Radiation Physics and Chemistry 166 (2020) 108452

Contents lists available at ScienceDirect

Radiation Physics and Chemistry

journal homepage: www.elsevier.com/locate/radphyschem

Interactions between raw meat irradiated by various kinds of ionizing radiation and transglutaminase treatment in meat emulsion systems

Tae-Kyung Kim[a], Ko-Eun Hwang[b], Youn-Kyung Ham[b], Hyun-Wook Kim[c], Hyun-Dong Paik[b], Young-Boong Kim[a], Yun-Sang Choi[a,*]

[a] Research Group of Food Processing, Korean Food Research Institute, Wanju, 55365, Republic of Korea
[b] Department of Food Science and Biotechnology of Animal Resources, Konkuk University, Seoul, 05029, Republic of Korea
[c] Department of Animal Science & Biotechnology, Gyeongnam National University of Science and Technology, Jinju, 52725, Republic of Korea

ARTICLE INFO

Keywords:
X-ray
Electron-beam
Gamma-ray
Irradiation
Transglutaminase
Emulsion systems

ABSTRACT

Meat processing involves many treatments for improving the quality and durability of products. However, these treatments also affect other meat properties. The objective of this study was to investigate the effects of minced pork ham irradiated with various kinds of ionizing radiation (X-ray, E-beam, and γ-ray) and transglutaminase (TG) on emulsion systems. Ionizing radiation of various kinds ($P < 0.05$) was found to affect protein, fat, and ash content, as well as protein solubility, and textural properties. On the contrary, moisture content, fat content, emulsion stability, pH, color, protein solubility, and textural properties were affected by TG ($P < 0.05$). The apparent viscosity of irradiated ham was higher than that of the control, and TG treatment increased the value further. The effect on meat and meat products using different types of irradiation provides useful information about the combined treatments of irradiation and TG in emulsion systems.

1. Introduction

The World Health Organization reported in 1999 that food irradiated with up to 10 kGy is considered safe for human consumption and does not lead to any adverse effect regarding nutritional properties. Food irradiation technology represents an effective preservation method that extends the shelf life of meat and related products by controlling the growth of microorganisms (Farkas, 2006; Choi et al., 2015). Although X-rays are not commonly used as an ionizing radiation in food processing, some new advantages of food irradiation with X-rays are that they allow a better operation system, higher productivity, and no radioactive waste (Cleland and Stichelbaut, 2013). Ham et al. (2017) reported that three kinds of ionizing radiation (gamma rays, E-beams, and X-rays) had a different effect on cooked meat products regarding color, lipid oxidation, and antimicrobial properties. Furthermore, ionizing radiation can accelerate the oxidation-based deterioration of raw meat and this oxidation can change protein gelation properties (Feng et al., 2017; Zhou et al., 2014). According to Li et al. (2018), gelation properties of meat protein were collapsed upon irradiation with gamma rays over 7 kGy because the hydrophobic interaction of myofibril protein was strengthened, along with further unfolding of the protein and rearrangement of hydrogen bonds inside the actin network (Song et al., 2017; Yim et al., 2019). Therefore, ways to improve gelation properties when irradiating meat with high doses of ionizing radiation need to be developed.

Among many kinds of meat products, emulsified meat has been used as a product itself or as raw material for other meat products. Emulsification of meat components, such as protein, fat, and moisture is an important factor to determine meat quality (Choi et al., 2016). Transglutaminase (TG) is an enzyme that is active at a pH of 5.0–8.0 and a temperature of 2–60 °C (Canto et al., 2014). It covalently cross-links lysine and glutamine residues, causing protein aggregation (Tseng et al., 2000; Temiz and Dağyıldız, 2017). TG has been employed to improve the emulsion stability and textural properties of muscle protein-containing food (Ando et al., 1989; Hemung and Chin, 2015). When raw meat gets oxidized, N^{ε}-carboxymethyllysine and N^{ε}-carboxyethyl-lysine are linearly increased (Park et al., 2017; Yu et al., 2016). Mildly oxidized meat protein gelation properties might be improved by the addition of TG, since cross linking between mildly oxidized meat protein and TG is well organized as compared to that between non-oxidized meat protein an TG. However, over-oxidation hampers the gel formation ability of TG. Protein denaturation might be affected by ionizing radiations and interaction between proteins denatured through different types of radiations and TG could be different. However, the

* Corresponding author. Research Group of Food Processing, Korea Food Research Institute, Wanju, 55362, Republic of Korea. Tel.: 82 63 219 9387; fax: 82 63 219 9076.

E-mail address: kcys0517@kfri.re.kr (Y.-S. Choi).

https://doi.org/10.1016/j.radphyschem.2019.108452
Received 16 May 2017; Received in revised form 7 August 2019; Accepted 12 August 2019
Available online 13 August 2019
0969-806X/

Table 1
Formulation of emulsion meat formulated with irradiated mined raw meat by various kinds of ionizing radiation[a] and transglutaminase (TG). (Unit: g/100 g).

