Irradiation of shell egg on the physicochemical and functional properties of liquid egg white

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ABSTRACT This study was aimed at determining the effect of irradiation of shell eggs on the physiochemical and functional properties of liquid egg white during storage. Color and textural parameters of irradiated liquid egg white after cooking were also determined. Shell eggs were irradiated at 0, 2.5, 5, or 10 kGy using a linear accelerator. Egg white was separated from yolk and stored in at 4°C up to 14 d. Viscosity, pH, turbidity, foaming properties, color, and volatile profile of liquid egg white, and color and texture properties of cooked egg white were determined at 0, 7, and 14 d of storage. Irradiation increased the turbidity but decreased viscosity of liquid egg white. Foaming capacity and foam stability were not affected by irradiation at lower dose (2.5 kGy), but were deteriorated at higher doses (≥5.0 kGy) of irradiation. Sulfur-containing volatiles were generated by irradiation and their amounts increased as the irradiation dose increased. However, the sulfur volatiles disappeared during storage under aerobic conditions. Lightness (L* value) and yellowness (b* value) decreased, but greenness (−a* value) increased in cooked egg white in irradiation dose-dependent manners. All textural parameters (hardness, adhesiveness, cohesiveness, chewiness, and resilience) of cooked egg white increased as the irradiation dose increased, but those changes were marginal. Our results indicated that irradiation of shell egg at lower doses (up to 2.5 kGy) had little negative impact on the physiochemical and functional properties of liquid egg white, but can improve the efficiency of egg processing due to its viscosity-lowering effect. Therefore, irradiation of shell eggs at the lower doses has high potential to be used by the egg processing industry to improve the safety of liquid egg without compromising its quality.

Key words: egg white, irradiation, functional property, physicochemical property

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INTRODUCTION

Foodborne illness is a major concern for public health in the United States. The Centers for Disease Control and Prevention estimated that foodborne pathogens cause 47.8 million cases of foodborne diseases, 128,000 hospitalizations, and 3,000 deaths in the United States annually (Scallan et al., 2011a,b). They indicated that *Salmonella* is a leading pathogen causing an estimated 19,336 hospitalizations and 378 deaths annually. In addition, the incidence of *Salmonella* infection has not decreased substantially over the last 15 yr and was the most common infection accounting for 43% of total laboratory-confirmed pathogen infection cases reported in 2010 (Centers for Disease Control and Prevention, 2011). Shell eggs and egg-containing products are the most significant source of *Salmonella*. They were responsible for 80% of Salmonellosis outbreaks of which food sources are confirmed from 1985 to 1999 (Patrick et al., 2004). In addition, a nationwide outbreak of *Salmonella* Enteritidis infection associated with shell eggs caused more than 1,900 foodborne illness and led to a recall of 500 million eggs in 2010 (Centers for Disease Control and Prevention, 2010). Due to the significance of egg-related *Salmonella* infection, the Food and Drug Administration (2009) implemented a new egg safety regulation named "Egg Safety Final Rule" to prevent *Salmonella* contamination of shell eggs during production, transportation, and storage.

Salmonella contamination can occur on the outer shell as well as internal contents such as egg yolk and white (Gast and Beard, 1990; Gantois et al., 2009). External contamination can occur through contaminated

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environmental factors such as feces as well as the infected oviduct of laying hens (Braden, 2006; Gantois et al., 2009). *Salmonella* on the shell may penetrate into the inside of eggs via the cracks and contaminate the internal contents. In addition, direct contamination of internal contents can occur from the infected reproductive organs before laying eggs (Gast and Beard, 1990; Braden, 2006; Gantois et al., 2009). Traditional disinfection processes such as washing can eliminate *Salmonella* on the surface of shell eggs, but are not effective on *Salmonella* in the internal contents of eggs. Therefore, a pasteurization process that can remove internally contaminated *Salmonella* in shell egg is needed. Recently, in-shell pasteurization processes at a low temperature (~55°C) have been used to reduce *Salmonella* in shell eggs, but they need extended time to achieve a 5-log reduction of *Salmonella* (Hou et al., 1996; Hank et al., 2001).

