Sterilization of Scrambled Eggs in Military Polymeric Trays by Radio Frequency Energy

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ABSTRACT: There is a current need for fresh-cooked-like yet shelf-stable egg products for U.S. military combat rations. Novel thermal processes based on radio frequency (RF) energy can shorten the heating time and reduce overheating. This technology was explored to produce shelf-stable egg products for combat ration development. *Clostridium sporogenes* (PA 3679) spores were used as a surrogate to validate the RF sterilization process to control *Clostridium botulinum*. Decimal reduction time (D value) of PA 3679 in scrambled eggs was determined using aluminum thermal-death-time (TDT) tubes. The thermal inactivation kinetic information was then used in inoculated pack studies to validate a novel thermal process based on 27.12 MHz radio frequency (RF) pilot scale unit. Trays of scrambled eggs inoculated with PA 3679 were subjected to 3 processing levels: target process (F_0 about 5.3 min), under-target process (F_0 about 3.0 min), and over-target process (F_0 about 9.1 min). The results of the microbial challenge study showed that microbial destruction from the RF process agreed with sterilization values calculated from time-temperature data measured at the cold spot in the treated trays. A comparison of RF- and retort-treated scrambled eggs showed significant differences in the degree of lightness (*L) and redness (*a**). RF-processed egg was less brown compared with conventional retorted eggs. Retort treatment of fully cooked scrambled eggs had higher hardness, springiness, and smaller cohesiveness than RF-treated samples. This study suggests that RF thermal processes can produce safe, shelf-stable sterilized scrambled eggs for both military and civilian uses.**

Keywords: dielectric heating, radio frequency, sterilization, decimal reduction time, scrambled eggs, military rations

Introduction

Shelf-stable foods are one of the major food products in the market. Commercial sterilization has been used to ensure that neither spoilage nor pathogenic bacteria can proliferate under normal storage conditions. Quality in terms of appearance, texture, and palatability is highly important to the consumers, as is proof of microbiological safety (Brown 1991). In conventional sterilization processes that rely on pressurized hot water or steam, slow heat conduction from the heating medium to the center of pre-packaged solid or semi-solid foods often results in a long process time and overheating at the corners and edges of the food package. Radio frequency (RF) heating, a method of heating dielectrics, has the potential for fast heating in solid and semi-solid foods. RF energy is dissipated through the products based on direct interaction between electromagnetic waves and foods. RF energy can penetrate dielectric materials more deeply than microwave energy due to its lower frequencies (13.56, 27.12, and 40.68 MHz) and longer wavelengths compared with those of microwaves at 915 or 2450 MHz (Wang and others 2003b).

The U.S. army is in need of fresh-cooked-like shelf-stable food items such as egg products for combat rations with a shelf-life of at least 3 years. Product sterility must be ensured. Due to the high sensitivity of egg components to heat, color, texture, and flavor of egg products are degraded by conventional thermal processes at high temperatures. Two common problems reported in thermally processed eggs are greenish-black discoloration caused by the formation of ferrous sulfide (Tinkler and Soar 1920; Baker and others 1967; Gravani 1969; Wesley and others1982; Song and Cunningham 1985; Cotterill 1995), an undesirable change of texture, and syneresis (Wesley and others 1982; Woodward and Cotterill 1986). Extensive syneresis increases the area of discoloration in sterilized scrambled eggs. Addition of chelating agents or lowering the pH to create acidic condition can prevent formation of ferrous sulfide (Cotterill 1995). Formulation of scrambled eggs suitable for RF sterilization was developed in our laboratory in a previous study. In this formulation, citric acid and a combination of different water-holding substances were added to prevent discoloration and syneresis. But microbial safety of RF sterilized eggs needs to be evaluated.

Clostridium botulinum is heat resistant and produces botulinum toxin in anaerobic conditions such as in sealed cans or trays. It is the target microorganism in the sterilization process of low-acid (pH>4.6), high-moisture food. To ensure food safety, a minimum of 12-log reduction of *C. botulinum* is required for a commercial thermal process. *Clostridium sporogenes* (PA 3679) has been used as a surrogate microorganism for *C. botulinum* in developing processes for sterilized food because of its non-toxin producing and similar biochemical requirement to *C. botulinum* (Ocio and others 1994). Decimal reduction time (D value) of a microorganism is greatly affected by its environment such as pH, and the composition of substrate, including carbohydrate, fat, and moisture content (Banwart 1989). It is, therefore, necessary to determine the D value of PA

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3679 in a selected food to validate a new thermal process for this food.

The objectives of this research were to determine the D value of *C. sporogenes* (PA 3679) in scrambled eggs at 121.1 °C, conduct inoculated pack studies, and compare quality attributes of RF-sterilized scrambled eggs with that of conventional retorted products by instrumentation.

