1 **Full Title**

2 Rapid (microwave) heating rate effects on texture, fat/water holding,
3 and microstructure of cooked comminuted meat batters

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5 **Name(s) of Author(s)**

6 Wenjie Liu, and Tyre C. Lanier

7
8 **Author Affiliation(s)**

9 Department of Food, Bioprocessing and Nutrition Sciences

10 North Carolina State University

11 Box 7624, Raleigh, NC 27695

12
13 **Contact information for Corresponding Author**

14 Wenjie Liu

15 9000 Plymouth Ave. N

16 Minneapolis, MN 55427

17 Wenjie1108@gmail.com

18 607-339-8622 Phone

19 763-764-6811 Fax

ABSTRACT

Comminuted and gelled, fat-containing meat products such as frankfurters and luncheon meats are commercially processed by heating relatively slowly (for up to 2 h or more) to an endpoint of about 70 °C prior to cooling. This study compared such a slow, ramp heating regime (0.5 °C/min), terminated at 70 °C, to rapid, square-wave cooking (one step: rapid 100 °C/min heating to 70°C endpoint, plus isothermal holding prior to cooling, or two-step: rapid heating to 50°C, holding, then rapid heating to 70 °C plus holding prior to cooling) on meat batter gel properties (fracture and small strain rheology, microstructure, cook loss, and expressible water). The results indicated that a rapid cooking process, with its inherent advantages of reduced process time, lower equipment footprint, and more efficient use of energy, can produce a product nearly equivalent in textural properties and cook yield to one processed by traditional smokehouse cooking when the cook value of the processes are similar and an intermediate (near 50 °C) holding step is included (two-step rapid heating). One-step rapid heating negatively affected gel structural homogeneity and water/fat holding properties of fat-containing gels.

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45 **Keywords:** Comminuted meat products, Microwave heating, Fracture, Water holding

46 capacity, Cook loss

1. Introduction

Comminuted meat gel products from mammalian and avian meats, which would include such products as hot dogs and bologna, are prepared by first chopping meat with the addition of salt, ice water, fatty tissues and seasonings to a fine homogenate, or batter. A thermo-irreversible gel matrix forms upon staged or slow ramp heating, typically requiring 2 hours or longer to reach a desired endpoint temperature of 70-72°C (Zayas, 1997), whereupon the product is then rapidly cooled. Such a slow heating rate is necessitated partly because conductive heat transfer in the industrial ovens ('smokehouses') used for cooking would overcook the outer portion of the product if the heating rate was too rapid; maintaining a low ΔT between product surface and center helps minimize this. The time-consuming process and large footprint of such ovens, plus the wasted energy and time involved in their equilibration prior to commencing cooking, could be ameliorated by adopting rapid heating methods such as radio-frequency (RF), microwave, or ohmic (rapid) heating.

But a slow heating rate is thought to maximize yield and desirable texture in such products (Komarik, Tressler, & Long, 1974). Many workers have reported that a faster heating rate adversely affects the heat-induced gelation of both globular and myofibrillar protein sols or pastes relative to producing a homogeneous gel structure exhibiting desirable texture and water/fat holding properties (Gossett, Rizvi, & Baker, 1984; Camou, Sebranek, & Olson, 1989; Barbut & Mittal, 1990; Yongsawatdigul & Park, 1996; Yoon & Park, 2001). Foegeding, Allen, & Dayton (1986) compared similar treatments for purified myosin sols and found that rapid heating always resulted in lower gel strength (rigidity) than slow heating. The explanation offered is that during rapid heating

there is insufficient time for proteins to denature and properly align prior to aggregating to form the gel structure, resulting in gels that are more coarse and weak (Hermansson, 1978; Schmidt, Mawson, & Siegel, 1981). This derives from the two-step theory of protein gelation advanced by Ferry (1948) which, simply stated, asserted that a protein dispersion upon heating first denatures to expose active sites that can then align and aggregate to form a gel (Ferry, 1948).

However, most of the foregoing studies compared effects of process treatments that, while varying in heating rate, also greatly differed in cook value (CV), the integrated heating time with respect to physical and chemical changes of product quality (Houben, Schoenmakers, Van Putten, Van Roon, & Krol, 1991). This occurred because heating at the varying rates being compared was always terminated by rapid cooling upon reaching the same endpoint temperature. Riemann, Lanier, & Swartzel (2004) compared rapid, square-wave heating to slower ramp heating for low fat Alaskan pollock (surimi) and turkey breast meat pastes. They concluded that rapid heating, plus isothermal holding at the endpoint temperature, yielded similar cooked gel properties (fracture stress and strain, cook loss) as those obtained by slow cooking just to the same endpoint temperature when the processes were approximately equal in CV.