	Non-TG	TG
Irradiated pork meat	50	50
Pork back fat	25	25
Ice	25	25
Total	100	100
NaCl	1.5	1.5
Sodium phosphate	0.15	0.15
Transglutaminase (TG)	0	2

[a] Only minced pork ham was irradiated with three different irradiation sources (gamma ray, E-beam, X-ray) with 10 kGy.

interplay between irradiation and TG in meat processing has not been examined yet.

Therefore, the objective of this study was to investigate the effects of the interaction between irradiated meat and transglutaminase on the physical properties of irradiated meat emulsion systems.

2. Materials and methods

2.1. Sample preparation

Meat emulsions were manufactured according to the method described by Choi et al. (2015). Fresh pork ham and pork back fat were purchased from a local processor 48 h postmortem. There were two different formulations of meat emulsions, which are detailed in Table 1. Lean materials, pork back fat and TG were homogenized and ground in a silent cutter (Nr-963009; Hermann Scharfen GmbH & Co., Germany). TG (activity: 85 units/g, Dairyzym PT 100C; SternEnzym GmbH & Co., Germany) was purchased from BISION (Seongman, Korea). A temperature probe (KM330; Kane-May, UK) was used to monitor the temperature of the meat emulsion, which was maintained at < 10 °C. The meat emulsion batter was stuffed into collagen casings (#240, approximate diameter, 25 mm; NIPPI Inc., Tokyo, Japan) using a stuffer (IS-8; Sirman, Italy). The meat batters were held at 15 °C for 24 h, cooked at 80 °C for 60 min in a chamber (MAXi3501; Kerres, Germany) to hold the meat protein network, and then cooled at 21 °C for 3 h. These cooked samples were used to determine proximate composition, cooking loss, pH, color, and texture analysis (Utama et al., 2018). The procedure was performed in triplicate for each meat emulsion system.

2.2. Irradiation procedure

The vacuum-packaged samples were irradiated with 10 kGy using three ionizing radiations at an ambient temperature of 20 °C. Gamma-ray irradiation was conducted in a cobalt-60 irradiator (AECL, IR-79, MDS Nordion Inc., Ottawa, Canada) at the Korea Atomic Energy Research Institute (Jeongeup, Korea) with a source activity of approximately 11.1 PBq, and dose rate of 10 kGy/h (Cho and Yang, 2018). E-beam and X-ray irradiation were performed with an ELV-4 electron beam accelerator (10 MeV) and an X-ray linear accelerator (7.5 MeV), respectively, at the EB-Tech Co. (Daejeon, Korea). E-beam and X-ray irradiation were performed with a beam current of 1 mA and dose rates of 2.9 kGy/s and 5 kGy/h, respectively. For dosimetry of samples, alanine dosimeters (5 mm diameter; Bruker Instruments, Bremen, Germany) were attached to the top and bottom of the samples. Perpendicular to the beam, the absorbed dose was measured with an electron paramagnetic resonance analyzer in accordance with international standards (ISO/ASTM51607, 2004). The dose uniformity (min/max ratios) of all ionizing radiations was less than 1.2 and the actual dose was within 75% of the target dose. After irradiation, the irradiated meat was used for manufacture emulsion meat on the day (Park et al., 2010; Ham et al., 2017).

2.3. Proximate composition

Compositional properties of the cooked meat emulsion were determined using method approved by AOAC (2000): moisture content (950.46B) was determined by weight loss after 12 h of drying at 105 °C in a drying oven (SW-90D, Sang Woo Scientific Co., Bucheon, Korea), fat content (960.69) was determined by the Soxhlet method with a solvent extraction system (Soxtec® Avanti 2050 Auto System, Foss Tecator AB, Höganas, Sweden), protein content (981.10) was determined by Kjeldahl method with an automatic Kjeldahl nitrogen analyzer (Kjeltec® 2300Analyzer Unit, Foss Tecator AB, Höganas, Sweden) and ash content (920.153) was determined with a muffle furnace.

2.4. Cooking loss

The meat batters stuffed into the casing were weighed and heated at 80 °C for 60 min in a chamber (MAXi3501). Cooked samples were cooled to room temperature (21 °C) for 3 h. After cooling, cooked meat batters were weighed and a cooking loss was calculated as follows:

Cooking loss (%) = [(weight of raw meat batter (g) – weight of cooked meat batter (g))/weight of raw meat batter (g)] × 100.

2.5. Emulsion stability

The meat batters were analyzed for emulsion stability using the method of Blouka and Honikel (1992) with the some modifications. The total expressible fluid and fat separated in the bottom of each graduated glass tube were determined as follows (Choi et al., 2007):

Total expressible fluid separation (ml/g) = [(water layer (ml) + fat layer (ml))/weight of raw meat batter (g)] × 100.

Fat separation (ml/g) = [the fat layer (ml)/weight of raw meat batter (g)] × 100.