Materials and Methods

Decimal reduction time (D value) determination

The D value of *C. sporogenes* (PA 3679 at 121.1°C) was determined using the multiple-point method in a M/15 phosphate buffer (Na_2HPO_4 5.675 g, KH_2PO_4 3.63 g in 1000 mL of distilled water, pH 7.0) and in scrambled eggs (pH 7.0) using aluminum thermal-death-time (TDT) tubes (Figure 1). Scrambled eggs were prepared with frozen pasteurized liquid whole eggs containing 0.15% citric acid (Michael Foods Egg Products Co., Gaylord, Minn., U.S.A.), water, vegetable oil, salt, additional citric acid, modified waxy corn starch (PenCling® 570, Penford Food Ingredients, Co., Englewood, Colo., U.S.A), xanthan gum (Keltrol® RD, CP Kelco Inc., San Diego, Calif., U.S.A.), guar gum (Sigma Aldrich, Inc., St. Louis, Mo., U.S.A.), black pepper flavor (Aquaresin black pepper, Kalsec, Inc., Kalamazoo, Mich., U.S.A.), and yellow color (Vegetone Oil Soluble, Kalsec, Inc.), in the amounts shown in Table 1. The mixture was scrambled on a stainless-steel griddle at 135 °C for 1 min. PA 3679 spores in phosphate buffer, with a concentration of 1.6×10^8 colony-forming units (CFU)/mL (NFPA nr SC 199), were obtained from the Technical Service Center of National Food Processors Association (NFPA) in Dublin, Calif., U.S.A. Scrambled eggs were cooled by an ice bath before they were inoculated with a spore suspension to approximately 1.0×10^6 CFU/g. The inoculated samples were mixed well in a sterile stomacher bag by hand rubbing for 10 min and kept in an ice bath at 0 ± 0.2 °C. Inoculated samples of 1 g were transferred to sterile aluminum TDT tubes. The tubes were sealed with screw caps and then placed in a rack before being immersed completely in a 28-L circulating oil bath (Polyscience, Niles, Ill., U.S.A.) set at 121.1 °C. The temperature of the sample during heating in the oil bath (±0.2 °C accuracy) was monitored using inserted T-type thermocouples (0.51-mm dia, Omega, Stamford, Conn., U.S.A.) through air-tight fittings in the caps of the TDT tubes. Temperature data were collected using a data logger (Delta-T devices, Cambridge, U.K.). Immediately after the sample reached the designated temperature (±0.2 °C), the heating time was recorded and the 1st TDT tube was removed from the oil bath. The remaining samples were each subjected to 6 different exposure times ranging from 30 s to 180 s.

Table 1—Ingredients of the selected scrambled egg formulation

Ingredients	Amount (%)
Liquid whole eggs	75.08
Water	20.00
Vegetable oil	2.98
Salt	0.59
Corn starch	1.00
Citric acid	0.15
Xanthan gum	0.10
Guar gum	0.10
Pepper flavor	0.01
Yellow color	0.0075

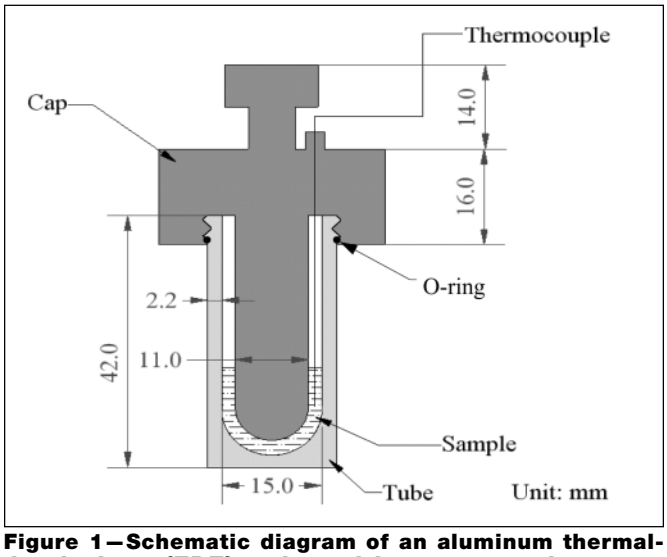

Figure 1—Schematic diagram of an aluminum thermal-death-time (TDT) tube with a screwed-on cap (Luechapattanporn and others 2004).

After heating, the tubes were immersed promptly into an ice bath at 0.0 ± 0.2 °C. The average come-up time from 0 °C to 121.1 °C and cool-down time from 121.1 °C to 0 °C in scrambled egg samples were 155 s and 120 s, respectively. The unheated control samples were activated by heating in a test tube for 10 min in a water bath set at 90 °C.

