

Quality changes in chicken livers during cooking

Zhi Qu,^{*} Juming Tang,^{*,1} Shyam S. Sablani,^{*} Carolyn F. Ross,[†] Sindhuja Sankaran,^{*} and Devendra H. Shah[‡]

^{*}Department of Biological Systems Engineering, Washington State University, Pullman, WA, 99164-6120, USA;

[†]School of Food Science, Washington State University, Pullman, WA, 99164-6120, USA; and [‡]Department of Veterinary Microbiology and Pathology, Washington State University, Pullman, WA, 99164-7040, USA

ABSTRACT Raw chicken livers are often contaminated with *Campylobacter* and *Salmonella*. Cooking is considered the last defense of pathogen control for meals containing chicken livers. However, consumers' preference for pink color and a creamy texture as desired attributes in preparing liver pâté may lead to inadequate cooking, thereby increasing the risk of foodborne illness. This study aimed to investigate the effects of different cooking conditions (60–90°C, 0–65 min) on quality changes in frozen and fresh chicken livers and develop cooking recommendations to produce safe liver products with desired qualities. Frozen storage reduced the water holding capacity of raw chicken livers and led to more cooking loss (reduction in the weight of liver pieces during cooking) and area shrinkage after heating. The cooking loss and area shrinkage increased with increasing

heating time and temperature, following the first-order fractional model. Compared with fresh livers, the shear resistance for cutting through the cooked livers increased after heating at 73.9°C to 90°C and decreased at 60°C, whereas the livers heated at 70°C had shear resistance (~4.5 N/g) similar to the fresh liver, regardless of the heating times used in this study. Heating resulted in color changes in livers, shifting from red hue (0°) toward yellow hue (90°), as characterized by the increased hue angles after heating. Cooking livers to an internal temperature of 70°C to 73.9°C and hold for 101 to 26 s is recommended for food processing plants or restaurants to prepare ready-to-eat meals containing chicken livers to achieve microbial safety with respect to *Salmonella* and provide cooked livers with desired texture and pink color.

Key words: chicken liver, cooking loss, area shrinkage, shear resistance, color

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INTRODUCTION

The world consumption of poultry meat was 131 million tons (Mt, ready to cook equivalent) in 2020 and is expected to increase to 145 Mt in 2029 (OECD-FAO, 2020). The production of poultry meat generates large amounts of by-products that can be further consumed or utilized as food ingredients. Chicken liver, which constitutes 1.6 to 2.3% of chicken's live weight (Ockerman and Basu, 2004), is one of the most consumed and nutritious offal meat and edible chicken by-products. It has a similar protein content as that of muscle meat (~20%) (Pereira and Vicente, 2013) and is also a rich source of vitamins A, B₁₂, and minerals (Ockerman and Basu, 2004). Livers are prepared and

cooked in different ways along with other ingredients in traditional cuisine across the world, such as fried liver and liver pâté.

But chicken liver is a potential cause of foodborne illness due to *Campylobacter* and *Salmonella*. In addition to surface contamination, *Campylobacter* is reported to be existing in the internal tissue of chicken livers (Whyte et al., 2006; Firlieyanti et al., 2016), which makes it difficult to be inactivated thoroughly. A total of 28 foodborne *Campylobacter* or/and *Salmonella* outbreaks due to contaminated chicken livers were reported during 2000–2016 in the US, and 10 additional outbreaks during 2017–2018 (Lanier et al., 2018; CDC, 2020). These outbreaks resulted in a total of 464 illnesses and 54 (11.6%) hospitalizations (Lanier et al., 2018; CDC, 2020). The majority of these outbreaks were related to the consumption of inadequately cooked chicken liver products, mostly chicken liver pâté, at sit-down restaurants or private homes (Lanier et al., 2018). Undercooked poultry liver pâté was also reported to be associated with outbreaks and an increased risk of foodborne *Campylobacter* infection in the United Kingdom

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¹Corresponding author: jtang@wsu.edu

(Little et al., 2010). Thus, proper cooking of chicken liver is essential to achieve a microbiologically safe product. USDA Food Safety and Inspection Service (FSIS) recommends cooking poultry livers to an internal temperature of 165°F (73.9°C) to mitigate the food-safety risks (FSIS, 2020).

However, chefs in restaurants and people at home tend to undercook livers to maintain pinkness and perceived palatability preferences (Jones et al., 2016), as cooking is known to cause undesired changes in eating qualities, such as toughening in texture and discoloration (Pathare and Roskilly, 2016). Tenderness, which can be reflected by instrumental shear resistance (Sánchez-Valencia et al., 2014), is an essential sensory attribute that determines meat quality and consumer acceptability (Caine et al., 2003). High-temperature cooking often leads to toughening, while low-temperature, long-time cooking, such as sous vide cooking, improves meat tenderness (Baldwin, 2012). Area shrinkage and cooking loss (defined as the reduction in the weight of the liver pieces, in percentage, due to cooking (w/w)), are also critical sensory attributes correlated with juiciness, tenderness, and the final product's size and yield (Dominguez-Hernandez et al., 2018). Besides these eating qualities, heating alters the meat color from red to pink or dull brown. Color determines the visual attraction of the cooked meat. Consumers, including restaurant chefs, are more likely to assess cooking adequacy status by color.

