.21^{ay}	0.21^{ay}	0.16^{b}	0.01
10 day model 1[2]	0.15^{ex}	0.44^{ax}	0.33^{cx}	0.37^{bx}	0.31^{cdx}	0.28^{dx}	0.17^{e}	0.01
10 day model 2[3]	0.15^{ex}	0.46^{ax}	0.38^{bx}	0.29^{cy}	0.22^{dy}	0.24^{dy}	0.17^{e}	0.01
SEM	0.01	0.01	0.01	0.01	0.01	0.01	0.01	

[a-e]Different letters within a row are significantly different ($P < 0.05$), $n = 4$.
[x, y]Different letters within a column are significantly different ($P < 0.05$).
[1]Vn/Am: Stored under vacuum and aerobic conditions for n d and m d, respectively.
[2]Double packaging model 1: vacuum-packaged for n d and then aerobically packaged for m d.
[3]Double packaging model 2: aerobically packaged for m d and then vacuum-packaged for n d.

Table 2. Color values of irradiated raw pork loin with different packaging conditions during the refrigerated storage

	Nonir	Irradiated						
Storage	Vacuum	Aerobic	V3/A7[1]	V5/A5[1]	V7/A3[1]	V9/A1[1]	Vacuum	SEM
L-value								
0 day	42.3	43.9	42.1^{y}	45.0	43.2	45.2	40.2^{y}	1.7
10 day model 1[2]	45.5	46.8	50.5^{x}	48.6	48.3	46.7	46.3^{x}	1.7
10 day model 2[3]	44.8	48.0	45.7^{y}	44.2	42.6	42.9	44.1^{x}	1.4
SEM	1.2	1.8	1.6	2.2	1.6	1.5	1.2	
a-value								
0 day	6.6^{c}	8.2^{b}	11.1^{ax}	11.2^{ax}	10.7^{a}	10.5^{ax}	10.6^{a}	0.4
10 day model 1[2]	7.0^{c}	8.9^{b}	9.0^{by}	10.9^{ax}	10.8^{a}	10.1^{abx}	10.0^{ab}	0.4
10 day model 2[3]	6.1^{c}	8.7^{b}	8.4^{by}	8.1^{by}	9.2^{ab}	8.5^{by}	10.1^{a}	0.4
SEM	0.5	0.4	0.5	0.5	0.5	0.5	0.4	
b-value								
0 day	10.0^{bx}	12.3^{ab}	12.4^{aby}	12.8^{a}	12.3^{ab}	12.7^{ab}	11.8^{ab}	0.6
10 day model 1[2]	10.4^{cx}	12.3^{ab}	12.9^{aby}	14.1^{a}	13.2^{ab}	11.7^{bc}	11.4^{bc}	0.5
10 day model 2[3]	6.2^{dy}	11.5^{c}	14.1^{ax}	13.9^{b}	12.9^{bc}	11.7^{c}	11.1^{c}	0.6
SEM	0.6	0.5	0.6	0.7	0.6	0.5	0.5	

[a-c]Different letters within a row are significantly different ($P < 0.05$), $n = 4$.
[x, y]Different letters within a column with same color value are significantly different ($P < 0.05$).
[1]Vn/Am: Stored under vacuum and aerobic conditions for n d and m d, respectively.
[2]Double packaging model 1: vacuum-packaged for n d and then aerobically packaged for m d.
[3]Double packaging model 2: aerobically packaged for m d and then vacuum-packaged for n d.