2.6. pH determination

The pH values of cooked meat emulsion were measured in triplicate using an electronic pH-meter (Model 340, Mettler-Toledo GmbH, Schwerzenbach, Switzerland).

2.7. Color evaluation

The color characteristics (CIE L*, a* and b*) of meat batter and cooked meat emulsion were determined with six measurements using a colorimeter (Minolta Chroma meter CR-210, Minolta Co., Osaka, Japan; illuminate C, calibrated with a white plate, $L^* = +97.83$, $a^* = -0.43$, $b^* = +1.98$).

2.8. Apparent viscosity

Apparent viscosity of meat batter was determined in triplicate with a rotational viscometer (HAAKE Viscotester® 500, Thermo Electron Corporation, Karlsruhe, Germany) set at 10 rpm (Park et al., 2004). The standard cylinder sensor (SV-E) was positioned in a 20 ml plastic cup filled with meat emulsion and allowed to rotate under a constant share rate for 30 s. The temperature was set at 18 ± 1 °C and recorded for each samples.

2.9. Texture profile analysis (TPA)

The textural properties of cooked meat emulsion were determined using a texture analyzer (TA-XT2*i*, Stable Micro Systems, Surrey, England) with a 25 kg load cell. Cylindroid samples (20 mm diameter, 15 mm height) were prepared from each heat-induced gel. The samples were compressed twice to 30% of their original height with a constant cross-head speed of 2.0 mm/s. Hardness (N), springiness, cohesiveness, gumminess (N) and chewiness (N) of heat-induced gels were recorded

Table 2
Proximate composition of emulsion meat formulated with irradiated mined raw meat by various kinds of ionizing radiation[a] and transglutaminase (TG).

		Control	X-ray	E-beam	γ-ray	SEM[b]
Moisture contents (%)	Non TG	37.83	37.57	37.35**	37.47	0.14
	TG	38.24	38.62	38.79**	38.12	0.17
Protein contents (%)	Non TG	12.57**	12.75	12.27	12.96***	0.11
	TG	12.07^{b}**	12.41^{b}	12.21^{b}	13.48^{a}***	0.17
Fat contents (%)	Non TG	18.24^{b}**	21.94^{a}	17.23^{b}	17.70^{b}*	0.61
	TG	14.22^{b}**	20.96^{a}	15.78^{b}	13.71^{b}*	0.91
Ash contents (%)	Non TG	1.75^{a}	1.55^{b}*	1.78^{a}	1.74^{a}	0.03
	TG	1.75	1.71*	1.68	1.66	0.02

Significance of main effects and their interactions

	Moisture contents (%)	Protein contents (%)	Fat contents (%)	Ash contents (%)
Irradiation source effect (IS)	NS	***	***	*
Transglutaminase (TG)	**	NS	***	NS
Interaction (IS × TG)	NS	*	*	**

$^{a, b}$ means within a row with different letters are significantly different ($P < 0.05$).
*$P < 0.05$, **$P < 0.01$, ***$P < 0.001$.
[a] Only minced pork ham was irradiated with 10 kGy radiation by irradiation source (X-ray, E-beam, γ-ray).
[b] SEM: the standard error of means.

(Bourne, 1978).

2.10. Statistical analysis

A total of three batches were processed. Data were analyzed using the general linear model (GLM) procedure of SPSS Ver. 20.0 (SPSS Inc., Chicago, IL, USA), with the kinds of ionizing radiation (X-ray, E-beam, γ-ray) and addition of TG fixed as the main factors. When a significant effect was found, Duncan's multiple range test ($P < 0.05$) and the independent samples *t*-test were used to compare the mean values.

3. Results and discussion

3.1. Proximate composition

The proximate composition and significance of effects on the emulsion systems formulated with minced pork ham subjected to different ionizing radiations and TG are given in Table 2. The proximate composition, which includes moisture, crude protein, crude fat and crude ash composition of a food could be a primary index to determine the quality characteristics of a meat product, and there are many factors that can affect it, such as material characteristics, pH of emulsion and protein solubility (Choi et al., 2016). Lipid is known to be the component most sensitive to irradiation (Venugopal et al., 1999). According to Li et al. (2018), protein properties of raw meat were changed by the activity of ionizing radiation. The moisture content of emulsion meat was only affected by TG ($P < 0.01$). According to Tseng et al. (2000), protein aggregation accelerated by TG can change the proximate composition of a meat product, such as the composition of moisture and fat, by changing emulsion stability. TG also affects fat content significantly ($P < 0.001$). Ionizing radiation affected protein, fat and ash contents ($P < 0.05$). There was no significant difference in the moisture content of meat emulsions irradiated with different ionizing radiations ($P > 0.05$), and, when compared with addition of TG, only the meat emulsion treated with an E-beam showed significant difference in moisture content ($P < 0.05$). The protein contents of meat emulsion treated with different ionizing radiations were not different. However, when combined with TG, emulsion meat treated with gamma rays had the highest protein content ($P < 0.05$). According to another study (Yıldırım et al., 2005), there was no specific effect on fat content upon irradiation with gamma rays; our study showed a similar result that the gamma ray-irradiated meat emulsion had no significant difference in fat content compared with the control ($P > 0.05$). However, the X-ray treated meat emulsion had the highest fat content and the lowest ash content ($P < 0.05$) in this work. Thus, further studies on the effect of X-rays on the proximate composition of a meat product have to be carried out in the future.