The effects of cooking conditions on eating qualities have been reported in different muscle meat (Niu et al., 2015; Wang et al., 2018; Blikra et al., 2020). Livers share many of the quality attributes as muscle meat, but they are different in structure. Muscle fibers are mainly composed of myofibrils (Tornberg, 2005). In contrast, about 80% of the total liver mass is occupied by hepatocytes, which includes a large nucleus, many mitochondria, lysosomes, and other organelles (Zaefarian et al., 2019). The hepatocytes are supported by a sparse collagen III fiber meshwork (Zaefarian et al., 2019). A variety of proteins may undergo denaturation during cooking due to the heterogeneous composition of the liver structure. Li et al. (2018) reported a complex array of proteins in goose liver analyzed by sodium dodecyl sulfate-polyacrylamide gel electrophoresis (SDS-PAGE), especially in the low molecular weight range (<100 kDa), which was attributed to the considerable cytoplasm in liver cells.

Besides cooking conditions, the storage temperature also impacts the quality of raw and cooked meat. Fresh meat has limited shelf-life; frozen storage is, thus, employed for raw meat preservation. However, freezing and thawing may change the water fraction in meat proteins. Consequently, freezing may adversely affect the raw meat quality and subsequent eating qualities after cooking. The ability to retain water, referred to as water holding capacity, is a principal indicator of raw meat quality. The water holding capacity of meat is reported to be reduced by freezing, frozen storage, and thawing (Leygonie et al., 2012a). Frozen storage also induces

increased tenderness and color changes in raw meat (Muela et al., 2010; Leygonie et al., 2012b). However, parallel comparison studies of the eating qualities of fresh and frozen meat after cooking are lacking. Such information is needed to understand the influence of freezing on meat qualities.

Limited research has reported quality changes in cooked livers. Hadi (2020) observed a cooking loss of 26 to 34% (w/w) in the fresh raw chicken liver when different cooking conditions were applied. Moreover, pâté made from fresh or frozen chicken livers differed significantly ($P < 0.05$) in the internal color (Hutchison et al., 2015).

The changes in eating qualities during cooking are correlated with proteins' thermal changes (Tornberg, 2005). The rate and extent of the changes are closely related to heating temperature and time. Kinetic models of quality changes in isothermal heating tests can be established and used to understand, predict, and control quality changes during heating (Ling et al., 2015). More importantly, understanding how the quality change kinetics correlate with microbial inactivation can aid in designing and optimizing cooking practices to minimize undesired quality losses while maintaining food safety. The main objectives of this study were to: investigate the changes of cooking loss, area shrinkage, color, and texture of chicken livers under different cooking conditions (60–90°C, 0–65 min); study the effect of storage conditions (fresh vs. frozen) on both raw and cooked liver quality; extrapolate the minimum cooking times at different temperatures to achieve a 7-log reduction of *Salmonella* in poultry products; and discuss cooking recommendations for chicken livers.

MATERIALS AND METHODS

Material

The fresh raw chicken livers were purchased from a local market in Pullman, WA. They were stored at 2°C and used for experiments within 5 d. The frozen chicken livers were obtained by storing the fresh livers at -18°C for 30 d before thermal treatments. Before tests, the frozen livers were thawed in the refrigerator at 7°C overnight (~18 h). The chicken livers were cut into pieces of 10 ± 1 g with a thickness of approximately 8 mm. The liver pieces were equilibrated at room temperature (~23°C) for 30 min before thermal treatments.

Thermal Treatment

For thermal treatments, the liver pieces were sealed into aluminum thermal kinetic test (TKT) cells. The internal dimensions of the TKT cell are 50×8 mm (diameter \times height), with a cell wall thickness of 3 mm. The come-up time (CUT), which is defined as the time required for the center of the sample to reach within 0.5°C of the target temperature, was monitored by a Type-T thermocouple installed in the middle of

Table 1. Target temperatures and times for heating chicken livers.

Temperature (°C)	CUT ¹ (min)	Heating time (min)						
60.0	2.75	0 ^b	7	15	25	37	50	65
70.0	2.93	0	5	10	18	28	40	55
73.9	3.08	0	3	8	15	25	37	47
80.0	3.31	0	2	6	12	18	26	35
90.0	3.67	0	1	3	6	10	15	20

¹CUT: come-up time, the time required for the center of the chicken liver to reach within 0.5°C of the target temperature.