Table 3. ORP of irradiated raw pork loin with different packaging conditions during the refrigerated storage

	Nonir	Irradiated						
Storage	Vacuum	Aerobic	V3/A7[1]	V5/A5[1]	V7/A3[1]	V9/A1[1]	Vacuum	SEM
	---------- (mV) ----------							
0 day	-43^{a}	0^{a}	-202^{by}	-202^{by}	-202^{by}	-202^{by}	-225^{by}	21
10 day model 1[2]	-80^{c}	21^{a}	-8^{abx}	-17^{abx}	-26^{abcx}	-61^{bcx}	-67^{bcx}	14
10 day model 2[3]	-55^{b}	9^{a}	4^{ax}	-40^{bx}	-43^{bx}	-41^{bx}	-69^{bx}	10
SEM	11	10	23	21	18	16	7	

$^{a-c}$Different letters within a row are significantly different ($P < 0.05$), $n = 4$.
$^{x, y}$Different letters within a column are significantly different ($P < 0.05$).
[1]Vn/Am: Stored under vacuum and aerobic conditions for n d and m d, respectively.
[2]Double packaging model 1: vacuum-packaged for n d and then aerobically packaged for m d.
[3]Double packaging model 2: aerobically packaged for m d and then vacuum-packaged for n d.

Table 4. Gas production of irradiated raw pork loin with different packaging conditions during the refrigerated storage

	Nonir	Irradiated						
Storage	Vacuum	Aerobic	V3/A7[1]	V5/A5[1]	V7/A3[1]	V9/A1[1]	Vacuum	SEM
Carbon monoxide	---------- (ppm) ----------							
0 day	0^{b}	121^{ax}	123^{ax}	123^{ax}	123^{ax}	123^{a}	121^{ax}	8
10 day model 1[2]	0^{c}	84^{aby}	66^{by}	86^{aby}	108^{abx}	114^{a}	107^{abxy}	11
10 day model 2[3]	0^{c}	50^{by}	56^{by}	80^{aby}	65^{by}	117^{a}	95^{aby}	11
SEM	0	13	6	6	8	13	9	
Methane	---------- (ppm) ----------							
0 day	0^{b}	4^{b}	38^{ax}	38^{ax}	38^{ax}	38^{ax}	41^{ax}	2
10 day model 1[2]	0^{c}	4^{c}	3^{cy}	4^{cy}	5^{cy}	14^{by}	49^{ax}	1
10 day model 2[3]	0^{b}	0^{b}	0^{by}	0^{by}	0^{by}	0^{bz}	24^{ay}	1
SEM	0	1	2	1	2	2	2	
Carbon dioxide	---------- (%) ----------							
0 day	3.1^{ax}	1.3^{bx}	3.1^{ax}	3.1^{ax}	3.1^{ax}	3.1^{ax}	3.4^{a}	0.3
10 day model 1[2]	1.6^{bcy}	0.8^{cxy}	0.7^{cy}	0.9^{cy}	1.5^{bcy}	2.3^{abxy}	2.8^{a}	0.2
10 day model 2[3]	2.5^{ax}	0.6^{by}	0.7^{by}	0.7^{by}	0.5^{bz}	1.4^{by}	3.2^{a}	0.5
SEM	0.4	0.2	0.3	0.3	0.2	0.2	0.4	

$^{a-c}$Different letters within a row are significantly different ($P < 0.05$), $n = 4$.
$^{x, y}$Different letters within a column with same gas are significantly different ($P < 0.05$).
[1]Vn/Am: Stored under vacuum and aerobic conditions for n d and m d, respectively.
[2]Double packaging model 1: vacuum-packaged for n d and then aerobically packaged for m d.
[3]Double packaging model 2: aerobically packaged for m d and then vacuum-packaged for n d.

Table 5. Volatile compounds of irradiated raw pork loin with different packaging conditions at 0 day

Volatile compounds	Nonirradiated Vacuum	Irradiated Aerobic	Irradiated V7/A3[1]	Irradiated Vacuum	SEM
	(Total ion counts x 10^4)				
Acetaldehyde	324	496	648	755	179
Methanethiol	0[c]	887[c]	3886[a]	2238[b]	342
Pentane	0[c]	526[a]	349[b]	349[b]	27
Dimethyl sulfide	0[b]	610[b]	2771[a]	2345[a]	382
2-Propanone	1169	6344	3155	3473	2435
Hexane	0[b]	723[a]	232[b]	217[b]	132
Ethanol	3317	2184	1056	1457	934
Methylthio ethane	0	0	85	406	182
2-Propanol	229	777	147	340	360
2-Butanone	74[c]	930[a]	350[b]	417[b]	97
Benzene	0	41	83	16	33
1-Heptene	0	111	51	53	40
Heptane	0	373	63	82	190
2-Pentanone	36	0	121	0	41
Dimethyl disulfide	37[c]	773[c]	1761[b]	2678[a]	290
Toluene	0	185	0	0	70
Octane	30	582	125	201	187
Hexanal	0	65	0	0	32
Total	4894[b]	15207[a]	14241[a]	14274[a]	1457