Fat-containing batters could present a greater challenge for the application of rapid heating techniques. Rapid heating might not allow sufficient time for meat protein gelation to properly occur prior to fat fluidization, or could lead to formation of a less homogenous gel structure which, even if displaying similar rheological and water holding properties as reported by Riemann, Lanier, & Swartzel (2004), could nonetheless entrap the fluid fat less well. While there have been reports of good fat stability in rapidly heated

(by RF or ohmic) high-fat meat batters (Shirsat, Brunton, Lyng, & McKenna, 2004; Shirsat, Brunton, Lyng, McKenna, & Scannell, 2004), the formulations used in these studies all included other additives that might enhance fat binding: one group added 4% beef plasma, and the other two a large percentage of soy and grain product. Even with such additives, however, Shirsat, Brunton, Lyng, & McKenna (2004) reported decreased springiness in ohmically-cooked meat emulsion gels, which could relate to structural differences in the protein matrix formed.

Lanier & Labudde (1995) reported that, when attempting to cook using a waterbath, only by heating a comminuted meat product in two stages could they produce a product with similar rheological and fat/water holding properties as when the product was slowly ramp heated as in a commercial smokehouse. They first heated frankfurter pastes, sealed in cellulose casings, at 50 °C for 30 min, then transferred the casings to a 70 °C water bath to finish cook the product for 45 min prior to subsequent cooling. No non-meat additives were used in their formulations for the enhancement of fat binding; rendered fat (lard) was the main fat ingredient.

Swift, Townsend & Witnauer (1968) concluded that fat physical properties can greatly affect fat stability of comminuted meat products. The fats used in comminuted meat products are from animal adipose tissue primarily composed of neutral lipids (triglyceride) wherein the ratio and composition of saturated-to-unsaturated fatty acids in triacylglycerols impart the characteristics specific to that fat in terms of melting temperature and thus fluidity or hardness at a given temperature. Acton, Ziegler, & Burge (1983) stated that, in order to produce stable meat products, for most formulations made with pork and beef fat the final chopping temperature should not exceed 16 to 18 °C

whereas a maximum of 10 to 12 °C should be used for meat products made with poultry fat.

However, some researchers have reported that substituting animal fat with different types of liquid oils, such as peanut, olive, sunflower, and soy oils, showed little effect on emulsion stability (i.e. fat release during cooking) or on the smokehouse yield of frankfurters (Marquez, Ahmed, West, & Johnson, 1989; Park, Rhee, Keeton, & Rhee, 1989; Hammer, 1992; Ambrosiadis, Vareltzis, & Georgakis, 1996). Two studies (Bloukas & Paneras, 1993; Paneras & Bloukas, 1994) did report some adverse effects of using oils vs fats, but also reported that reduced-fat frankfurters (10%) made with oils showed firmer texture than ones made with animal fats. Ambrosiadis, Vareltzis, & Georgakis (1996) conversely reported that replacing the pork fat in beef frankfurters with oils yielded lower textural firmness.

The present study investigated the effect of different cooking regimes (slow ramp vs rapid one- or two-step heating) on fat/water retention and rheological properties during and after cooking of high fat meat gels. Rendered animal fat (lard) was compared to soy oil in these formulations to determine if differences in gel structure due to heating rate or regime might thereby be better revealed.

2. Materials and Methods

2.1. Materials

Boneless skinless chicken breast meat as a lean meat source was purchased from a local chicken processor (Pilgrim's, Sanford NC), packaged in ~ 3.5 kg portions in freezer bags and frozen at -20 °C until use (<5 months). Frozen chicken was thawed at 4 °C for at least 12 h before the trimming of visible fat and connective tissue. Pork fat, in the form of lard, and

vegetable oil (soybean oil) was obtained from a local grocery store packaged in sealed plastic containers and kept at 4 °C and room temperature (25 °C), respectively, until used.