^bThe end of CUT was considered as heating time 0.

the cell lid, with 3 mm inside of the lid (Wang et al., 2018).

The loaded TKT cells were then heated to target temperatures for different times in a precision digital circulating water bath (Model 260, Thermo Scientific, Marietta, OH) (Table 1). The target temperature range (60–90°C) covered 60°C, which is often used in sous vide cooking (Baldwin, 2012), and 73.9°C, which is the minimum end-point temperature in cooking instructions from FSIS for pathogen control in chicken livers (FSIS, 2020). The temperature of the water bath was set at one degree above the target temperature. The heating time in Table 1 was initiated after the livers reached the target temperatures. That is, the end of CUT was considered as heating time 0. After heating, the TKT cells were immersed immediately in ice water for 10 min to cool down. For each temperature-time combination, three TKT cells with liver pieces from different livers were tested in each of the two independent experiments (n = 6).

Water Content and Water Holding Capacity

The water content of fresh and frozen chicken livers was measured gravimetrically after drying for 18 h at 100°C in an oven (Yamato 116 Scientific Inc., Santa Clara, CA) (AOAC, 1991). Water holding capacity (WHC) was determined according to Sánchez-Valencia et al. (2014). Three grams (g) of chicken livers were placed in a centrifuge tube with 3 sheets of filter paper (Grade 2, 90 mm in diameter, Whatman, UK) centrifuged for 15 min at 3000 × g at room temperature. The results were expressed as % of water retained by the samples after centrifugation.

Cooking Loss

Cooking loss was determined gravimetrically as the difference in liver weight before and after the thermal treatment. The samples after thermal treatment were gently wiped with tissue paper to remove the surface water. Cooking loss was calculated as:

$$\text{Cooking loss (\%)} = \frac{(W_0 - W_T)}{W_0} \times 100 \quad (1)$$

where W_0 and W_T are the weight of the chicken liver before and after thermal treatment.

Color and Area Shrinkage

A Computer Vision System (CVS) was employed to take photos of chicken liver pieces before and after thermal treatment for area and surface color measurements. The CVS is described in detail by Zhang et al. (2014). All the images were captured at manual mode at 5500 K color temperature with a focal length of 100 mm, an aperture of f/5.6, exposure time of 1/100 s, and ISO 640. The resolution was 5184 × 3456 pixels. The calibration of the images was conducted using a color reference card (QPcard 203, QPcard AB, Helsingborg, Sweden) in Adobe Photoshop CC (Adobe system, Inc., San Jose, CA).

The chicken liver area in the calibrated images was selected using a Magic Wand Tool in Adobe Photoshop. Pixel numbers and average color parameters, L^* (lightness), a^* (redness), and b^* (yellowness) of the selected region were derived. The color values obtained in Photoshop were converted into standard CIE L^* , a^* , and b^* values using the formula in Yam and Papadakis (2004). Hue angle (h°) was then calculated to quantify the color changes in livers before and after heating. For meat products, hue angle is the development of color from red (0°) to yellow (90°), and larger angles indicate a less red product (Tapp et al., 2011). The difference in lightness and hue angle before and after thermal treatments was calculated based on Eqs. (2) and (3):

$$\Delta L^* = L_T^* - L_0^* \quad (2)$$

$$\Delta h^\circ = \tan^{-1}(b_T^*/a_T^*) - \tan^{-1}(b_0^*/a_0^*) \quad (3)$$

where L_0^* , a_0^* , b_0^* , and L_T^* , a_T^* , b_T^* correspond to the color values of chicken livers before and after thermal treatment.

Area shrinkage was calculated based on the difference in the sample area (pixel numbers) before and after treatment:

$$\text{Area shrinkage (\%)} = \frac{(A_0 - A_T)}{A_0} \times 100 \quad (4)$$

where A_0 and A_T are the pixel numbers of the chicken liver before and after treatment.

Shear Resistance

A 5-blade mini Kramer shear cell (model TA-91M) connected to a TA-XT Plus Texture Analyzer (Stable Micro Systems, Surrey, UK) was employed to determine the shear resistance at room temperature following the method described by Sánchez-Valencia et al. (2014) with modifications. The liver pieces with a thickness of 8 mm were cut into 25 × 25 mm (length × width) pieces to fit in the blade holder frame (27 × 27 mm), and sample weight was determined before tests. The test was performed with a load cell of 25 kg, a crosshead speed of 1 mm/s, and a compression distance of 20 mm. The force-distance graph was recorded and analyzed using Texture Expert Exceed software (Stable Micro Systems,

v. 2.64, Surrey, UK). The results were expressed as the maximum shear force per gram of sample (N/g).