Irradiation is one of the most effective nonthermal pasteurization technologies and may be the most suitable to destroy *Salmonella* contaminated in the internal contents of shell eggs. Accumulated evidences have indicated that irradiation is very effective in controlling *Salmonella* and other foodborne pathogens that contaminate shell eggs internally and externally (Serrano et al., 1997; Cabo Verde et al., 2004; Rodrigues et al., 2011). However, irradiation can also cause significant changes in functional properties of egg white due to the oxidation of egg components by hydroxyl radicals produced through the radiolysis of water (Branka et al., 1992; Min et al., 2005). Free radicals can cause fragmentation, aggregation, and cross-linking of protein molecules, and induce changes in physicochemical and functional properties such as viscosity, foaming, binding, emulsification, thermal gelation, and thickening properties of egg white (Ma et al., 1993; Moon and Song, 2001; Liu et al., 2009). Changes in physicochemical and functional properties of egg white can significantly influence the quality of many food products using egg as an ingredient. Yet, the effect of irradiation on physicochemical and functional properties of egg white is still controversial. Several studies (Ma et al., 1990; Katusin-Razem et al., 1992; Min et al., 2005) showed that irradiation caused oxidation of egg components such as proteins, polyunsaturated fatty acids, cholesterols, and carotenoids, deteriorated internal and sensory quality, changed color, and decreased the viscosity of egg white. On the other hand, other studies (Huang et al., 1997; Serrano et al., 1997) indicated that low-dose irradiation (1.5 to 2.5 kGy) did not cause substantial changes in physicochemical and functional properties of shell eggs and egg products. Some researchers (Ma et al., 1993; Liu et al., 2009; Song et al., 2009) suggested that the foaming properties of egg white can be improved by low-dose irradiation (1 to 5 kGy).

The objective of this study was to investigate the effect of irradiating shell eggs on the physiochemical and foaming properties of liquid egg white during storage. In addition, changes in color and texture properties of cooked egg white made from irradiated liquid egg white were determined.

MATERIALS AND METHODS

Sample Preparation

One thousand four hundred forty fresh shell eggs (1-d-old) were received from a local egg producer after processing (washed, inspected, and packaged) and were immediately stored in a refrigerator at 4°C for 3 d. The eggs were irradiated on pulp trays at 0, 2.5, 5, and 10 kGy using a Linear accelerator (Circe IIIR, Thomsom CSF Linac, St. Aubin, France) under the conditions of 10 MeV energy, 5.6 kW power level, and 61.3 kGy/min of average dose rate at room temperature. A 2-side irradiation method was used to achieve a uniform dose distribution: one side of the eggs was irradiated first, and then the eggs were turned upside down for the second irradiation. The alanine dosimeters were placed on the top and bottom of an egg per cart, and the absorbed doses were measured by 104 Electron Paramagnetic Resonance Instrument (Bruker Instruments Inc., Billerica, MA). During irradiation, nonirradiated control (0 kGy) samples were kept in the irradiation facility to be exposed to the same temperature conditions as the irradiated ones. After irradiation, egg white was separated from yolk. Egg white from 30 eggs were pooled in a 2-L beaker, blended smoothly to avoid foam formation, and then stored in a refrigerator at 4°C up to 14 d. The beaker was used as a replication unit (n = 4). No additives were added to the pooled egg white. A part of egg white was placed in cellulose casings (25 mm in diameter, 100 mL egg white per casing) and cooked in boiling water for 18 min to produce cylinder-shape sticks. After cooling to room temperature, the sticks with casing were stored in a refrigerator in oxygen-permeable bags (polyethylene, 215.9 × 279.4 mm, 2 mil, Associated Bag Co., Milwaukee, WI) up to 14 d. Viscosity, pH, turbidity, foaming properties, color, and volatile profile of liquid egg white, and color and texture properties for cooked egg white were determined at 0, 7, and 14 d of storage. Before analysis, all of the samples were taken out from a refrigerator and set on the laboratory bench for 1 h to equilibrate the sample temperature to room temperature. All analyses were conducted at room temperature.

pH, Viscosity, Turbidity, and Foaming Properties of Liquid Egg White

A 10-fold dilution of each liquid white sample was prepared using deionized, distilled water (**DDW**) and the pH was determined using a pH meter (model 420Aplus, Thermo Orion, Beverly, MA). Viscosity of liquid egg white was determined using a viscometer (model DV-II+, Brookfield Engineering Labs Inc., Stoughton, MA) with a No. 1 RV spindle rotating at 100 rpm by the method of Min et al. (2005). The spindle was placed

in a 600-mL beaker containing 400 mL of liquid egg white and rotated at room temperature to measure the viscosity. Turbidity of liquid egg white was determined using the method of Xiong (1992) with some modifications. Briefly, liquid egg white was diluted 20 times with DDW and the optical density of the diluted sample was determined at 320 nm against a blank containing only DDW using a spectrophotometer (Cary 50, Varian Analytical Instruments, Palo Alto, CA).

Foaming capacity and foam stability of liquid egg white were determined using the modified method of Min et al. (2005). Liquid egg white (100 g) was mixed in a mixer with a wire whip (KitchenAid, St. Joseph, MI) at maximum speed (280 rpm) for 5 min to produce foam and the foam was transferred into a preweighed 1,000-mL graduated cylinder. The volume and weight of the foam were measured to determine specific density of the foam (g/mL foam) as a foaming capacity. Foam stability was determined by measuring a volume of drainage (mL) in the 1,000-mL graduated cylinder after 30 min of holding the foam at room temperature.