2.2. Preparation of meat batters and paste

Finely comminuted batters were prepared by chopping thawed chicken (proximate analysis 23.21% protein, 1.34% fat, 69.45% water; at 51.17% w/w) with water (24.83%, w/w), fat or oil (20%, w/w), salt (2%, w/w), sugar (1.7%, w/w), and tripolyphosphate (0.3%, w/w) in a Stephan UMC-5 vertical-cutter/mixer (Stephan Machinery Corp., Columbus, OH) under vacuum for 6 min at 25,000 rpm. The formulation is similar to that used in a leading brand of frankfurters. Final chopping temperature did not exceed 10 °C. Meat batters were vacuum-packaged in Cryovac B-series bags (Cryovac, Duncan, SC, U.S.A.) with a Multivac 8941 (Multivac, Allgau, Germany) and cooled to 5 °C. A corner of the bag was cut before placing into a manually operated sausage stuffer for extrusion of the batter into tared Teflon tubes (for microwave heating) or water-impermeable cellulose casings (for water bath heating), 1.9 cm inner diameter and 17.8 cm long. Tubes and casings were sealed at both ends with threaded end caps or by tying with string, respectively, and samples weighed before heating. [All preparations of batters were conducted twice.](#)

2.3. Heating regimes of gels

2.3.1. Conventional ramp heating process

Batter-filled cellulose casings were immersed and cooked in a programmable water bath (Neslab Instruments Inc., Portsmouth, NH) from 5 to 70 °C at the rate of 0.5 °C/min, to simulate a conventional smokehouse process. Product temperature was monitored with a thermocouple inserted into the geometrical center of the cylindrical gels.

2.3.2. *Microwave cooking*

Filled Teflon tubes were rapidly microwave heated at 100 °C/min in an Industrial Microwave Systems (IMS, Morrisville NC) focused (equal energy distribution) chamber (custom built for this experimentation; Riemann, Lanier & Swartzel, 2004) to endpoint temperatures of 70 °C by one of two processes: one-step (directly to 70° and held for 20 min) or two-steps (firstly to 50 °C and isothermally held for 30min, secondly to 70°C and held for 20 min). 300 watts and 150 watts power settings were used for rapid heating and isothermal holding, respectively. Immediately upon completion of the heating step, all gels were quickly removed from tubes or casings, any released liquid remaining on gel surfaces was removed by wicking with filter paper, and weighed. Gels were then immediately placed in plastic bags, evacuated and sealed, and immersed into an ice-water bath for cooling.

2.4. *Rheological properties of pastes/gels*

2.4.1. *Fracture testing of cooked, cooled gels and commercial products*

Both a commercial product (Classic wienersTM by Oscar Mayer, Madison, WI) and cylindrical gels, prepared by heating in tubes in a water bath or microwave applicator and ice bath cooling, were held overnight under refrigeration, and subsequently cut into specimens 2.54 cm long, each end of which was glued to plastic disks (Gel Consultants Inc., Raleigh N.C.) using an instant adhesive. Capstan-shaped samples were milled from each specimen to 1 cm minimum diameter on a milling machine (Gel Consultants Inc.), wrapped in plastic wrap (to prevent moisture loss), and brought to room temperature before torsion testing. For testing, gel specimens were vertically mounted and twisted to the point of fracture at 2.5 rpm on a Hamann Torsion Gelometer (Gel Consultants Inc,

Raleigh NC.). Stress (kPa) and strain (dimensionless) at fracture were calculated with the manufacturers software for each sample, corresponding to the strength and deformability of the gels, respectively (Hamann, Amato, Wu, & Foegeding, 1990). Each variable has 6 replicates for data analysis.

2.4.2. Small strain oscillatory testing during heating

Rheological changes (G' , G'' and phase angle) of batters/gels were nondestructively and continuously measured as pastes were heated, held and cooled in the serrated plate and plate attachment of a constant stress, small strain rheometer (Stresstech, Rheologica Instruments AB, Lund, Sweden). An oscillation of 1.0 Hz with a resistance stress of 60 Pa was used for testing, pre-determined to assure measurements in the linear viscoelastic region. Heating conditions trialed were the same as used previously for water-bath (ramp) and microwave (rapid) heating except that rapid heating in this instrument was only 20 °C/min (maximum possible). All treatments in triplicate were randomized to minimize testing effects.

2.5. Cook loss determination

Cook loss (CL) was measured in triplicate by subtracting the post-cooked weight of gels from the pre-cooked weight of the batters (or pastes), expressed as a percentage of pre-cooked batter weight. Before measuring the weight of cooked gels, liquid release on the surface was removed; all weights of Teflon tubes & caps, or casings & string, were accounted for in calculating cooked weights.