Differential Scanning Calorimetry

Differential scanning calorimetry (DSC) was performed using the Q2000 Series differential scanning calorimeter (TA Instruments, Inc., New Castle, DE). Fifteen milligrams (mg) of each sample were hermetically sealed into aluminum pans and an empty sealed pan was used as the reference. After equilibration at 20°C for 5 min, the samples were heated at a rate of 10°C/min over the range of 20 to 120°C. Peak temperature (T_{max} , °C) and residual denaturation enthalpy (ΔH , J/g), which is the area under the denaturation peak, were determined using Universal Analysis 2000 software (TA Instruments, Inc., New Castle, DE).

Data Analysis

The kinetics of quality degradation under isothermal conditions could be modeled as follows (Van Boekel, 2008):

$$\frac{dC}{dt} = -k(C)^n \quad (5)$$

where k is the reaction rate constant, C is the quality at time t , and n is the reaction order.

The fractional conversion model (Eq. 6) based on first-order kinetics can be considered when any quality parameter varies from an initial value until an equilibrated value:

$$\frac{C - C_{\infty}}{C_0 - C_{\infty}} = e^{-kt} \quad (6)$$

where C_0 is the initial value of the food quality attribute and C_{∞} is the final equilibrium value. The reaction rate constant, k , is temperature-dependent and follows the Arrhenius relationship (Peleg et al., 2012):

$$k = k_0 \exp\left(-\frac{E_a}{RT}\right) \quad (7)$$

where E_a is the activation energy (kJ/mol), R is the universal gas constant (0.008314 kJ/mol K), T is the absolute temperature (K), and k_0 is the pre-exponential factor.

In thermal processing, D -value (min) is defined as the heating time required to cause a 1-log (90%) change of food quality attributes or reduce the microorganism numbers by 90% at a constant temperature. The thermal resistance constant, z -value (°C), indicates the temperature increment to reduce D -value by a factor of 10. It could be obtained through linear regression of the logarithm of D -value versus temperature. The D -value is related to the first-order reaction rate k and z -value by Eqs. (8) and (9), respectively:

$$D = \frac{2.303}{k} \quad (8)$$

$$D = D_{T_{ref}} \times 10^{\left(\frac{T_{ref}-T}{z}\right)} \quad (9)$$

The analysis of variance at a 95% confidence level ($P < 0.05$) and two-tailed Pearson correlation analysis at the significance level of 0.01 were performed using SPSS v25 (IBM Corp., Armonk, NY).

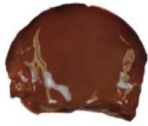

RESULTS AND DISCUSSION

Comparison of Fresh and Frozen Raw Chicken Livers

Quality attributes of fresh and frozen chicken livers are summarized in Table 2. Compared with fresh livers, the frozen ones had significantly ($P < 0.05$) higher L^* and b^* . The increase in meat lightness due to freezing was reported earlier (Holman et al., 2017; Medić et al., 2018), which could be attributed to the increased surface water reflection. Hutchison et al. (2015) reported that a test panel assessed the liver pâté made from fresh chicken livers as pinker than the pâté made from frozen livers ($P < 0.05$); however, the color difference did not influence the overall color likeability ($P > 0.05$). The chicken liver in the current study had higher a^* and b^* than that reported by Papazoglou et al. (2012) and Xiong et al. (2020), but lower a^* than that reported by Berrang et al. (2020). The differences are likely because the color of livers varies, depending on several factors such as chicken species, fat content, and chicken diet (Trampel et al., 2005). Normal chicken livers range in color from tan or yellow to deep mahogany red (USDA, 2019).

Frozen livers showed significantly ($P < 0.05$) lower WHC than fresh ones, while the difference in water content and shear resistance was not statistically significant ($P > 0.05$). Similarly, a decrease in the WHC of frozen meat was reported by Sánchez-Valencia et al. (2014). As water freezes, the concentration of the remaining solutes increases. The increased ionic strength may change the cell membrane characteristics and cause protein denaturation (Leygonie et al., 2012a; Zhang and Ertbjerg, 2018). Besides, the ice crystal size, localization, and

Table 2. Quality attributes of fresh and frozen chicken livers, $n = 12$.

	Fresh	Frozen ¹
Typical image		
L^* (lightness)	29.42 ± 2.74 ^b	35.50 ± 3.30 ^a
a^* (redness)	26.64 ± 1.61 ^a	27.55 ± 1.56 ^a
b^* (yellowness)	19.48 ± 1.93 ^b	22.70 ± 1.76 ^a
Hue angle (°)	35.33 ± 1.35 ^b	39.49 ± 2.55 ^a
Water content (%)	75.76 ± 1.61 ^a	75.74 ± 1.38 ^a
Water holding capacity (%)	80.03 ± 2.26 ^a	73.79 ± 3.16 ^b
Shear resistance (N/g)	5.05 ± 0.58 ^a	5.49 ± 0.89 ^a

^{a-b}Indicates significant difference within the row ($P < 0.05$).