[a-c]Different letters within a row are significantly different ($P < 0.05$), $n = 4$.
[1]Vacuum-packaged for 3 d then aerobically packaged for 7 d.

Table 6. Volatile compounds of irradiated raw pork loin with double packaging model 1 at 10 day

Volatile compounds	Nonir	Irradiated						SEM
	Vacuum	Aerobic	V3/A7[1]	V5/A5[1]	V7/A3[1]	V9/A1[1]	Vacuum	
	(Total ion counts x 10^4)							
Pentane	38^{b}	997^{a}	597^{ab}	564^{ab}	613^{ab}	450^{ab}	367^{ab}	141
Dimethyl sulfide	0^{d}	0^{d}	3690^{cd}	6805^{c}	10996^{b}	12676^{ab}	16328^{a}	1275
2-Propanone	3211^{b}	4021^{a}	174^{c}	84^{c}	182^{c}	57^{c}	86^{c}	269
Carbon disulfide	300^{a}	0^{b}	0^{b}	0^{b}	0^{b}	0^{b}	0^{b}	18
Methanol	1923^{b}	2905^{a}	1897^{b}	1776^{c}	1637^{c}	1657^{c}	1630^{c}	40
3-Methyl pentane	0^{b}	60^{ab}	28^{ab}	36^{ab}	153^{a}	56^{ab}	39^{ab}	29
1-Hexene	0	0	0	0	60	33	36	23
Hexane	412^{b}	3012^{a}	2784^{a}	743^{b}	560^{b}	317^{b}	220^{b}	357
Ethanol	2286^{d}	8806^{a}	8704^{ab}	6927^{bc}	6843^{bc}	6180^{c}	8333^{a}	459
2-Propanol	990	975	1132	1069	1119	1115	1108	63
2-Butanone	0^{c}	390^{a}	203^{b}	204^{b}	296^{b}	254^{b}	221^{b}	24
1-Heptene	0	127	52	60	91	41	33	35
Heptane	0	0	0	0	94	194	64	85
2-Pentanone	76^{c}	426^{a}	345^{ab}	257^{b}	120^{c}	94^{c}	105^{c}	30
Dimethyl disulfide	0^{b}	0^{b}	0^{b}	0^{b}	178^{b}	196^{b}	11648^{a}	1057
Toluene	0^{b}	413^{ab}	302^{ab}	324^{ab}	463^{a}	325^{ab}	154^{ab}	96
1-Octene	0^{b}	120^{a}	103^{a}	56^{ab}	87^{a}	0^{b}	0^{b}	18
Octane	237	603	653	573	551	337	349	97
2-Octene	0	45	35	45	102	0	0	28
3-Methyl 2-heptene	0^{b}	92^{a}	16^{ab}	22^{ab}	22^{ab}	0^{b}	0^{b}	19
Hexanal	0^{c}	169^{a}	122^{ab}	0^{c}	76^{bc}	0^{c}	0^{c}	22
Heptanal	0	32	20	36	0	0	0	20
Total	9476^{c}	23200^{b}	20865^{b}	19586^{b}	242521^{b}	23986^{b}	41058^{a}	2129

[a-d]Different letters within a row are significantly different ($P < 0.05$), $n = 4$.
[1]Vacuum-packaged for 3 d then aerobically packaged for 7 d.
[2]Vacuum-packaged for 5 d then aerobically packaged for 5 d.
[3]Vacuum-packaged for 7 d then aerobically packaged for 3 d.
[4]Vacuum-packaged for 9 d then aerobically packaged for 1 d.