2.6. Expressible water (EW) determination

EW of each gel was measured in triplicate using the microcentrifuge-based method of Kocher & Foegeding (1993). The center of each gel was cut into 10 x 4.8 mm cylinder

specimens using a cork borer and these specimens were placed into the microcentrifuge filtration unit which was comprised of a 2.0 mL microcentrifuge tube (Beckman Instruments, Inc., Palo Alto, California, U.S.A.) that collected moisture released through the bottom mesh of an inner container holding the specimen. Specimens were centrifuged at $153 \times g$ for 10 min. EW was calculated by the equation below:

$$EW(\%) = \frac{\text{Weight of water released}}{\text{Weight of samples}} \times 100$$

2.7. Microstructure by confocal microscopy

Meat gels, held in sealed bags at 4 °C overnight, were sliced into sections approximately 5 mm x 5 mm x 1 mm thick using a razor blade. A 0.2% solution of Nile Blue A Sulfate (MP Biomedicals, LLC; Solon, OH) fluorescent dye in de-ionized water was filtered twice using Whatman No. 3 (Maidstone, Kent UK) filter paper, and 20 µL of the solution was pipetted onto the cut surface of each meat gel slice. The dye was allowed to absorb into the gel at room temperature for 10 min. Gel samples were then turned over (dyed gel surface against the coverslip) onto a single-welled slide with a #1.5 coverslip adhered to the bottom of the slide via silicone grease. Samples were imaged on a Zeiss LSM 710 Confocal laser scanning microscope (CLSM) attached to a Zeiss Axio Observer Z1 inverted microscope using 10x 0.45 NA (Numerical Aperture) dry , 20x 0.8 NA dry and 40x 1.2 NA water immersion objectives. A 488 nm argon laser (to excite Nile Blue in the fat phase) and a 633 nm helium neon laser (to excite Nile Blue in the protein phase) were used sequentially to image the samples. Emission spectra were collected from 500-650 nm for the fat phase and 650-800 nm for the protein phase, and the resulting images were overlaid. The pinhole was optimized to the size of 1 airy unit (diameter of the airy disk produced by the objective) to reduce unwanted light dispersion that might blur the image, and the zoom was maintained at 1.0000

across all images, regardless of z-stack position. For each gel treatment, 2 samples were prepared; 3 images were taken per sample at the 10x objective, resulting in a total of 6 images per treatment.

2.8. Cook value

Cook value (CV) is the cumulative heat impact of a complex time/temperature history on a food quality attribute. According to the time/temperature data collected at the core during cooking of comminuted meat gels, the cook value (CV) (min) could be calculated by the following equation (Mansfield 1962):

$$CV = \int_0^{T_P} 10^{(T-\theta_c/Z_c)} dt$$

where T is the temperature at the core of gel tube at any time during the thermal processing and T_P (min) is the time at the end of the thermal processing. A reference temperature (θ_c) of 100 °C and a Z-value (Z_c) of 30 °C were used to calculate the CV (Vanroon, Houben, Koolmees, & van Vliet, 1994).

2.9. Statistical analysis of data

Statistical analysis was performed using a software package (SAS version 9.1, SAS Institute, Cary, NC, USA). The SAS General Linear Model (GLM) procedure was used for analysis of variance. Differences were assessed using the Tukey test. The level of significance was set at $P < 0.05$.

3. Results and Discussion

3.1. Fracture properties of cooked, cooled gels

Mastication induces fracture of foods such as comminuted meat products and thus mechanical fracture properties best predict sensory texture (Montejano and others 1984, 1985). The one- and two-step MW rapid heating/holding treatments produced gels that exhibited similar fracture stress (gel strength) ($P>0.05$) (Fig. 1) and strain (gel deformability) ($P>0.05$) (Fig. 2) as those produced by heating slowly at 0.5 °C to the same endpoint temperature (the latter with no subsequent holding). Laycock, Piyasena, & Mittal (2003) reported that rapidly heated (by ohmic or RF) meat batter gels had significantly lower fracture hardness values compared to those cooked by slower heating when measured by instrumental texture profile analysis. However their study, like those carried out for several pure protein gelling systems noted earlier, utilized rapid heating processes with much lower cook values than the slow heating processes they were compared to.

The formulation used for the batters in this trial closely approximated that used for production of a leading commercially produced frankfurter. It can be seen that the fracture properties of all cooked test gels closely matched that of that commercially produced product (Figs. 1, 2), validating that these findings can be applicable to commercial product applications.