After the heat treatment, spore suspension in phosphate buffer was diluted in 0.2% peptone water and survivors were enumerated by pour plating with Shahidi Ferguson Perfringens (SFP) agar (Difco Laboratories, Inc, Detroit, Mich., U.S.A.). For samples in scrambled eggs, the contents in the tube were aseptically removed with a sterile spatula to a stomacher bag and homogenized for 2 min in a Seward 80 circulator stomacher (Seward, Ltd., London, U.K.). Serial dilutions were made in 0.2% peptone water and 1 mL of the dilution was pour-plated with SFP agar. The plates were incubated at 37 °C for 48 h in anaerobic jars with an anaerobic atmosphere generator, Anaerogen (Oxiod, Ogdensburg, N.Y., U.S.A.) and anaerobic indicator, GasPak (VWR International, Brisbane, Calif., U.S.A.). Experiments were conducted in duplicate.

Survivor curves were plotted using Microsoft Excel software to determine D values. D value is the reciprocal of the slope from linear regression of the survivor curve in semi-log coordinates (log number of survivors versus time).

Inoculated pack studies

Spore suspension of *C. sporogenes* (PA 3679) was distributed into cooked scrambled eggs by to ensure food safety using a pipette before being well mixed. Inoculated scrambled egg samples of 2600 g were placed in each of polymeric trays (245 × 235 × 45 mm) that are commonly used as packages for U.S. military group rations. The height of egg samples in the trays was about 40 mm. Each tray contained approximately 1.0×10^7 viable spores. The trays were then vacuum-sealed with a 0.15-mm-thick aluminum foil lid (Jefferson Smurfit, Dublin, Ireland) in a laboratory vacuum tray sealer (Reynolds Metals Co., Richmond, Va., U.S.A.). After inoculation, the trays were processed immediately in a 6-kW pilot-scale RF sterilization system developed at Washington State Univ. based on a 27.12-MHz RF power supply (COMBI 6-S; Strayfield Fastran, U.K.) along with a water-conditioning system (Figure 2). Circulating water temperature was controlled by the conditioning system to match the

heated food temperature and to reduce possible fringe effect at the interface between the food package and the air in the RF chamber (Wang and others 2003b; Luechapattanaporn and others 2004). Based on preliminary results, immersion water conductivity was adjusted to about 60 μS/cm at room temperature (21 °C) to reduce food edge heating. Four fiber-optic temperature sensors (FISO Technologies, Inc., Sainte-Foy, Que., Canada) were inserted and secured at 4 different locations in the food that represented the most-heated and least-heated spots. These locations were determined based on a previous chemical marker study and inoculated pack studies (Luechapattanaporn and others 2004; Wang and others 2004) (Figure 3). The time interval for measuring the temperature was 5 s. Temperature data were monitored and recorded by a FISO UMI-8 signal conditioner communicated via RF-232 with a desktop PC and FISO commander data acquisition software (FISO Technologies, Inc.). The recorded temperature profile was used to calculate the sterilization value (F_0) using Eq. 1 (Stumbo 1973).

$$F_0 = \int_0^t 10^{\left[\frac{T-121.1}{z}\right]} dt \quad (1)$$

where T is temperature (°C), t is processing time (min), and z is 10 °C.

Three thermal processing times were selected based on the temperature profile at the least-heated spot (Luechapattanaporn and others 2004). These 3 process times corresponded to: (1) under-target process (F_0 about 3.0 min), (2) target process (F_0 about 5.3 min), and (3) over-target process (F_0 about 9.1 min). The target process was designed to deliver an F_0 value 7 times the D value of PA 3679 in scrambled eggs, just enough to inactivate the inoculated population of 1 10^7 PA 3679 spores/tray. The over-target process was aimed to inactivate the spores completely with F_0 greater than that of the target process. The under-target process was designed to allow certain survival of PA 3679 spores in inoculated trays to confirm the vitality of the spores in the egg samples. After RF processing, 100 g of scrambled egg samples each were aseptically acquired with an alcohol flamed spoon from 5 different locations (Figure 3) and homogenized in 200 mL sterile 0.2% peptone water using a stomacher (Seward 400 Circulator Stomacher, Seward, Ltd.) at 260 rpm for 2 min. Four 2.5-mL portions of homogenate from each location were pour-plated with Shahidi Ferguson Perfringens (SFP) agar (Difco Laboratories, Inc.). The plates were incubated at 37 °C for 72

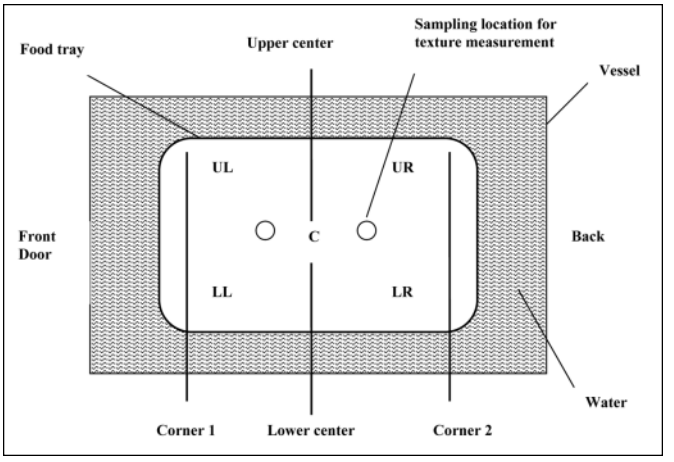

Figure 3—Positions of fiber-optic probes in scrambled eggs inside the trays (top view). The probes were secured at half height from the bottom of the tray.