Volatile Analysis of Egg White

A dynamic headspace analysis was performed using a vial autosampler (Solatek 72 Multimatrix, Tekmar-Dohrmann, Cincinnati, OH) and a Purge-and-Trap concentrator (3100, Tekmar-Dohrmann) as described by Nam et al. (2004). A gas chromatograph (GC, model 6890, Hewlett Packard Co., Wilmington, DE) equipped with a mass selective detector (MSD, model 5973, Hewlett Packard Co.) was used to qualify and quantify volatile compounds. Liquid egg white (3 g) was transferred to a 40-mL sample vial, and headspace was flushed with helium (99.999% purity) for 5 s to minimize oxidative changes during the waiting period before analysis. Sample was purged with helium (40 mL/min) for 15 min at 40°C. Volatile compounds were trapped using a Tenax/silica/charcoal column (Tekmar-Dohrmann), focused in a cryofocusing module (−80°C), and then thermally desorbed into a GC column for 2 min at 225°C. The column used in this study was a combined column (Hewlett Packard) which consisted of 3 different columns, an HP-624 column (15 m × 0.25 mm i.d., 1.4 μm nominal), an HP-1 column (60 m × 0.25 mm i.d., 0.25 μm nominal), and an HP-Wax column (15 m × 0.25 mm i.d., 0.25 μm nominal) were connected using zero dead-volume column connectors (J&W Scientific, Folsom, CA). Ramped oven temperature was used to improve volatile separation. The initial oven temperature of 30°C was held for 6 min. After that, the oven temperature was increased to 60°C at 5°C/min, increased to 180°C at 20°C/min, increased to 210°C at 15°C /min, and then was held for 5 min at that temperature (15°C). Helium was the carrier gas at constant column pressure at 22.5 psi. The temperature of transfer lines was maintained at 155°C. The ionization potential of the mass spectrometer was 70 eV, and the scan range was 29.1 to 350 m/z. Identification of volatiles was achieved using the Wiley library (Hewlett Packard). The area of each peak was integrated using ChemStation software (Hewlett Packard) and the peak area (total ion counts × 10^4) for each volatile was reported as the amount of the volatile generated from liquid egg white.

Color Determination of Liquid and Cooked Egg White

Commission Internationale de l'Eclairage (CIE) L* (lightness), a*[redness (+)/greenness (−)], and b* (yellowness) values of liquid and cooked egg white samples were determined using a LabScan colorimeter (Hunter Associate Labs Inc., Reston, VA) under the conditions of illuminant A, 10° standard observer, 10-mm port size, and a 0.63-mm viewing area. Liquid egg white (100 mL) was placed into a transparent zipper bag (polyethylene, 101.6 × 152.4 mm, 2 mil) and the color values were determined by averaging 6 readings consisting of 3 readings on each side of the zipper bag. In order to measure the color values of cooked egg white, 2 egg white sticks per replication were cut into 20-mm pieces. Three cylindrical pieces per stick were collected and each was placed in the zipper bag. The color values of each piece were read 4 times (twice each from bottom and top sides) and the average of 4 readings was used as the color value. The colorimeter was calibrated with black and white reference tiles covered with the same zipper bag used for the samples.

Texture Profile Analysis of Cooked Egg White

Texture properties of cooked egg white sticks were determined using a Texture Profile Analyzer (model TA-XT2i, Texture Technologies, Scarsdale, NY) with a 5-kg loading cell and a cylinder plunger (TA-4, 38-mm in diameter). The cooked egg white sticks were cut into 20-mm pieces and compressed through 2 repeated cycles with 80% compression of the initial height at a crosshead speed of 60 mm/min. There was a 5-s resting duration between the 2 cycles to allow the sample to recover its height. Six pieces from 2 sticks (3 from each stick) per replication were taken and measured, and then the records from 6 pieces were averaged. Hardness, cohesiveness, springiness, chewiness, and gumminess calculated from the texture profile analysis curve were reported. Each textural term was defined as follows: 1) hardness [gram-force (**gf**)] is the peak force during the first compression cycle, 2) adhesiveness (gf·cm) is the work necessary to pull the compressing plunger away from the sample, 3) cohesiveness is the ratio of the positive force area under the second compression to that under the first compression, 4) chewiness (gf·cm) is the energy required to compress the sample and the product of hardness × cohesiveness × springiness, and 5)

Table 1. The pH, turbidity, viscosity, and foam stability of irradiated liquid egg white with different irradiation doses and their changes during storage[1]