Oil was substituted for fat in these formulations with the supposition that this might reveal any tendency of gels with a less fine and homogeneous microstructure to exhibit undesirably lower texture and/or fat/water holding properties. Such substitution of oil for fat did not however significantly affect fracture properties of gels, regardless of cooking regime (Figs. 1, 2).

3.2. Small strain rheology during heating

The two-step MW rapid heating/hold yielded fat-containing gels similar in storage modulus (G'), loss modulus (G''), and phase angle (δ) as those produced by heating slowly at

0.5 °C/min to the same endpoint temperature and immediately cooled (Table 1). The oil-containing gels cooked under the same two-step MW heating/holding regime exhibited slightly higher G' and G'' but these values were statistically insignificant in comparison (Table 1).

3.3. *CL and EW*

Both fat- and oil- containing gels cooked by the one-step MW heating regime trended toward higher CL (Fig. 3) and EW (Fig. 4) compared to those cooked by the two-step MW heating/holding regime or the slow ramp WB cook treatment. Oil-containing gels were, surprisingly, somewhat more stable than fat-containing gels, though these differences were not always statistically significant. Gels cooked by the slow ramp WB cook treatment did trend toward greater stability than gels made by MW rapid heating/holding but overall did not always differ significantly in CL or EW from MW cooked gels.

CL is likely the most commercially significant of these two measurements as it determines process yield and is evidence of how well fat and water are stabilized within the gel matrix. Clearly in the fat-containing batters CL was significantly diminished for the one-step MW heating treatment as compared to either ramp heating by WB or two step heating by MW. This is similar to the earlier report of Lanier and Labudde (1995) who reported that only a two step (rather than one step) cooking regime could approximate the finished product characteristics produced by slow ramp heating.

Intramuscular collagen is known to undergo shrinkage near 60-65 °C (Davey & Gilbert, 1974; Bailey & Light, 1989). Liu (2012) previously observed that during slow ramp heating (0.5 °C/min) the greatest rate of CL occurs from 65 to 70 °C in gels of similar composition. The two-step rapid MW heating regime may have allowed for this reinforcement of the gel matrix to occur by holding isothermally at a temperature (50 °C)

below that of collagen shrinkage. However it should be noted that collagen content of chicken breast is low compared to meats typically used for commercial production of comminuted meat products (Acton, Ziegler, & Burge, 1983). Interestingly, this difference in CL and EW caused by rapid heating was not so apparent in the oil-containing gels (Fig. 4).

Differences amongst the treatments were greater for EW than for CL, and this may indicate some change in gel structure, and thus in [water holding capacity](#) by the gel and possibly in eating characteristics of the cooked frankfurter.

3.4. Microstructure

Both fat- and oil-containing gels cooked by the one-step rapid MW heating process (Figs. 5, 6) exhibited a less homogeneous, more disrupted and coarse protein matrix as compared to other heating treatments. This difference in microstructure of gels cooked by the one-step rapid MW treatment may correspond to the higher CL and EW of fat-containing gels cooked in this way (Figs. 3, 4). However, these increases in CL and MW caused by one-step MW cooking were not sufficient to affect fracture properties of the cooked gels (Figs. 1, 2).

These micrographs seem to confirm that fat particles were evenly distributed throughout the gel matrix structure (Figs. 5, 6) regardless of fat type. Solid fat particles were however larger and more irregular in shape than oil droplets. The greater CL of the fat-containing gel may be attributed to the apparently larger droplet sizes of fat compared to those of the gel made with oil.

The phase distribution of fat/oil within these two treatments was not apparently affected by heating rate.

3.5. Cook value (CV) calculation

The cook values calculated for the three different heating regimes were all significantly different ($P < 0.05$) from one another (Table 2). The one-step MW heating regime had the lowest CV of the treatments. If gel formation is more rate limited by the protein aggregation step, as suggested by the results of Riemann et al. (2004), rather than by the protein denaturation step as was suggested by several other workers (Hermansson, 1978; Schmidt, Mawson, & Siegel, 1981), this lower CV could have resulted in less matrix formation and strengthening that led to the somewhat higher CL and EW of the fat-/oil containing gels (Figs. 3, 4). These differences were not large however, nor were there significant differences for CL and EW of oil-containing gels cooked by the same rapid treatment as compared to the slow ramp conventional cooking method (Figs. 3, 4).