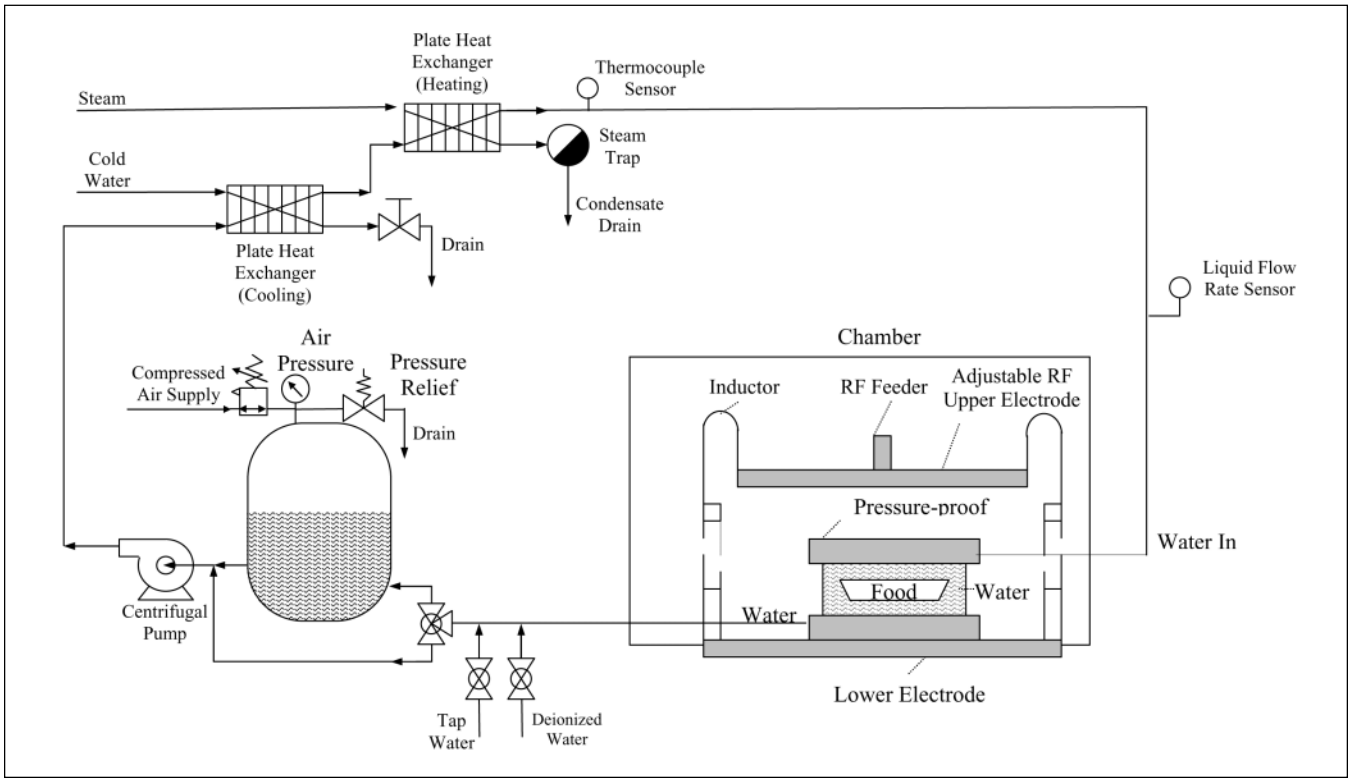

Figure 2—Simplified schematic diagram of the radio frequency (RF) sterilization unit with a water circulating system (Luechapattanaporn and others 2004).

h in anaerobic jars. To check for survival in target and over-target processes, enrichment tests were conducted on the remaining scrambled eggs. The remaining scrambled eggs were divided equally into 6 portions, and each portion was mixed with the same amount (1:1 wt/wt) of Fluid Thioglycollate Medium (Difco Laboratories, Inc) and incubated at 37 °C for 72 h. After the incubation, a loopful (10 μL) of each portion was streak-plated on SFP agar and incubated under anaerobic condition at 37 °C for 72 h. The experiments were conducted in duplicate.