3.2. Cooking loss and emulsion stability

Cooking loss, fluid separation, fat separation and the significant effects on meat emulsion formulated with minced pork ham irradiated with different ionizing radiations and TG are given in Table 3. These properties did not change significantly with a change in ionizing radiation ($P > 0.05$), but TG did affect the emulsion stability ($P < 0.05$). Although cooking loss and fat separation were not significantly affected by ionizing radiation with and without TG treatment, total fluid separation of emulsion meat with TG was higher than that of emulsion meat without TG ($P < 0.05$). This phenomenon might be due to excessive cross-linking reaction produced by TG (Choi et al., 2016). The narrowed space between proteins caused by TG cannot hold moisture or fat content in meat emulsion (Hemung and Chin, 2015).

3.3. pH and instrument color

The pH, color, and significant effects on the emulsion systems formulated with minced pork ham irradiated with different ionizing radiations and TG are given in Table 4. There was no interaction between those main factors of emulsion meat on pH and CIE b* ($P > 0.05$). Redness (CIE a*) of raw emulsion meat and lightness (CIE L*) of cooked emulsion meat were significantly impacted by the combined treatment ($P < 0.05$). Before cooking, TG affected pH and all measured color values ($P < 0.05$). After cooking, TG only affected CIE a* ($P < 0.05$). CIE L* of raw emulsion meat without TG was lower than that of emulsion meat with TG ($P < 0.05$), whereas CIE a* and CIE b* were higher ($P < 0.05$), except for the gamma ray treated emulsion meat ($P > 0.05$). CIE L* of cooked control and X-ray treated emulsion meat was higher than others ($P < 0.05$); however, TG treatment did not produce a significant difference on any cooked treatment ($P > 0.05$). It has been reported that the color of meat products was affected by both ionizing radiation and dose level (Ham et al., 2017). Our results are in agreement with a previous study, which reported that the lightness, redness, and yellowness of pork sausages were affected by the addition of TG and hydrocolloids (Lee and Chin, 2009). According to Ham et al. (2017), carbonmonoxy myoglobin could be related to a pink color when irradiated, increased CIE a*, and decomposition of nitrosyl

Table 3
Cooking loss and emulsion stability of emulsion meat formulated with irradiated mined raw meat by various kinds of ionizing radiation[a] and transglutaminase (TG).

		Control	X-ray	E-beam	γ-ray	SEM[b]
Cooking loss (%)	Non TG	9.57	10.26	10.38	10.54	0.58
	TG	9.82	10.75	10.72	11.01	0.74
Emulsion stability						
Total fluid separation (%)	Non TG	5.51***	5.67**	4.98*	4.31*	0.37
	TG	12.28***	11.58**	10.93*	9.90*	0.67
Fat separation (%)	Non TG	0.80	0.80	0.80	0.80	0.00
	TG	0.64	0.72	0.80	0.64	0.02

Significance of main effects and their interactions

	Cooking loss (%)	Total fluid separation (%)	Fat separation (%)
Irradiation source effect (IS)	NS	NS	NS
Transglutaminase (TG)	NS	***	*
Interaction (IS × TG)	NS	NS	NS

*$P < 0.05$, **$P < 0.01$, ***$P < 0.001$.
[a] Only minced pork ham was irradiated with 10 kGy radiation by irradiation source (X-ray, E-beam, γ-ray).
[b] SEM: the standard error of means.

hemochrome could be a factor of decreasing CIE a*. However, there were no specific differences in the TG group, because the white color of TG itself might disturb the development of redness in the meat emulsion. TG had a bigger relative effect on pH and color of meat emulsion than ionizing radiation, regardless of cooking. Ionizing radiation had no significant effect on pH and color. Moreover, Ham et al. (2017) studied the effects of ionizing radiations (gamma ray, X-ray, and electron beam) on meat products and they reported similar results to those of our study that ionizing radiations had no significant effect on the pH of a meat product. Although our study is not related to the effect of the dose of ionizing radiation, irradiation doses of gamma ray also did not affect the pH of meat products (Yıldırım et al., 2005). However, individually, there were significant differences among ionizing radiations.

3.4. Protein solubility

Results of protein solubility and significant effects in minced pork ham irradiated with different ionizing radiations with and without TG treatment are summarized in Table 5. Significant differences were observed on myofibrillar protein solubility and total protein solubility

Table 4
pH and color of emulsion meat formulated with irradiated mined raw meat by various kinds of ionizing radiation[a] and transglutaminase (TG).