¹The samples were frozen at -18°C for 30 d.

orientation can also cause modifications in the techno-functional properties of the protein (Barraza et al., 2015). All these factors likely contributed to the loss of ability to hold water and water movement from inside to the outside of the livers tested in this study.

Cooking Loss and Area Shrinkage

The cooking loss and area shrinkage of fresh and frozen chicken livers after thermal treatment are shown in Figures 1 and 2, respectively. In general, the cooking loss and area shrinkage increased with increasing temperature and heating time. The increment reduced with holding time at each temperature and around 80% of the final losses took place within the first 40% of the total cooking time. The cooking loss and area shrinkage appeared to reach an equilibrium value during heating, and this value increased with heating temperature. For example, the cooking loss and area shrinkage of frozen samples were 23 and 25% after being heated at 60°C for 65 min, while the values were 37 and 42% after heating at 90°C for 20 min. Frozen chicken livers had significantly ($P < 0.05$) more cooking loss and area shrinkage than the fresh samples under the same treatment conditions, which may be a consequence of damage due to freezing. Hadi (2020) also observed a higher cooking loss in frozen chicken livers than fresh samples (26 vs. 32%) when boiling was applied as a form of thermal treatment.

The changes in both cooking loss and area shrinkage fitted well with the first-order fractional conversion model, with the kinetic parameters summarized in Table 3. The fresh and frozen livers had similar reaction rates (k) at the same temperature. The k increased from 3 to 15 min^{-1} when the temperature rose from 60°C to 90°C. The E_a for both cooking loss and area shrinkage was between 40 and 45 kJ/mol. Compared to fresh livers, frozen livers had a slightly smaller E_a and larger z -value in cooking loss and area shrinkage, which implies that they are less sensitive to temperature.

The cooking loss in cooked chicken livers is mainly caused by the loss of moisture, melting of fat, and denaturation of protein (Xiong et al., 2020). Most of the cooking loss constitutes water, along with a small number of other components such as vitamins and solubilized proteins (Tornberg, 2005). Water in chicken liver tissue exists in both forms, tightly bound to proteins and relatively freely moving. Upon heating, the liver tissue loses the ability to hold water due to the unfolding of protein and disruption of the cell structure. The increased water loss and more extensive destruction of cell structure lead to substantial cooking loss at the higher temperature. Choi et al. (2013) observed the water content in the porcine liver changed from 77% at 25°C to 55% at 80°C. Li et al. (2018) reported a cooking loss of 25% in fresh goose liver after heating to 80°C and holding for 30 min, which is similar to the result of fresh chicken liver in the current study. Xiong et al. (2020) reported a cooking loss of 13% in fresh chicken livers after heating at 80°C for 30 min without indicating the actual temperature the liver reached.

In terms of area shrinkage, when the heat is applied to tissues, shrinkage occurs as a result of dehydration and contraction of the supportive collagen at temperatures higher than 50°C (Liu and Brace, 2014). Contraction increases with temperature and time; this was also presented in the dynamic of shrinkage in the porcine liver during heating at 60°C to 95°C (Rossmann et al., 2014).

Color

Regardless of the storage conditions (i.e., fresh vs. frozen) of chicken livers before cooking, heating resulted in increased lightness ($\Delta L^* > 0$) and yellowness ($\Delta b^* > 0$), and decreased redness ($\Delta a^* < 0$). A similar trend was reported in chicken livers after heating at 60°C for different times (Berrang et al., 2020) and in ostrich liver heated to an internal temperature of 72°C to prepare liver pâté (Fernández-López et al., 2004). The increased lightness is due to an increased reflection of light from

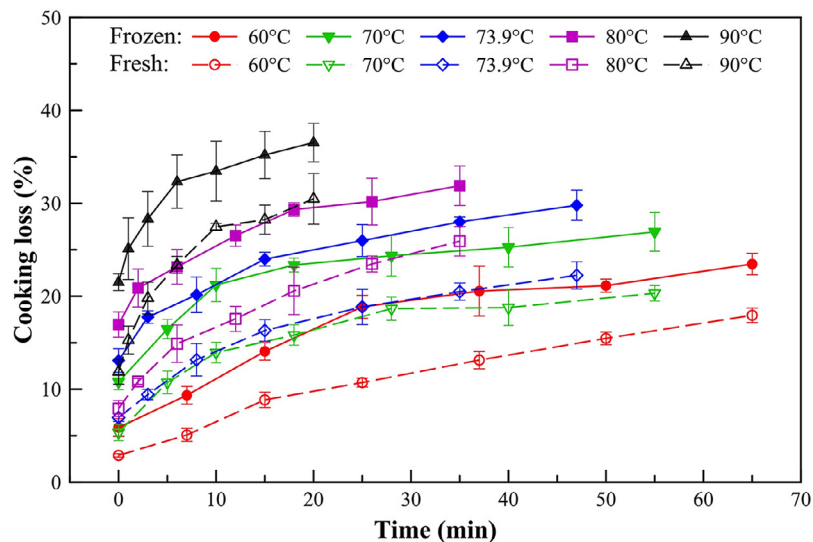


Figure 1. The changes of cooking loss of frozen and fresh chicken livers with different treatment temperatures and times, $n = 6$.