RF and retort sterilization of egg products for quality evaluation

Scrambled eggs for RF or retort treatment were prepared with ingredients as shown in Table 1. For each tray, 4 batches of 750 g liquid egg mixture each was scrambled on a stainless-steel griddle at 135 °C. Preliminary results indicated that minimum cooking before sterilization would lead to minimal degradation of egg products. Two different cooking times on the griddle were used to prepare the scrambled egg samples to examine the effect of doneness on the final product quality after the sterilization processes: (1) 1 min for partially cooked scrambled eggs and (2) 2 min for fully cooked scrambled eggs. The total amount of 2600 g of cooked scrambled eggs was placed in the 6-lb capacity polymeric tray (245 × 235 × 45 mm). Trays were vacuum-sealed with a 0.15-mm-thick aluminum laminated foil lid (Jefferson Smurfit, Dublin, Ireland) in a laboratory vacuum tray sealer (Reynolds Metal Co.).

Freshly cooked scrambled eggs for control were prepared with the same formulation (Table 1) as thermal-treated samples. The cooking time on the griddle was 2 min.

The D value for PA 3679 used in our inoculated pack studies was determined to be 0.76 min at 121.1 °C. This value was much higher than that of *C. botulinum*, which is generally considered to be 0.25 min at 121.1 °C (Pflug and Odlaugh 1978). The minimum thermal treatments used in the food industry for low-acid foods should result in a 12-log (12D) reduction of *C. botulinum* population, which is equivalent to a full exposure of foods to 121.1 °C for 3 min (Banwart 1989; Larousse and Brown 1997). A 6D inactivation of *C. sporogenes* spores is equivalent to at least a 12D inactivation of *C. botulinum* spores. Therefore, the F_0 of 4.6 min (6D of *C. sporogenes*) was selected in this study.

For RF sterilization, a tray of egg products was placed in the RF vessel before being heated in a 6-kW, 27.12-MHz pilot-scale RF system along with a water-conditioning system (Figure 2). Four fiber-optic temperature sensors (FISO Technologies, Inc.) were inserted into the food in 4 different locations as shown in Figure 3. Thermal processing was conducted based on the temperature profile at the least heated spot to reach sterilization value (F_0) of about 4.6 min.

For conventional retort sterilization as a comparison, the product was packaged in the same trays used for RF processing and placed in the RF pressurized vessel, but only circulating water at 125 °C was used to heat the sample under the over-pressure of 206.8 kPa. The processing time (heating and holding time) was about 80 min to provide an F_0 of about 4.6 min at the core center of the tray.

After heating by either RF or retort method, the food tray was cooled in the RF pressurized vessel with circulating water at 21 °C for about 20 min to allow the temperature at the center of the food to reach about 80 °C.

Comparisons of quality were done between RF and retort treated scrambled eggs after both types of samples were processed and stored at 4 °C for 7 d.

Cook value for the processed scrambled eggs

The relative thermal effect on food quality was quantified using cook values (C_{100}). The cook values were calculated based on recorded temperature profiles by Eq. 2 (Lund 1986).

$$C_{100} = \int_0^t 10^{\left[\frac{T-100}{z}\right]} dt \quad (2)$$

The z values are in the range of 25 °C to 47 °C for different quality parameters, that is, texture and sensory attributes. The value of 33 °C is generally used to calculate the overall quality loss (Lund 1986*)*. Therefore, we used a z value of 33 °C to calculate cook values for the processed egg products.

Quality instrumental measurements

Color parameters of freshly cooked and sterilized egg products were measured. Texture parameters were determined only for sterilized egg products. Texture parameters of freshly cooked eggs could not be measured because of the small and non-uniform size of the egg nuggets. The thermally processed samples were equilibrated to 20 °C overnight before the measurements.

Color measurement. CIELAB color scales were used to measure the color of scrambled eggs by measuring the degree of lightness (L^*), ranging from zero for black to 100 for perfectly white, the degree of redness or greenness ($\pm a^*$), and the degree of yellowness or blueness ($\pm b^*$) (Giese 2003). Color parameters (L^*, a^*, b^*) were measured using a Minolta colorimeter (Minolta Spectrophotometer CM-2002; Minolta Camera Co., Ltd., Osaka, Japan). The measurements were conducted in triplicate.

Texture measurement. Texture profile analysis (TPA) is used to imitate the action of the jaw by compressing a bite-size piece of food 2 times (Bourne 2002). Scrambled eggs were cut into a 25-mm-dia cylinder with a thickness of 10 mm using a stainless-steel tube and a wire cutter. Sampling location was shown in Figure 3. In a double compression test, the samples were pressed to 50% of their original height (Woodward and Cotterill 1986) by the flat aluminum probe at a cross-head speed of 1 mm/s, allowed to rebound for 12 s, and compressed again using a TA.XT2 Texture Analyzer (Texture Technologies Corp., Scarsdale, NY/Stable Micro Systems, Godalming, Surrey, U.K.) equipped with a 5-kg load cell. The results are reported as the means of duplicate tests. Hardness, springiness, and cohesiveness were computed from a TPA curve and were defined as follows (Bourne 2002):

Hardness: the height of the force peak on the 1st compression cycle (g).