	Irradiation dose (kGy)				
Storage	0	2.5	5	10	SEM
pH					
d 0	9.10^{a,x}	9.04^{b,x}	9.02^{c,x}	8.97^{d,x}	0.01
d 7	9.00^{a,z}	9.00^{a,y}	8.97^{b,y}	8.91^{c,z}	0.01
d 14	9.04^{a,y}	9.02^{b,y}	8.99^{c,y}	8.95^{d,y}	0.01
SEM	0.01	0.01	0.01	0.01	
Turbidity					
d 0	0.59^{d}	0.94^{c,y}	1.33^{b,z}	2.07^{a,y}	0.01
d 7	0.57^{d}	1.04^{c,x}	1.44^{b,y}	2.13^{a,x}	0.01
d 14	0.55^{d}	1.07^{c,x}	1.48^{b,x}	2.16^{a,x}	0.01
SEM	0.01	0.01	0.01	0.01	
Viscosity (cP[2])					
d 0	26.4^{a,y}	20.0^{b,y}	19.2^{c,z}	16.8^{d,y}	0.1
d 7	29.6^{a,x}	19.8^{b,y}	20.0^{b,y}	17.0^{c,y}	0.2
d 14	30.2^{a,x}	21.4^{b,x}	21.6^{b,x}	21.6^{b,x}	0.1
SEM	0.2	0.2	0.2	0.1	
Foaming capacity (g/mL foam)					
d 0	0.118^{c}	0.125^{c,y}	0.176^{a,x}	0.155^{b}	0.006
d 7	0.131^{c}	0.142^{b,x}	0.142^{b,y}	0.155^{a}	0.003
d 14	0.124^{b}	0.130^{b,y}	0.160^{a,x}	0.152^{a}	0.005
SEM	0.005	0.001	0.005	0.006	
Foam stability (mL drainage)					
d 0	23.7^{c}	25.9^{c}	56.5^{a,x}	39.3^{b,x}	3.9
d 7	19.3^{d}	27.1^{b}	23.1^{c,y}	30.2^{a,y}	0.8
d 14	16.2^{c}	22.4^{b}	32.1^{a,y}	28.8^{a,y}	1.3
SEM	2.0	1.9	3.7	1.5	

$^{a–d}$Means with different letters within the same row are significantly different ($P < 0.05$).

$^{x–z}$Means with different letters within the same column are significantly different ($P < 0.05$).

[1]n = 4.

[2]cP = centipoise.

resilience is the ratio of the area during the withdrawal of the first compression to the area of the first compression (Bourne, 2002).

Statistical Analysis

This study was conducted using a completely randomized design with 4 replications. Data were analyzed using the SAS software (version 9.2, SAS Institute Inc., Cary, NC). Data were reported as means and SEM. Student-Newman-Keuls multiple-range test ($P < 0.05$) was used to compare the means of each treatment.

RESULTS AND DISCUSSION

The pH of liquid egg white was slightly but significantly decreased by irradiation ($P < 0.05$) and the decrease was irradiation dose-dependent (Table 1). It was reported that the pH of egg white increases gradually from pH 7.6 to 8.5 in newly laid shell eggs up to approximately pH 9.7 during storage due to the escape of carbon dioxide gas through pores on egg shell (Li-Chan et al., 1995). The pH of irradiated and nonirradiated egg white was around pH 9.0, which was higher than that of the newly laid eggs but not as high as 9.7 due to short storage period (2 wk). Irradiation can cause radiolysis of water molecule, which produces various decomposed products including hydrogen ion that can influence the pH of egg. After 7 d of storage, the pH of all samples decreased significantly, but they increased significantly during the further storage (7 d or longer) due to the loss of carbon dioxide from liquid egg white under the oxygen permeable conditions.

The turbidity of liquid egg white was increased by irradiation, and the increase was proportional to irradiation dose (Table 1). In addition, the turbidity in all irradiated egg white increased significantly during storage ($P < 0.05$) even though the increase was not proportional to storage time. Storage had no effect on the turbidity of nonirradiated control egg white. Irradiation has been reported to increase protein oxidation in liquid egg white in an irradiation dose-dependent manner (Min et al., 2005; Liu et al., 2009). It has been suggested that irradiation caused changes in distribution of molecular weight, fragmentation, and subsequent aggregation of egg white proteins such as ovalbumin and ovomucoid from shell eggs (Moon and Song, 2001; Vučkovič et al., 2005). This indicated that the increase of turbidity in irradiated egg white could be caused by the decreased solubility of egg white proteins.