The two-step rapid heating/hold cooking regime had the highest CV, but also it may have provided for gel matrix strengthening at a temperature below that at which collagen shrinkage occurs; the latter could possibly contribute to CL from 65 °C onwards during cooking (Osburn & Mandigo, 1998; Tornberg, 2005; Puolanne & Ruusunen, 1981).

However, as we earlier pointed out, the fracture properties of gels produced by all three cooking regimes did not differ significantly. This observation, plus that the oil-containing gels did not differ remarkably from slow ramp cooked gels in CL and EW, supports the finding by Simunovic and others (2001) that there is a particular subset of time/temperature heat treatments, employing both rapid and slow heating rates yet all similar enough in CV, which can produce gels having acceptable texture and water holding properties.

4. Conclusions

Rapid heating can produce acceptable properties of water/fat holding and texture (fracture and small strain mechanical properties) in cooked comminuted meat batters (gels) of relatively high fat content. In terms of water/fat holding properties and homogeneity of gel structure of fat-containing gels the two-step microwave rapid heating/holding scheme appeared preferable to the one-step rapid cook and hold process. The two-step process allows process time near 50 °C which may be required for sufficient gel matrix development to minimize CL that occurs most markedly above 60 °C (Liu, 2012). Gel matrix microstructure as viewed by CLSM revealed a less homogeneous gel matrix formed by the one-step rapid heating/holding regime, which also had the lowest CV of the three heating processes. Likely a minimum CV is needed for whatever heating process is used, to allow time for unfolded proteins to aggregate and to form a fine structured matrix of minimum pore size to optimally retain liquid fat and water. However, sufficient time at intermediate temperatures may also be necessary during cooking, especially for stability of batters with relatively high fat content, such that a minimum CV alone may not be the only criterion for forming a product that exhibits both acceptable texture or fracture properties as well as acceptable fat/water holding properties. Though differences induced by the one- vs two-step rapid heating methods were small in the present work, batters which are formulated to be much less robust in terms of available myofibrillar protein content etc. could perform much more poorly in a rapid one-step heating treatment of insufficient CV.

380 Regardless of heating regime, oil-containing batters/gels actually appeared to be more
381 stable than fat-containing gels of the same total lipid content, showing a smaller fat
382 droplet size distribution under identical conditions of batter preparation.

383
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Tables

Table 1

Dynamic rheological measurements of gels from different cooking regimes after cooling to 25 °C

Cooking Regime	Lipid form	G' (kPa)		G'' (kPa)		δ	
		Mean	SD	Mean	SD	Mean	SD
Slow ramp heating	fat	29.91 _a	2.44	6.57 _a	0.56	12.40 _a	0.00
	oil	28.25 _a	3.00	5.41 _a	0.54	10.87 _b	0.67
2-step rapid heating	fat	29.91 _a	3.27	5.49 _a	0.50	10.40 _b	0.44
	oil	34.15 _a	1.60	6.31 _a	0.29	10.47 _b	0.15

Different following letters in a column indicate a significant difference between means

Table 2

Cook value (CV) for the different cooking regimes

Cooking regime	Cook value (equiv min at 100 °C)	
	Mean	SD
Slow WB (0.5 °C/min) (130 min total)	6.24 _b	0.17
2-step MW (100 °C/min) 50 °C for 30min + 70 °C for 20 min (50 min total)	6.91 _a	0.03
1-step MW (100 °C/min) 70 °C for 20 min (20 min total)	5.45 _c	0.06

Different following letters in a column indicate a significant difference between means

Fig. 1. Fracture stress (kPa) of gels cooked by different heating regimes, as compared to a commercially prepared frankfurter of similar composition. Different following letters in a column indicate a significant difference between means

Fig. 2. Fracture strain of gels cooked by different heating regimes, as compared to a

commercially prepared frankfurter of similar composition.

Different following letters in a column indicate a significant difference between means

Fig. 3. Cook loss in gels cooked by different heating regimes

Different following letters in a column indicate a significant difference between means

Fig. 4. EW in gels cooked by different heating regimes

Different following letters in a column indicate a significant difference between means

Fig. 5. CLS micrographs of cooked fat-containing gels, (A) waterbath-heated; (B) 2-step MW heated; (C) 1-step MW heated. Red represents the protein matrix; Green represents the fat phase. Scale bar =20 μ m

Fig. 6. CLS micrographs of cooked oil-containing gels, (A) waterbath-heated; (B) 2-step MW heated; (C) 1-step MW heated. Red represents the protein matrix; green represents the oil phase. Scale bar =20 μ m