Springiness: the height in distance that the sample recovered during the time that elapsed between the end of the 1st bite and the start of the 2nd bite.

Cohesiveness: the ratio of the work during the 2nd compression and the work during the 1st compression.

Statistical analysis was performed using Statistical Analysis System software (SAS version 8.1, SAS Inst. Inc., Cary, N.C., U.S.A.). An analysis of variance (ANOVA) method was used to analyze data from color and texture measurements. Differences were considered significant when P values were <0.05. When the ANOVA method showed one or more significant differences, the least significant difference (LSD) method was used to separate treatment means.

Results and Discussion

Decimal reduction time (D value) of *C. sporogenes*

D values of *C. sporogenes* (PA 3679) were determined by plotting the number of survivors in logarithmic scale versus time (Figure 4). The averaged D values at 121.1 °C in phosphate buffer and scram-

Table 2—Inoculated pack study results of radio frequency (RF)-treated scrambled eggs inoculated with *Clostridium sporogenes*

Process level	F_0(min)[a]	Designed sterilization per tray	Log reduction value (SV)[b]	Enrichment result
Under-target process	3.0	4.0	3.61	Positive
Target process	5.3	7.0	>4.10	Negative
Over-target process	9.1	12.0	>4.10	Negative

[a]F_0, SV $D_{121.1}$.
[b]SV, Log_{10} reduction for *C. sporogenes*.
[c]Enrichment was done by 1:1 (wt/wt) of Fluid Thioglycollate Medium at 37 °C for 72 h.

Table 3—Sterilization value (F_0) and cook value (C_{100}) of radio frequency (RF) and retort treated scrambled eggs

Location		RF	Retort
Left (corner 1)	F_0 (min)	10.2	23.9
	C_{100} (min)	78.1	175.2
Right (corner 2)	F_0 (min)	6.4	20.8
	C_{100} (min)	62.2	164.8
Upper center	F_0 (min)	6.7	18.8
	C_{100} (min)	61.9	163.8
Lower center	F_0 (min)	5.9	7.3
	C_{100} (min)	74.4	111.9

bled eggs were 0.75 min and 0.76 min, respectively. *C. sporogenes* is most resistant at an optimal growth pH of 7.0 (Hersom and Hulland 1980). Based on our results, the D value in scrambled eggs (pH 7.0) at 121.1 °C was 0.01 min greater than in phosphate buffer (pH 7.0). D_{121} of *C. sporogenes* in low-acid foods normally is in the range of 0.1 to 1.5 min with a z value of 7.8 °C to 10 °C (Stumbo 1973). D values of PA 3679 in phosphate buffer and mashed potatoes at 121.1 °C from our previous study were 0.62 min and 0.61 min (Luechapattanaporn and others 2004). The slightly different D value in phosphate buffer was due to the different spore batch. Our results, in general, agreed with these literature values.

The result from this study and the previous study (Luechapattanaporn and others 2004) showed that aluminum TDT tubes were used effectively to determine thermal resistance of *C. sporogenes* in solid food such as scrambled eggs and in semi-solid food such as mashed potatoes, at high temperatures. The greater heat-transfer rate of metal tubes led to the shorter come-up time compared with heating the food suspension in relatively large TDT glass tubes, and consequently reduces errors in determining D values (Luechapattanaporn and others 2004).

Inoculated pack studies

The results from the inoculated pack studies are summarized in Table 2. The log reduction for the under-target process was 3.61D, which is slightly less than the calculated sterilization value (4D). In addition, there was no growth of PA 3679 observed from direct plating above the detection limit (150 CFU/tray) in the target and over-target processes. This corresponds to more than a 4.1 log reduction in PA 3679. There was no growth of PA 3679 after enrichment from streak-plating of the target and over-target processed sample. This indicates that the RF process delivered the desired lethality, and RF heating can be used to produce safe shelf-stable scrambled eggs.

Cook value of RF and retort sterilized egg products

The heating time of scrambled eggs from 70 °C to reach 121.1 °C in RF heating was about 20 min compared with about 60 min of retort heating as shown in Figure 5. Foods were heated relatively uniformly by RF energy due to its deep penetration depths and simple uniform field patterns (Wang and others 2003b). In the heating stage, the greatest temperature difference among 4 locations (Figure 5) was less than 5 °C. But during the cooling stage, egg samples at the upper center were cooled faster than the rest because of the greater heat-transfer rate through the aluminum lid foil.

Sterilization value (F_0) and cook value (C_{100}) of processed scrambled eggs were summarized in Table 3. Cook values (C_{100}) of RF-treated egg products were half of those of retort-treated egg products while delivering approximately the same sterilization values (F_0). The results agreed with our previous studies of RF-treated macaroni and cheese and mashed potatoes (Wang and others 2003a; Luechapattanaporn and others 2004). RF heating can be used as a sterilization method to produce safe food while maintaining food quality.