Table 7. Volatile compounds of irradiated raw pork loin with double packaging model 2 at 10 day

Volatile compounds	Nonir	Irradiated					
	Vacuum	Aerobic	V3/A7[1]	V5/A5[1]	V7/A3[1]	V9/A1[1]	Vacuum	SEM
	---------- (Total ion counts x10^4) ----------							
Pentane	58^{b}	645^{a}	601^{a}	566^{a}	524^{a}	527^{a}	345^{a}	69
Dimethyl sulfide	0^{b}	0^{b}	0^{b}	0^{b}	0^{b}	0^{b}	6982^{a}	170
2-Propanone	2164^{b}	3099^{ab}	3500^{ab}	2675^{ab}	2859^{ab}	4355^{a}	0^{c}	478
Carbon disulfide	45^{a}	0^{b}	0^{b}	0^{b}	0^{b}	0^{b}	0^{b}	4
Methanol	1189	1171	1324	1184	1205	1420	1160	58
Hexane	24^{b}	552^{a}	612^{a}	308^{ab}	313^{ab}	367^{ab}	269^{ab}	111
Ethanol	499^{c}	3524^{ab}	3707^{ab}	3120^{b}	3475^{ab}	3867^{a}	3695^{ab}	155
2-Propanol	258	796	849	803	795	858	855	138
2-Butanone	0^{c}	34	115	39	42	107	40	41
Benzene	0^{b}	0^{b}	0^{b}	0^{b}	0^{b}	0^{b}	184^{a}	6
1-Heptene	0	0	35	0	0	21	0	15
Heptane	0^{b}	956^{a}	1337^{a}	1107^{a}	808^{a}	996^{a}	219^{ab}	159
2-Pentanone	0^{c}	137^{ab}	166^{a}	123^{ab}	98^{b}	86^{b}	0^{c}	13
S-methyl ethanethioate	0^{b}	0^{b}	0^{b}	0^{b}	0^{b}	0^{b}	177^{a}	14
Dimethyl disulfide	0^{b}	0^{b}	0^{b}	0^{b}	0^{b}	0^{b}	1088^{a}	228
Toluene	0^{e}	144^{d}	205^{cd}	225^{cd}	260^{bc}	327^{b}	457^{a}	26
1-Octene	0	19	35	23	0	30	28	23
Octane	616	835	1163	1053	831	1086	820	275
2-Octene	219^{a}	0^{b}	0^{b}	34^{b}	18^{b}	31^{b}	297^{a}	33
Hexanal	32^{c}	130^{a}	110^{a}	102^{a}	102^{a}	112^{a}	52^{b}	24
Dimethyl trisulfide	0	0	0	0	0	0	28	10
Total	5107^{c}	12028^{b}	13762^{ab}	11367^{b}	11334^{b}	14214^{ab}	16674^{a}	923

$^{a-e}$Different letters within a row are significantly different ($P < 0.05$), $n = 4$.
[1]Aerobically packaged for 7 d then vacuum-packaged for 3 d.
[2]Aerobically packaged for 5 d then vacuum-packaged for 5 d.
[3]Aerobically packaged for 3 d then vacuum-packaged for 7 d.
[4]Aerobically packaged for 1 d then vacuum-packaged for 9 d.

Table 8. Sensory characteristics of irradiated raw pork loin with different double packaging methods at 10 day

	Nonirradiated	Irradiated			
Off-odor[1]	Vacuum	Aerobic	V7/A3[2]	Vacuum	SEM
Double packaging model 1					
Irradiation odor	1.0^{d}	3.8^{c}	9.5^{b}	11.3^{a}	0.6
Rancid odor	1.4	4.8	3.9	3.6	1.4
Double packaging model 2					
Irradiation odor	1.3^{c}	4.4^{b}	5.6^{b}	12.4^{a}	1.0
Rancid odor	3.6	5.5	2.7	2.8	1.2

$^{a-d}$Different letters within a row are significantly different ($P < 0.05$), $n = 12$.
[1]0.0: not detectable ~ 15.0: highly intense.
[2]Vacuum-packaged for 7 d then aerobically packaged for 3 d.