		Control	X-ray	E-beam	γ-ray	SEM[b]
Raw						
pH	Non TG	6.00	6.03	6.02	5.99	0.11
	TG	5.94	6.01	5.98	5.96	0.13
CIE L*	Non TG	74.85*	64.49**	72.24*	73.54*	0.60
	TG	76.50*	75.54**	76.25*	76.28*	0.28
CIE a*	Non TG	11.04[b]*	13.82[a]***	11.31[b]***	10.97[b]	0.41
	TG	10.28*	8.24***	8.72***	10.35	0.21
CIE b*	Non TG	14.45***	15.62*	14.12***	13.67	0.35
	TG	13.49***	12.48*	12.81***	13.24	0.12
Cooked						
pH	Non TG	6.09	6.10	6.11	6.10	0.01
	TG	6.08	6.10	6.07	6.08	0.01
CIE L*	Non TG	78.14[a]*	78.94[a]*	77.12[b]*	76.41[b]	0.21
	TG	77.32*	77.33*	77.93*	77.51	0.18
CIE a*	Non TG	6.00*	6.03	6.02	5.99	0.09
	TG	5.94*	6.01	5.98	5.96	0.09
CIE b*	Non TG	11.35	11.20	11.46	11.32	0.06
	TG	11.32	11.42	11.35	11.36	0.09

Significance of main effects and their interactions

	pH	CIE L*	CIE a*	CIE b*
Raw				
Irradiation source effect (IS)	NS	NS	NS	NS
Transglutaminase (TG)	*	**	***	***
Interaction (IS × TG)	NS	NS	***	NS
Cooked				
Irradiation source effect (IS)	NS	*	NS	NS
Transglutaminase (TG)	NS	NS	*	NS
Interaction (IS × TG)	NS	***	NS	NS

[a, b] means within a row with different letters are significantly different ($P < 0.05$).
*$P < 0.05$, **$P < 0.01$, ***$P < 0.001$.
[a] Only minced pork ham was irradiated with 10 kGy radiation by irradiation source (X-ray, E-beam, γ-ray).
[b] SEM: the standard error of means.

Table 5
Protein solubility of emulsion meat formulated with irradiated mined raw meat by various kinds of ionizing radiation[a] and transglutaminase (TG).

		Control	X-ray	E-beam	γ-ray	SEM[b]
Sarcoplasmic protein solubility (mg/g)	Non TG	38.15[a]*	30.97[c]	33.65[b]***	33.90[b]***	0.51
	TG	34.70*	28.45	29.80***	31.10***	0.86
Myofibrillar protein solubility (mg/g)	Non TG	76.90[c]***	92.12[b]***	89.70[b]***	104.60[a]***	2.45
	TG	43.18***	36.00***	28.45***	36.25***	2.13
Total protein solubility (mg/g)	Non TG	115.05[b]***	123.10[b]***	123.35[b]***	138.50[a]***	2.32
	TG	77.88[a]***	64.45[b]***	58.25[b]***	67.35[b]***	1.96

Significance of main effects and their interactions

	Sarcoplasmic protein solubility (mg/g)	Myofibrillar protein solubility (mg/g)	Total protein solubility (mg/g)
Irradiation source effect (IS)	***	*	**
Transglutaminase (TG)	***	***	***
Interaction (IS × TG)	NS	***	***

a, b means within a row with different letters are significantly different ($P < 0.05$).
*$P < 0.05$, **$P < 0.01$, ***$P < 0.001$.
[a] Only minced pork ham was irradiated with 10 kGy radiation by irradiation source (X-ray, E-beam, γ-ray).
[b] SEM: the standard error of means.

($P < 0.05$). Furthermore, fixed-main effect, ionizing radiation and TG affected protein solubility ($P < 0.05$). Gamma ray-treated emulsion meat showed the highest myofibrillar protein solubility, and when raw meat was irradiated, regardless of sources added in meat emulsion without TG, myofibrillar protein solubility was higher than that of the control ($P < 0.05$), likely due to protein denaturation (Kim et al., 2017). However, TG treated emulsion meat showed no significant difference ($P > 0.05$), and this phenomenon may be caused by protein aggregation by TG, that could inhibit dissolution of proteins in emulsion meat (Tseng et al., 2000).

3.5. Texture profile analysis

Results on textural properties and effects of minced pork ham irradiated with different ionizing radiation and TG treatment on emulsion systems are summarized in Table 6. Springiness was only affected by ionizing radiation ($P < 0.05$) and the interaction of the two treatments (TG and irradiation) was found to produce significant changes in hardness, gumminess and chewiness ($P < 0.05$). The results are in agreement with a previous study (Kim et al., 2017), which reported that these properties can be affected by irradiation due to denaturation of salt-soluble proteins. Although E-beam-treated emulsion meat had the highest hardness, gumminess and chewiness, other treatments had lower values than control ($P < 0.05$). With TG treatment, the values of hardness, gumminess and chewiness of all emulsions were increased ($P < 0.05$). It has been previously reported that TG significantly increased the hardness and gumminess of chicken sausages (Choi et al., 2016). It is hypothesized that TG assists in the formation of cross-links that contribute to gelation of the emulsions (Lee and Chin, 2009). With TG, gamma ray has no significant difference compared with E-beam treated and control emulsion meat ($P > 0.05$).