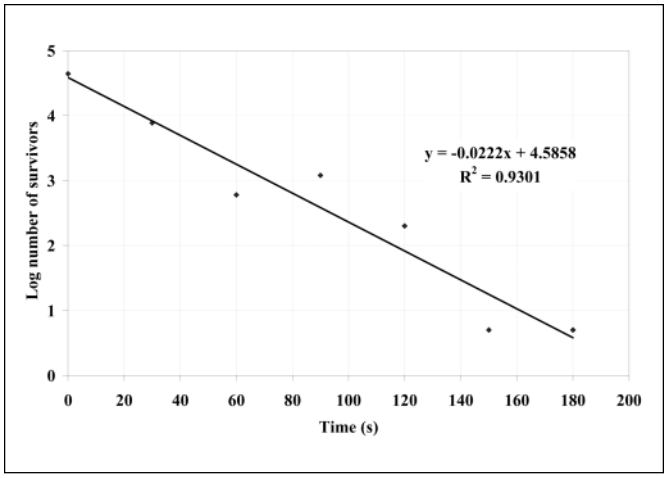

Figure 4—Typical survival curve of *Clostridium sporogenes* in phosphate buffer at 121.1 °C.

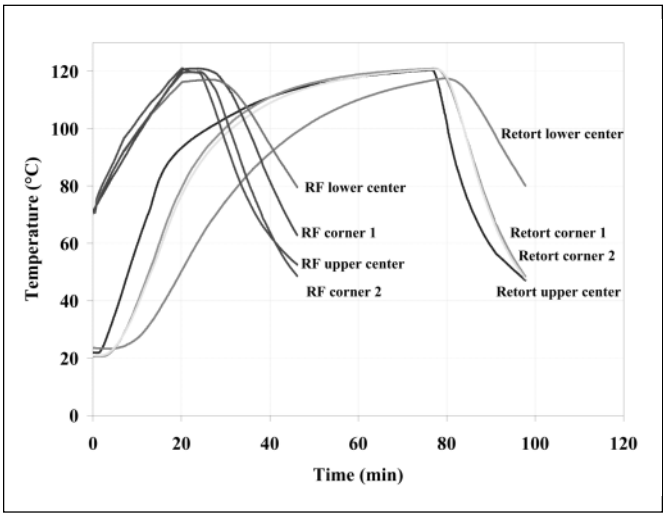

Figure 5—Time-temperature profile for scrambled eggs thermally processed by radio frequency (RF) and retort heating.

Table 4—Color parameters of scrambled eggs processed by fresh cooking, radio frequency (RF) heating, and retort heating[a]

Formulation	*L**	*a**	*b**
Surface layer			
Freshly cooked[b]	85.92 ± 0.08a	5.56 ± 0.36b	40.99 ± 2.02a
RF partially cooked scrambled eggs[c]	83.55 ± 1.48a	3.32 ± 0.27c	30.25 ± 1.20b
Retort partially cooked scrambled eggs	75.61 ± 2.51b	6.81 ± 1.03a	32.20 ± 1.26b
RF fully cooked scrambled eggs[d]	82.56 ± 0.65[a]	4.13 ± 0.54[c]	32.74 ± 3.23[b]
Retort fully cooked scrambled eggs	77.66 ± 1.69b	5.93 ± 0.21ab	29.75 ± 1.00b
Middle layer			
Freshly cooked	85.92 ± 0.08a	5.56 ± 0.36a	40.99 ± 2.02a
RF partially cooked scrambled eggs	82.30 ± 0.56b	5.40 ± 0.67a	32.10 ± 1.18b
Retort partially cooked scrambled eggs	82.02 ± 0.74b	4.27 ± 0.57b	31.27 ± 0.96b
RF fully cooked scrambled eggs	82.45 ± 0.58b	4.82 ± 0.24ab	31.22 ± 1.21b
Retort fully cooked scrambled eggs	80.92 ± 0.43bc	5.11 ± 0.71ab	30.39 ± 1.16b
Bottom layer			
Freshly cooked	85.92 ± 0.08a	5.56 ± 0.36a	40.99 ± 2.02a
RF partially cooked scrambled eggs	82.31 ± 0.90b	3.78 ± 0.57b	30.11 ± 0.94bc
Retort partially cooked scrambled eggs	79.53 ± 0.90c	5.19 ± 0.09a	28.89 ± 0.45c
RF fully cooked scrambled eggs	80.54 ± 0.41c	3.86 ± 0.09b	32.15 ± 2.28b
Retort fully cooked scrambled eggs	80.38 ± 0.65c	4.97 ± 0.26a	29.45 ± 0.91bc

[a]Values of each layer within a column with the same letter are not significantly different (P >/= 0.05, least significant difference test).
[b]Freshly cooked scrambled eggs were cooked on a griddle at 135 °C for 2 min.
[c]Partially cooked scrambled eggs were cooked on a griddle at 135 °C for 1 min.
[d]Fully cooked scrambled eggs were cooked on a griddle at 135 °C for 2 min.