Irradiation considerably decreased the viscosity of liquid egg white in an irradiation dose-dependent manner (Table 1). The egg white irradiated at 10 kGy was very thin. This result agrees with other similar studies irradiating shell eggs (Ma et al., 1990; Min et al., 2005). Several studies (Ball and Gardner, 1968; Moon and Song, 2001; Liu et al., 2009), where irradiation was applied to either separated liquid egg white or individual

egg white proteins, indicated that irradiation degraded major protein molecules such as ovomucin, conalbumin, ovalbumin, and ovotransferrin in egg white. Ma et al. (1990) suggested that irradiation caused structural changes in ovomucin network, which is responsible for gel-like structure of egg white. These changes in major proteins in egg white by irradiation were responsible for lower viscosity of irradiated egg white. Min et al. (2005) emphasized that the watery characteristics of irradiated egg white can increase the flow of liquid egg white in egg processing facilities and improve equipment efficiency. The viscosity of liquid egg white gradually increased during 14 d of storage in all samples, but that of irradiated egg white was still significantly lower than that of the nonirradiated control ($P < 0.05$).

Egg white is well-known for its excellent foaming properties and has been widely used in manufacturing many food products such as bakery and confectionary products. The major factors affecting foam formation in food systems are the surface activity and film-forming properties of individual proteins (Kinsella, 1981). Egg white contains various proteins that can contribute to foam formation and stability: conalbumin and globulin contribute to the formation of foam and ovomucin and lysozyme to foam stability (Ball and Gardner, 1968; Yang and Baldwin, 1995; Liu et al., 2009). This study determined foaming capacity and foam stability, the 2 most important indicators of foaming capacity of the liquid egg white: foaming capacity as the specific density of foam and foam stability as a volume of drainage after foaming (Table 1). The foaming capacity and foam stability of egg white were affected by irradiation. Right after irradiation (d 0) and after 14 d of storage (d 14), the foaming capacity and foam stability of nonirradiated liquid egg white were not different from those of the egg white irradiated at 2.5 kGy, but were significantly greater than those irradiated at 5 and 10 kGy. This indicated that low-dose irradiation ($\leq$2.5 kGy) had little effect, but higher-dose irradiation ($\geq$5 kGy) had a negative impact on the foaming capacity and foam stability of liquid egg white. Yang and Baldwin (1995) suggested that the viscosity of liquid egg white is positively related to foaming capacity as well as foam stability. Therefore, physicochemical and structural changes in egg white proteins caused by irradiation may lead to deterioration of foaming properties of liquid egg white irradiated at higher doses. Other studies (Ball and Gardner, 1968; Min et al., 2005) also reported similar results. However, Song et al. (2009) and Liu et al. (2009) reported that foaming capacity of liquid egg white was improved when irradiation was applied to liquid egg white at 1 to 5 kGy. Those studies employed high-speed homogenizers with homogenizing speeds at 1,900 rpm and 24,200 $\times$ g, respectively, to produce foam from egg white, which were much higher than the speed (280 rpm) employed in this study. Foaming capacity of egg white can be affected by various processing factors such as methods of beating, pretreatments, and presence of ingredients (Yang and Baldwin, 1995). Therefore, different foaming methods employed may yield different results.

Interestingly, liquid egg white irradiated at 10 kGy showed better foaming capacity and foam stability than that at 5 kGy right after irradiation (d 0). Vučkovič et al. (2005) suggested that free radicals produced by irradiation cannot only degrade egg white proteins but also agglomerate protein fragments degraded by irradiation. They also indicated that extents of protein degradation and agglomeration are irradiation dose-dependent, but the latter is higher than the former at higher doses. This leads to the assumption that a higher level of agglomerates in liquid egg white irradiated at 10 kGy may have produced greater air-water interface network during foam formation, resulting in better foaming capacity and foam stability than those at 5 kGy.

Foaming capacities of all samples were not changed after 14 d of storage (Table 1). The foaming capacity of egg white irradiated at 0 and 2.5 kGy was significantly greater than that at 5 and 10 kGy after storage. Foam stabilities of egg white irradiated at 0 and 2.5 kGy did not significantly change during 14 d of storage (Table 1). However, foam stability of egg white irradiated at 5 and 10 kGy were significantly improved during storage, but they were still lower than those irradiated at 0 and 2.5 kGy. It is assumed that protein fragments generated in liquid egg white irradiated at 5 and 10 kGy were agglomerating during storage (Vučkovič et al., 2005), resulting in improved foam stability. Therefore, storage of egg white irradiated at higher doses ($\geq$5 kGy) could be helpful in restoring foam stability to some extent. Overall, the results suggested that low-doses irradiation ($\leq$2.5 kGy) of shell egg can be used to improve the safety of liquid egg white without deteriorating its foaming capacity and stability.