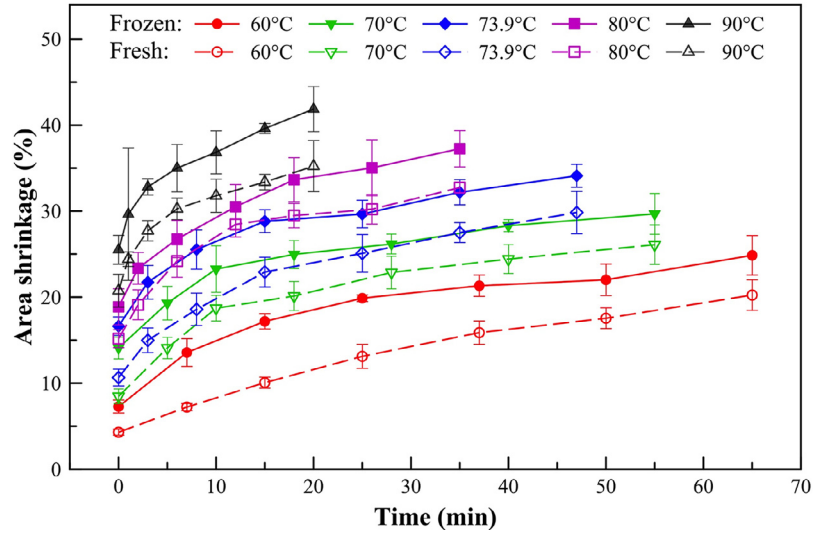


Figure 2. The changes of area shrinkage of frozen and fresh chicken livers with different treatment temperatures and times, $n = 6$.

light reflectance and scattering by denatured protein and leakage of water (Liu et al., 2013). An increase in ΔL^* was anticipated at the early heating stage at 60°C to 73.9°C (Figure 3a). Oxidation and browning resulted in a decrease in ΔL^* at the later stage of 60°C to 73.9°C heating and heating at 80°C to 90°C (Kong et al., 2008; Wang et al., 2018). The decrease in a^* and increase in b^* led to the rise in hue angle ($\Delta h^\circ > 0$) (Figure 3b). The Δh° kept increasing and reached a maximum value of 28° C to 30° in extended heating at 60°C to 80°C. In contrast, the Δh° was stable with a value of 30°C throughout the heating at 90°C. The hue angle increased with temperature and time indicated that cooking resulted in color shifting in chicken livers from red hue (0°) toward yellow hue (90°).

Liver color is highly dependent on the amount of heme-containing compounds such as myoglobin and hemoglobin. Jiménez-Colmenero and Cassens (1987) reported that in sausages containing liver extract, the lower the heme pigment content, the higher L^* and the lower a^* were observed. The total heme pigments in chicken livers were reported to be ~ 6 mg/g liver, and the primary pigment is myoglobin (Xiong et al., 2017). Oxidation and breakdown of heme molecules during cooking cause the release of iron from globin and lead to discoloration in livers (Estévez and Cava, 2004). Fernández-López et al. (2006) observed the increase in metmyoglobin and decrease in heme iron correlated well with the decrease in a^* and increase of h° in ostrich liver during storage. The metmyoglobin is an oxidation product of

Table 3. Kinetic parameters for cooking loss, area shrinkage, and shear resistance of frozen and fresh chicken livers after thermal treatment at different temperatures.