3.6. Apparent viscosity

Apparent viscosity and the effect of minced pork ham irradiated with different ionizing radiation and TG treatment are shown in Fig. 1. All emulsion systems showed thixotropic behavior and apparent viscosity decreased along with the rotation time. The apparent viscosity of meat emulsion formulated with minced meat irradiated by X-ray was higher than that of meat emulsion formulated with minced meat

Table 6
Texture profile analysis of emulsion meat formulated with irradiated mined raw meat by various kinds of ionizing radiation[a] and transglutaminase (TG).

		Control	X-ray	E-beam	γ-ray	SEM[b]
Hardness (N)	Non TG	2.76[b]***	2.49[c]***	3.43[a]***	2.59[c]***	0.08
	TG	4.51[a]***	3.42[b]***	4.44[a]***	4.24[a]***	0.09
Gumminess (N)	Non TG	2.72[b]***	2.44[c]***	3.38[a]***	2.54[c]***	0.09
	TG	4.44[a]***	3.38[b]***	4.36[a]***	4.08[a]***	0.09
Springiness	Non TG	0.99[a]	0.98[b]	0.98[b]	0.98[b]	0.00
	TG	0.99	0.98	0.99	0.98	0.00
Chewiness (N)	Non TG	2.69[b]***	2.39[c]***	3.33[a]**	2.49[c]***	0.09
	TG	4.41[a]***	3.32[b]***	4.30[a]**	4.00[a]***	0.09
Cohesiveness	Non TG	0.20	0.20	0.25	0.18	0.03
	TG	0.21	0.26	0.20	0.21	0.03

Significance of main effects and their interactions

	Hardness (N)	Gumminess (N)	Springiness	Chewiness (N)	Cohesiveness
Irradiation source effect (IS)	***	***	*	***	NS
Transglutaminase (TG)	***	***	NS	***	NS
Interaction (IS × TG)	**	*	NS	*	NS

a, b means within a row with different letters are significantly different ($P < 0.05$).
*$P < 0.05$, **$P < 0.01$, ***$P < 0.001$.
[a] Only minced pork ham was irradiated with 10 kGy radiation by irradiation source (X-ray, E-beam, γ-ray).
[b] SEM: the standard error of means.

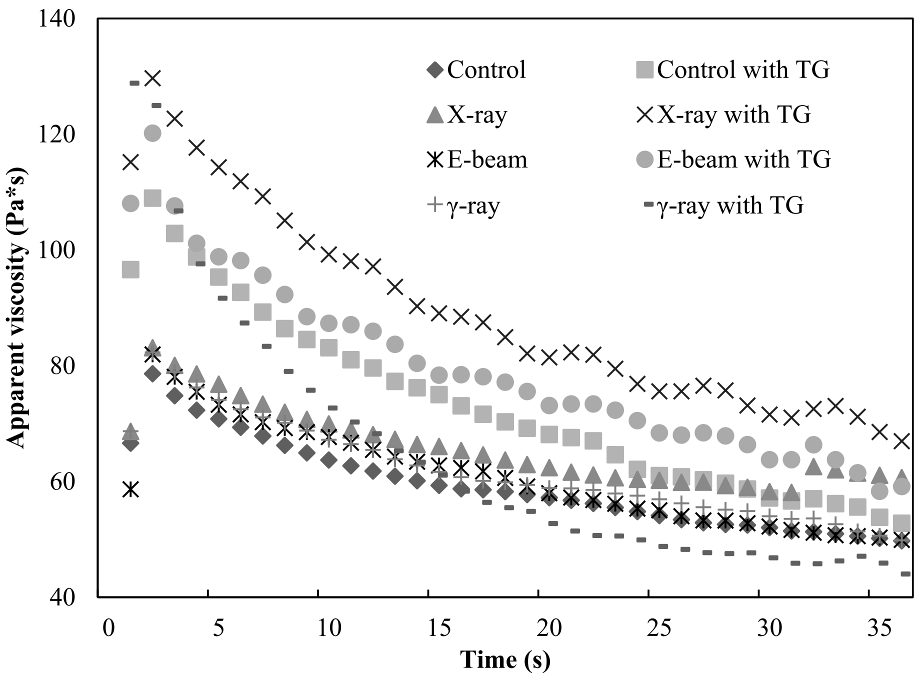

Fig. 1. Apparent viscosity of emulsion meat formulated with irradiated mined raw meat by various kinds of ionizing radiation and transglutaminase (TG). Apparent viscosity of emulsion meat formulated with irradiated mined raw meat by various kinds of ionizing radiation and transglutaminase (TG). Only minced pork ham was irradiated with 10 kGy radiation by irradiation source (X-ray, E-beam, γ-ray).

irradiated with other sources of radiation. The control had slightly lower apparent viscosity compared with that of the treatments. The apparent viscosity of emulsion systems with TG was higher than treatments without TG. These results were in agreement with a previous study which reported that the increased viscosity of fish gelatin could be attributed to TG-induced cross-linking (Bae et al., 2009). Another report indicated that the apparent viscosity is a better predictor than chemical analyses to ascertain the textural properties of the final products (Choi et al., 2014). Based on our results, the apparent viscosity of the meat emulsion composed of X-ray irradiated raw meat and TG showed the most desirable quality.