The amounts of total volatile compounds in liquid egg white significantly increased as irradiation doses increased (Table 2). The amounts of benzene, toluene, and hexanal in liquid egg white increased by irradiation and some hydrocarbons, ketones, aldehydes, and sulfur-containing compounds were newly produced. Egg white proteins are the major sources for the newly generated volatiles by irradiation because the contents of lipids and carbohydrates are the minor components of egg white. Those newly generated volatiles by irradiation may be produced by the radiolytic or oxidative degradation (or both) of amino acid side chains in egg white proteins, and the secondary reactions between the primary degradation products. Many sulfur-containing volatiles, including methanethiol, dimethyl sulfide, methylthio ethane, ethanethioic acid, dimethyl disulfide, and dimethyl trisulfide, were generated by irradiation, and their amounts increased as the irradiation dose increased. Dimethyl disulfide was the major sulfur volatiles produced by irradiation, and methanethiol, dimethyl sulfide, and methylthio ethane appeared at higher dose irradiation ($\geq$5 kGy). It was suggested that sulfur-containing volatile compounds are responsible for irradiation off-odor in irradiated meat and

Table 2. Volatiles profiles of liquid egg white with different irradiation doses and their changes during storage[1]

	Irradiation dose (kGy)														
	d 0					d 7					d 14				
Compound	0	2.5	5	10	SEM	0	2.5	5	10	SEM	0	2.5	5	10	SEM
Acetaldehyde	0	256	0	181	113	—	—	—	—		—	—	—	—	
Methanethiol	0^{b}	0^{b}	213^{b}	$1{,}367^{a}$	263	—	—	—	—		—	—	—	—	
Pentane	0^{d}	245^{c}	317^{b}	495^{a}	21	0	0	0	34	21	—	—	—	—	
2-Propanone	0	1,932	689	154	887	—	—	—	—		—	—	—	—	
Dimethyl sulfide	0^{c}	75^{c}	296^{b}	808^{a}	61	—	—	—	—		—	—	—	—	
2-Methyl propanal	0^{d}	$3{,}217^{c}$	$4{,}246^{b}$	$7{,}302^{a}$	331	0^{d}	$1{,}380^{c}$	$2{,}245^{b}$	$4{,}078^{a}$	84	0^{b}	0^{b}	0^{b}	741^{a}	31
Hexane	$1{,}412^{b}$	$3{,}337^{a}$	$3{,}255^{a}$	588^{c}	213	353^{b}	892^{a}	694^{a}	0^{c}	80	$5{,}949^{b}$	$4{,}482^{b}$	$6{,}068^{b}$	$10{,}703^{a}$	128
Methylthio ethane	0^{b}	0^{b}	0^{b}	302^{a}	11	—	—	—	—		—	—	—	—	
Ethyl acetate	160	437	218	311	111	—	—	—	—		—	—	—	—	
Benzene	347^{d}	988^{c}	$1{,}989^{b}$	$5{,}838^{a}$	153	0^{d}	103^{c}	563^{b}	$2{,}438^{a}$	104	—	—	—	—	
3-Methyl butanal	0^{d}	$5{,}549^{c}$	$7{,}868^{b}$	$13{,}783^{a}$	602	0^{d}	$1{,}799^{c}$	$3{,}050^{b}$	$5{,}633^{a}$	106	0^{b}	0^{b}	213^{b}	$1{,}075^{a}$	128
2-Methyl butanal	0^{d}	$3{,}849^{c}$	$5{,}958^{b}$	$10{,}930^{a}$	390	0^{d}	$1{,}408^{c}$	$2{,}609^{b}$	$5{,}015^{a}$	57	0^{b}	0^{b}	177^{b}	$1{,}048^{a}$	107
Heptane	0^{d}	157^{c}	200^{b}	314^{a}	9	—	—	—	—		—	—	—	—	
Ethanethioic acid	0^{c}	513^{b}	718^{b}	$1{,}610^{a}$	123	—	—	—	—		—	—	—	—	
Pentanal	71^{b}	430^{a}	282^{a}	315^{a}	42	—	—	—	—		—	—	—	—	
Dimethyl disulfide	0^{d}	$5{,}729^{c}$	$9{,}017^{b}$	$14{,}000^{a}$	543	0^{d}	$1{,}261^{c}$	$2{,}363^{b}$	$3{,}772^{a}$	53	—	—	—	—	
Toluene	278^{d}	$7{,}943^{c}$	$13{,}615^{b}$	$21{,}857^{a}$	443	0^{d}	$1{,}872^{c}$	$3{,}943^{b}$	$7{,}490^{a}$	555	0^{b}	$1{,}099^{ab}$	$1{,}412^{ab}$	$2{,}497^{a}$	504
Hexanal	414^{b}	850^{a}	852^{a}	864^{a}	124	—	—	—	—		—	—	—	—	
Nonane	131^{b}	156^{a}	168^{a}	171^{a}	5	—	—	—	—		—	—	—	—	
Dimethyl trisulfide	0^{b}	40^{b}	180^{a}	246^{a}	35	—	—	—	—		—	—	—	—	
Total	$3{,}214^{d}$	$36{,}120^{c}$	$50{,}088^{b}$	$81{,}445^{a}$	2,668	353^{d}	$8{,}716^{c}$	$15{,}470^{b}$	$28{,}566^{a}$	590	$5{,}949^{b}$	$5{,}582^{b}$	$7{,}872^{b}$	$16{,}460^{a}$	1,284

[a–d]Means with different letters within the same row with the same storage day are significantly different ($P < 0.05$).