Quality		Temp. (°C)	$k \times 10^{-2}$ (min ⁻¹)	D -value (min)	R^2	E_a (kJ/mol)	R^2	z -value (°C)	R^2
Cooking loss (%)	Frozen	60.0	4.4	52.5	0.96	42.4	0.92	54.3	0.93
		70.0	5.5	41.6	0.93				
		73.9	6.1	38.0	0.99				
		80.0	8.5	27.3	0.98				
		90.0	15.5	14.8	0.98				
	Fresh	60.0	3.5	65.2	0.98				
		70.0	5.9	38.6	0.94				
		73.9	6.1	37.8	0.99				
		80.0	7.3	31.5	0.98				
		90.0	14.7	15.6	0.97				
Area shrinkage (%)	Frozen	60.0	3.6	63.4	0.95	40.2	0.98	57.5	0.98
		70.0	5.6	41.1	0.97				
		73.9	5.8	40.1	0.96				
		80.0	8.1	28.4	0.99				
		90.0	12.1	19.1	0.97				
	Fresh	60.0	3.6	64.0	0.99				
		70.0	5.7	40.5	0.98				
		73.9	5.8	40.0	0.99				
		80.0	7.7	30.0	0.93				
		90.0	13.0	17.7	0.98				
Shear resistance (N/g)	Frozen	73.9	5.9	39.3	0.96	59.0	0.99	40.9	0.99
		80.0	8.0	28.7	0.96				
		90.0	14.4	15.9	0.94				
	Fresh	73.9	4.8	48.0	0.91				
		80.0	8.8	26.2	0.97				
		90.0	11.9	19.3	0.88				

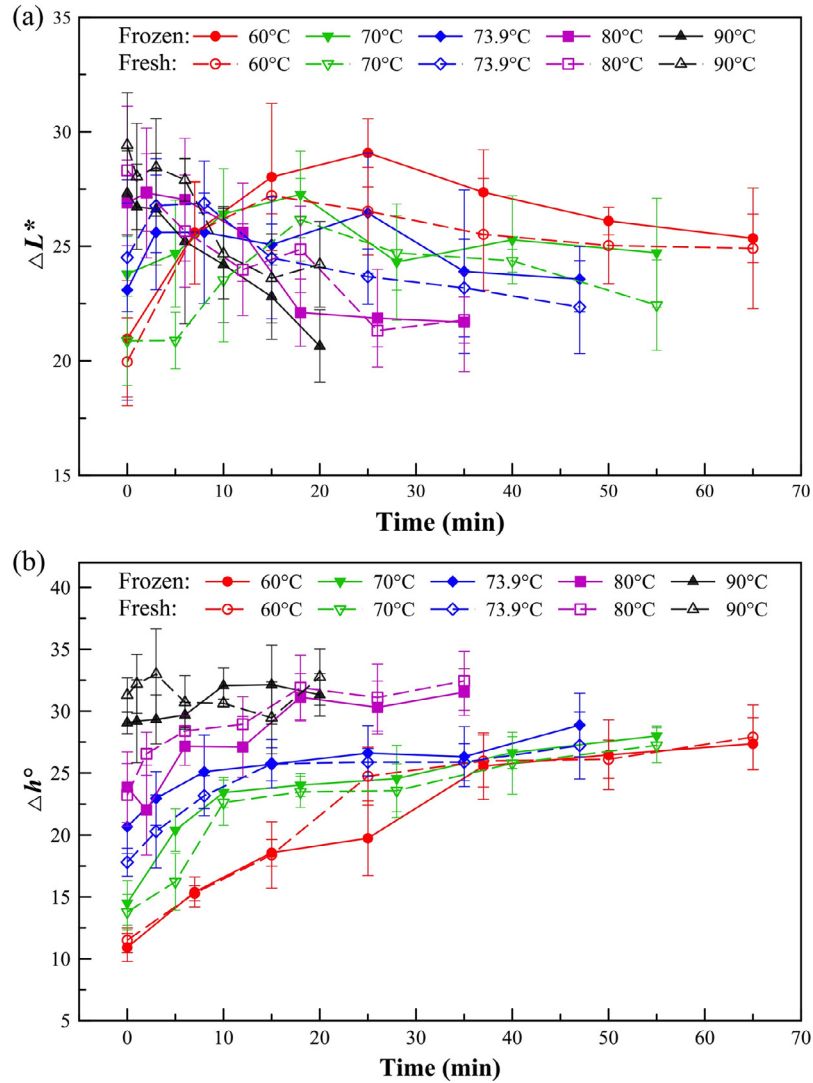


Figure 3. The changes of (a) ΔL^* , (b) Δh° of frozen and fresh chicken livers with different treatment temperatures and times, $n = 6$.

myoglobin and appears gray brown. Based on the current results, the color of cooked chicken livers could be correlated with the cooking level. However, it is worth noting that consumers, including restaurant chefs, have poor identification of whether chicken livers have been cooked to a safe microbiological state based on the color (Jones et al., 2016).

Shear Resistance

Figure 4 shows the changes in shear resistance of fresh and frozen chicken livers after cooking. The shear resistance increased with heating time to 9 to 12 N/g when heated at 73.9°C to 90°C and a larger value was observed at higher temperatures after the same holding time. However, heating at 70°C for 55 min did not result in changes in shear resistance; the liver tissues retained a similar tenderness as fresh livers. Heating at 60°C decreased the shear resistance from ~ 4 N/g to less than 1 N/g after holding for 65 min.