4. Conclusions

Our results demonstrate that different ionizing radiations in combination with TG treatment could significantly affect the physicochemical properties of emulsion systems. When manufacturing a meat product with irradiated meat, the increased amount of total fluid separation by TG and protein reaction was decreased, and myofibrillar protein solubility was increased. Above these ionizing radiations, gamma rays had the lowest difference of total fluid separation after addition of TG and the highest protein solubility. The property changes are most likely due to the denaturation of protein caused by irradiation and protein aggregation caused by TG. There has been no study regarding the effect of minced meat irradiated with various ionizing radiations on the final meat product; therefore, this study can give some information about the final emulsion meat product formulated with irradiated raw meat. Further studies should be carried out focusing on different fat levels or low-fat emulsified sausage for application in meat product industry widely.

Acknowledgement

This research was supported by Main Research Program (E0193118-01) (E0145100-06) of the Korea Food Research Institute (KFRI) funded by the Ministry of Science & ICT (Republic of Korea).

References

Ando, H., Adachi, M., Umeda, K., Mastuura, M., Nonaka, M., Uchoi, R., Tanaka, H., Otoki, M., 1989. Purificaltion and characteristics of novel transglutaminase derived from microorganisms. Agric. Biol. Chem. 53, 2613–2617.

AOAC, 2000. seventeenth ed. Official Methods of Analysis of AOAC, vol. 41 Assoc. of Official Analytical Chemists, Washington, DC.

Bae, H.J., Darby, D.O., Kimmel, R.M., Park, H.J., Whiteside, W.S., 2009. Effects of transglutaminase-induced cross-linking on properties of fish gelatin-nanoclay composite film. Food Chem. 114, 180–189.

Bloukas, I., Honikel, K.O., 1992. The influence of additives on the oxidation of pork back fat and its effect on water and fat binding in finely comminuted batters. Meat Sci. 32, 31–43.

Bourne, M.C., 1978. Texture profile analysis. Food Technol. 32, 62–66.

Canto, A.C.V.C.S., Costalima, B.R.C., Suman, S.P., Lazaro, C.A., Monteiro, M.L.G., Contejunior, C.A., Freitas, M.Q., Cruz, A.G., Santos, E.B., Silva, T.J.P., 2014. Physico-chemical and sensory attributes of low-sodium restructured caiman steaks containing microbial transglutaminase and salt replacers. Meat Sci. 96, 623–632.

Cho, Y.H., Yang, M.S., 2018. Antioxidant activity of gamma-irradiated *Asparagus cochinchinensis* (Asparagi radix) (Lour.) Merr. extract and inhibition effect on lipid oxidation of emulsion-type pork sausage. Korean J. Food Sci. An. 38, 1196–1202.

Choi, Y.S., Lee, M.A., Jeong, J.Y., Choi, J.H., Han, D.J., Kim, H.Y., Lee, E.S., Kim, C.J., 2007. Effects of wheat fiber on the quality of meat batter. Korean J. Food Sci. An. 27, 22–28.

Choi, Y.S., Kim, H.W., Hwang, K.E., Song, D.H., Choi, J.H., Lee, M.A., Chung, H.J., Kim, C.J., 2014. Physicochemical properties and sensory characteristics of reduced-fat frankfurters with pork back fat replaced by dietary fiber extracted from *makgeolli* lees. Meat Sci. 96, 892–900.

Choi, Y.S., Kim, H.W., Hwang, K.E., Song, D.H., Jeong, T.J., Seo, K.W., Kim, Y.B., Kim, C.J., 2015. Effects of gamma irradiation on physicochemical properties of heat-induced gel prepared with chicken salt-soluble proteins. Radiat. Phys. Chem. 106, 16–20.

Choi, Y.S., Jeong, T.J., Hwang, K.E., Song, D.H., Ham, Y.K., Kim, H.W., Kim, Y.B., Kim, C.J., 2016. Combined effects of *Laminaria japonica* and transglutaminase on physicochemical and sensory characteristics of semi-dried chicken sausages. Poult. Sci. 95, 1943–1949.

Cleland, M.R., Stichelbaut, F., 2013. Radiation processing with high-energy X-rays. Radiat. Phys. Chem. 84, 91–99.

Farkas, J., 2006. Irradiation for better foods. Trends Food Sci. Technol. 17, 148–152.