[1]n = 4. Unit = total ion counts × 10^4. — indicates that compounds were not detected.

Table 3. Color values of cooked egg white sticks made from liquid egg white irradiated at different doses and their changes during storage[1]

	Irradiation dose (kGy)				
Storage	0	2.5	5	10	SEM
L* value[2]					
d 0	86.8^{a}	$85.0^{b,x}$	83.0^{c}	76.5^{d}	0.2
d 7	86.4^{a}	$84.4^{b,y}$	81.7^{c}	76.3^{d}	0.4
d 14	86.6^{a}	$85.4^{b,x}$	82.6^{c}	76.7^{d}	0.2
SEM	0.1	0.2	0.5	0.2	
a* value[2]					
d 0	$-0.3^{a,x}$	$-0.7^{b,x}$	$-1.8^{c,x}$	-4.2^{d}	0.1
d 7	$-0.5^{a,y}$	$-1.0^{b,y}$	$-1.8^{c,x}$	-4.2^{d}	0.1
d 14	$-0.7^{a,z}$	$-1.3^{b,z}$	$-2.0^{c,y}$	-4.0^{d}	0.1
SEM	0.1	0.1	0.1	0.1	
b* value[2]					
d 0	$7.7^{a,x}$	$7.4^{a,x}$	5.9^{b}	$2.6^{c,z}$	0.1
d 7	$7.9^{a,x}$	$7.2^{b,x}$	6.0^{c}	$3.0^{d,y}$	0.1
d 14	$6.9^{a,y}$	$6.4^{b,y}$	6.1^{c}	$4.6^{d,x}$	0.1
SEM	0.1	0.2	0.1	0.1	

[a–d]Means with different letters within the same row are significantly different ($P < 0.05$).

[x–z]Means with different letters within the same column are significantly different ($P < 0.05$).

[1]n = 4.

[2]L* = lightness; a* = redness (+)/greenness (−); b* = yellowness.

were generated by the radiolytic degradation of sulfur-containing amino acids such as methionine and cysteine (Ahn et al., 2000; Ahn and Lee, 2002). The amount of total volatiles in all samples decreased significantly during 14 d of storage. Especially, all sulfur-containing volatiles except dimethyl disulfide were undetectable at d 7, and no sulfur volatiles were detected at d 14 because of their high volatility (Nam et al., 2004). This indicated that irradiation of shell egg may not influence odor if the liquid egg white is stored for 1 to 2 wk under aerobic conditions before use.

The color L* (lightness), a* [redness (+)/greenness (−)], and b* (yellowness) values of liquid egg white were not significantly influenced by irradiation (data not shown). However, all color values of the cooked egg white sticks made from irradiated egg white were significantly lower than those from nonirradiated control ($P < 0.05$; Table 3). Decreases in lightness and yellowness and increase in greenness of the sticks made from irradiated egg white were proportional to irradiation dose applied on shell eggs. Thermal treatments of egg white cause denaturation and subsequent aggregation of egg white proteins to form a 3-dimensional gel structure, which determines the physical characteristics of heat-induced gel such as color. Handa et al. (1998) reported that heat treatments of egg white under conditions that can cause protein denaturation (i.e., very high pH) results in gels with a uniform, fine 3-dimensional structure due to homogeneous crosslinkings of unfolded protein filaments, and the gel with a uniform structure has lower L* and b* values. Therefore, protein denaturation and fragmentation in egg white caused by irradiation may lead to the formation of heat-induced gel with a uniform structure, and consequently, has lower L*, a*, and b* values. Lightness (L* value) of all cooked egg white samples did not change after 14 d of storage. Greenness (a* value) and yellowness (b* value) of most samples changed slightly but significantly after 14 d of storage. Although such subtle but significant changes in color can be detected by the instrument, they may not be detectable by naked human eyes.