Table 5—Texture parameters of egg products processed by radio frequency (RF) and retort heating[a]

Formulation	Hardness	Springiness	Cohesiveness
RF partially cooked scrambled eggs[b]	898.29 ± 34.67ab	0.77 ± 0.00ab	0.47 ± 0.01a
Retort partially cooked scrambled eggs	684.15 ± 158.36b	0.64 ± 0.10b	0.53 ± 0.25a
RF fully cooked scrambled eggs[c]	793.16 ± 13.33ab	0.84 ± 0.10a	0.50 ± 0.04a
Retort fully cooked scrambled eggs	919.48 ± 10.36a	0.86 ± 0.00a	0.43 ± 0.10a

[a]Values within a column with the same letter are not significantly different (P >/= 0.05, least significant difference test).
[b]Partially cooked scrambled eggs were cooked on a griddle at 135 °C for 1 min.
[c]Fully cooked scrambled eggs were cooked on a griddle at 135 °C for 2 min.

Quality measurement

Color parameters of sterilized scrambled eggs in 3 different layers (surface, middle, and bottom of the tray) are summarized in Table 4. The a^* value (redness) of egg samples at the surface layer of the retort-treated trays was much higher than the samples in the rest of the tray. The a^* values of RF-treated and retort-treated samples in middle and bottom layers were smaller than that of freshly cooked samples. The b^* values (yellowness) of treated eggs were smaller than that of freshly cooked samples.

Retort treated partially cooked samples at the surface and bottom layers had a more brownish color (smaller L^*, greater a^*) compared with RF-treated partially cooked samples ($P < 0.05$). Color parameters (L^*, a^*, and b^*) for the sample in the middle layers of RF-treated trays were not significantly different from the samples in the middle layers of retorted containers.

Heat conduction was the main mechanism of heat transfer during retorting. In this process, the egg samples adjacent to the container walls were severely cooked by the time the cold spot in the center of the container reached the desired sterility. Development of brownish color in egg product exposed to heat is a result of the Maillard reaction involving albumen (Baliga and others 1969; Vadehra and Nath 1973). The intensity of the brown color increased with heating temperature and heating time (Baker and Darfler 1969). The surface layer of retort-treated samples was exposed to high temperature for a longer time than the rest of the tray due to a greater heat-transfer rate through the aluminum lid foil during retort treatments.

Yellow color in egg products result from 3 carotenoids: lutein, zeaxanthine, and cryptoxanthin (Li-Chan and others 1995). Carotenoids are heat sensitive and can be degraded at sterilization temperatures (Elbe 1986). Extended heating resulted in the decrease of yellowness in treated samples.

L^* values of RF-treated egg samples at the top surface layer were not significantly different from those of freshly cooked samples. It is clear that RF-treated eggs were less degraded than the retort-treated eggs, especially at the surface and bottom layers. The comparison of different precooking times showed no significant difference in color parameters of treated samples.

Significant differences ($P < 0.05$) were found in hardness and springiness between partially and fully cooked samples processed by retort (Table 5). Changes in the texture of the egg samples were due to the denaturation of egg proteins (Woodward and Cotterill 1986). Generally, hardness is correlated to the rupture strength of the sample, springiness represents rubberiness, and cohesiveness is the degree of difficulty to break down a sample (Sanderson 1990). Lower cohesiveness scores suggest a higher occurence of fractures. The cohesiveness score of 0.5 represents a minimal tendency to fracture, whereas a score of 0.4 represents a slight degree of fracturing in cooked egg yolk (Woodward 1988). There were no significant differences in hardness and cohesiveness scores among retort-treated samples and among RF-treated samples. The retort-treated fully cooked samples had higher hardness and springiness and smaller cohesiveness than RF-treated samples. Egg gel generally increased in hardness and cohesiveness with increasing temperature

and cook time (Woodward and Cotterill 1986). Retort-treated fully cooked samples tended to be more rubbery and have more grainy texture compared with RF-treated samples.

Conclusions

RF heating can reduce the processing time to 1/3 that of the conventional retort process in 6-lb capacity polymeric trays produced for U.S. military group rations to reach approximately the same lethality level. The results of inoculated pack studies and instrumental quality measurements indicate that sterilization based on RF energy can produce safe shelf-stable scrambled eggs with the potential of producing better quality compared with retort-treated food products. It is possible to produce shelf-stable, heat-sensitive, and high-value foods in large polymeric trays based on RF energy. Further development of a multi-tray RF heating system is needed for feasibility studies of the RF process in industrial applications.

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