Feng, X., Moon, S.H., Lee, H.Y., Ahn, D.U., 2017. Effect of irradiation on the parameters that influence quality characteristics of raw Turkey breast meat. Radiat. Phys. Chem. 130, 40–46.

Ham, Y.K., Kim, H.W., Hwang, K.E., Song, D.H., Kim, Y.J., Choi, Y.S., Song, B.S., Park, J.H., Kim, C.J., 2017. Effect of irradiation source and dose level on quality characteristics of processed meat products. Radiat. Phys. Chem. 130, 259–264.

Hemung, B.O., Chin, K.B., 2015. Evaluation of acidtreated fish sarcoplasmic proteins on physicochemical and rheological characteristics of pork myofibrillar protein gel mediated by microbial transglutaminase. Korean J. Food Sci. An. 35, 50–57.

Kim, H.W., Kim, Y.H.B., Hwang, K.E., Kim, T.K., Jeon, K.H., Kim, Y.B., Choi, Y.S., 2017. Effects of grmma-ray, electron-beam, and X-ray irradiation on physicochemical properties of heat-induced gel prepared with salt-soluble pork protein. Food Sci. Biotechnol. 26, 955–958.

Lee, H.C., Chin, K.B., 2009. Effect of transglutaminase, acorn, and mungbean powder on quality characteristics of low-fat/salt pork model sausages. Korean J. Food Sci. An. 29, 374–381.

Li, C., He, L., Ma, S., Wu, W., Yang, H., Sun, X., Peng, A., Wang, L., Jin, G., Zhang, J., Jin, Y., Ma, M., 2018. Effect of irradiation modification on conformation and gelation properties of pork myofibrillar and sarcoplasmic protein. Food Hydrocoll. 84, 181–192.

Park, S., Chung, M.G., Yoo, B., 2004. Effect of octenylsuccinylation on rheological properties of corn starch pastes. Starch 56, 399–406.

Park, J.G., Yoon, Y., Park, J.N., Han, I.J., Song, B.S., Kim, J.H., Kim, W.G., Hwang, H.J., Han, S.B., Lee, J.W., 2010. Effects of gamma irradiation and electron beam irradiation on quality, sensory, and bacterial populations in beef sausage patties. Meat Sci. 85, 368–372.

Park, Y.S., Choi, Y.S., Hwang, K.E., Kim, T.K., Lee, C.W., Shin, D.M., Han, S.G., 2017. Physicochemical properties of meat batter added with edible silkworm pupae (*Bombyx mori*) and transglutaminase. Korean J. Food Sci. An. 37, 351–359.

Song, D.H., Kim, C.J., Lee, J.H., Kim, T.K., Shin, D.J., Choi, Y.S., Ham, Y.K., Kim, Y.J., Hwang, K.E., Kim, H.W., Paik, H.D., 2017. Impacts of irradiation sources on quality attributes of low-salt sausage during refrigerated storage. Korean J. Food Sci. An. 37, 698–707.

Temiz, H., Dağyıldız, K., 2017. Effects of microbial transglutaminase on physicochemical, microbial and sensorial properties of kefir produced by using mixture cow's and soymilk. Korean J. Food Sci. An. 37, 606–616.

Tseng, T.F., Liu, D.C., Chen, M.T., 2000. Evaluation of transglutaminase on the quality of low-salt chicken at balls. Meat Sci. 55, 427–431.

Utama, D.T., Jeong, H.S., Kim, J.T., Lee, S.K., 2018. Formula optimization of a perilla-canola oil (O/W) emulsion and its potential application as an animal fat replacer in meat emulsion. Korean J. Food Sci. An. 38, 580–592.

Venugopol, V., Doke, S.N., Thomas, P., 1999. Radiation processing to improve the quality of fishery products. Crit. Rev. Food Sci. Nutr. 39, 391–440.

World Health Organization (WHO), 1999. High Dose Irradiation: Wholesomeness of Food Irradiated with Doses above 10 kGy. WHO Technical Report Series 890. Geneva.

Yim, D.G., Jo, C., Mahabbat, A., Park, J.Y., Lee, S.Y., Nam, K.C., 2019. Combined effect of aging and irradiation on physicochemical quality of pork shoulder. Food Sci. Anim. Resour. 39, 510–519.

Yu, L., Gao, C., Zeng, M., He, Z., Wang, L., Zhang, S., Chen, J., 2016. Effects of raw meat and process procedure on N ε-carboxymethyllysine and N ε-carboxyethyl-lysine formation in meat products. Food Sci. Biotechnol. 25, 1163–1168.

Yıldırım, I., Uzunlu, S., Topuz, A., 2005. Effect of gamma irradiation on some principle microbiological and chemical quality parameters of raw Turkish meat ball. Food Control 16, 363–367.

Zhou, F., Zhao, M., Su, G., Cui, C., Sun, W., 2014. Gelation of salted myofibrillar protein under malondialdehyde-induced oxidative stress. Food Hydrocoll. 40, 153–162.