All textural parameters (hardness, adhesiveness, cohesiveness, chewiness, and resilience) of the cooked egg white sticks from nonirradiated control at d 0 were not different from those from irradiated at 2.5 and 5 kGy (except adhesiveness for those at 5 kGy), but were significantly lower than those from irradiated at 10 kGy ($P < 0.05$; Table 4). However, all values of textural parameters, except cohesiveness, tended to increase as irradiation dose increased. Handa et al. (1998) reported that heat-induced gel made from egg white with very high pH (pH 11) showed higher textural values (hardness, cohesiveness, and elasticity) than those with neutral pH because of tight cross-linkings between denatured protein filaments in liquid egg white at high pH. Therefore, intensive interactions between denatured protein filaments and fragments in liquid egg white caused by irradiation might have facilitated heat-induced gelation and helped form a well-organized structure, which contributed to the higher textural values in irradiated cooked egg white sticks than nonirradiated ones. Most textural parameters were not changed during 14 d of storage, but hardness and chewiness significantly increased in the sticks made from liquid egg white irradiated at 10 kGy during the storage ($P < 0.05$). Stronger protein-protein interactions contribute to a tight protein network in heat-induced gel, but lead to less space within the network and less protein-water interactions, resulting in low water-holding capacity (Min and Green, 2008). Hence, it is assumed that the well-structured stick made from liquid egg white irradiated at 10 kGy may have low water holding capacity, and thus, lose moisture during storage and have high hardness and chewiness values.

Table 4. Texture profiles of cooked egg white stick made from irradiated liquid egg white with different irradiation doses and their changes during storage[1]

	Irradiation dose (kGy)				
Storage	0	2.5	5	10	SEM
Hardness[2] (gf)					
d 0	679.4^{b}	661.0^{ab}	725.0^{ab}	751.8^{a,y}	26.4
d 7	734.4^{c}	651.1^{d}	812.6^{b}	897.0^{a,x}	21.2
d 14	771.3^{b}	657.1^{c}	774.6^{b}	886.9^{a,x}	21.1
SEM	26.9	27.2	38.2	32.3	
Adhesiveness[3] (gf·cm)					
d 0	6.8^{b}	8.2^{b}	12.6^{a}	14.5^{a}	1.3
d 7	8.2^{b}	6.6^{b}	12.0^{a}	11.1^{a}	1.5
d 14	9.7^{ab}	9.2^{b}	11.6^{ab}	11.9^{a}	1.5
SEM	1.9	1.2	1.7	2.4	
Cohesiveness[4]					
d 0	0.536^{ab}	0.521^{b,x}	0.531^{ab,x}	0.551^{a}	0.006
d 7	0.526^{a}	0.454^{b,y}	0.459^{b,y}	0.550^{a}	0.016
d 14	0.539^{ab}	0.533^{ab,x}	0.529^{b,x}	0.577^{a}	0.009
SEM	0.007	0.01	0.017	0.005	
Chewiness[5] (gf·cm)					
d 0	294.9^{b}	310.5^{ab}	322.8^{ab}	379.3^{a,y}	21.4
d 7	386.9^{b}	292.5^{c}	368.2^{b}	487.1^{a,x}	14.7
d 14	368.0^{b}	302.1^{b}	352.6^{b}	485.3^{a,x}	25.4
SEM	15.1	17.7	24.2	16.8	
Resilience[6]					
d 0	0.332^{b}	0.342^{b}	0.343^{b}	0.389^{a}	0.01
d 7	0.347^{ab}	0.321^{b}	0.318^{b}	0.381^{a}	0.011
d 14	0.366^{b}	0.372^{b}	0.410^{ab}	0.425^{a}	0.013
SEM	0.008	0.014	0.014	0.004	

$^{a–d}$Means with different letters within the same row are significantly different ($P < 0.05$).

$^{x–z}$Means with different letters within the same column are significantly different ($P < 0.05$).

[1]n = 4.

[2]Hardness: the peak force during the first compression cycle.

[3]Adhesiveness: the work necessary to pull the compressing plunger away from the sample.

[4]Cohesiveness: ratio of the positive force area under the second compression to that under the first compression.

[5]Chewiness: the energy required to compress the sample and the product of hardness × cohesiveness × springiness.

[6]Resilience: the ratio of the area during the withdrawal of the first compression to the area of the first compression.

In conclusion, irradiation of shell eggs caused substantial changes in turbidity, viscosity, foaming properties, and volatile profiles of egg white due to oxidative changes in egg white proteins, and the extents of the changes were irradiation dose-dependent. However, the foaming properties of liquid egg white were minimal when the shell eggs were irradiated at a lower dose (2.5 kGy). The viscosity of egg white changed dramatically by irradiation even at a low dose ($\leq$2.5 kGy). Because of viscosity-lowering effect, irradiation of shell eggs at lower doses can improve efficiency of egg white processing by facilitating separation of egg yolk and white, flow of liquid egg white through pipelines, mixing it with other ingredients, spray-drying, and so on, without deterioration of physicochemical and functional properties in egg white. In addition, irradiation of shell eggs can reduce microbial loads in liquid egg white. Therefore, low dose irradiation of shell egg could be beneficial for the egg processing industry and the safety of food products that use liquid egg white can be improved.

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