As the changes in shear resistance behaved differently at different temperatures, only the heating temperatures

causing toughening were considered in the kinetic study (73.9, 80, and 90°C). Both frozen and fresh chicken livers showed comparable shear resistance after the same treatment and similar fractional first-order kinetic parameters (Table 3). However, Hadi (2020) reported that fresh chicken livers had a significantly higher texture acceptance score than frozen livers after the same cooking, but no instrumental analysis was included. The kinetic changes in shear resistance have a higher E_a and a lower z -value than cooking loss and area shrinkage. This indicates that shear resistance is more sensitive to temperature changes.

The softening at 60°C is caused by the unfolding of the proteins. On the one hand, the extracellular structural protein, collagen fibers, are converted to gelatin due to the mild heating and the function of proteolysis (Bouton and Harris, 1972). The typical denaturation temperature of collagen is 53°C to 63°C (Tornberg, 2005). Besides, the lysosome protease, cathepsin B, D, and L, have been isolated from chicken liver and are capable of degrading collagen due to their high thermal stability (Ali and Richards, 1975; Dufour et al., 1987; Wada and Tanabe, 1988). On the other hand, the

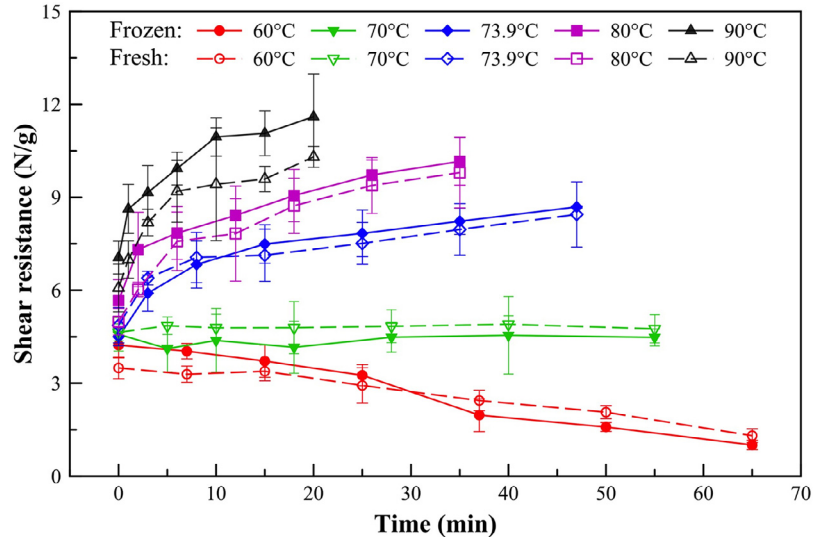


Figure 4. The changes of shear resistance of frozen and fresh chicken livers with different treatment temperatures and times, $n = 6$.

membrane proteins of hepatocytes and cytoplasmic components in the liver were reported to degrade at $\sim 60^\circ\text{C}$ (Lepock et al., 1993). The degradation of these intracellular proteins may result in the loss of cell support and tissue shape. Increasing the heating temperature to higher than 60°C caused thermal aggregation of the protein, resulting in increased shear resistance. The liver proteins underwent aggregation and complex formation due to cross-links after heating to 70°C , and the network became stronger as temperature increased to 90°C (Li et al., 2018). The more considerable area shrinkage and cooking loss at higher temperatures also contributed to a denser and firmer structure (Roldán et al., 2013; Choi et al., 2019).

Correlations Between Quality Attributes as Determined Instrumentally

The Pearson correlation coefficients between quality attributes in both fresh and frozen chicken livers after heating at 60°C to 90°C are shown in Table 4. Except for ΔL^* , all the other attributes were significantly positively correlated with each other ($P < 0.01$). As shown in Figure 3a, the changing trend of ΔL^* was highly dependent on individual treatment temperature and time; the correlation with other attributes was not established. A similar high correlation between cooking loss and shrinkage was also reported in the bovine liver (Brace et al., 2010). Area shrinkage could be employed to estimate

Table 4. Pearson correlation coefficients between quality attributes (combined data of fresh and frozen livers).

	Area shrinkage	Cooking loss	Shear resistance	ΔL^*
Cooking loss	0.96**			
Shear resistance	0.80**	0.69**		
ΔL^*	-0.15	-0.16	-0.26	
Δh°	0.86**	0.76**	0.68**	0.09

**Statistically significant ($P < 0.01$).

the cooking loss, shear resistance, and Δh° , as indicated by the significant correlation coefficients between them.

DSC

The endothermic peaks in the DSC scanning of the liver are correlated with protein denaturation, as it is the primary endothermic process occurring in liver tissue (Ritchie et al., 1994). Two endothermic transitions were observed in the thermogram of fresh chicken liver, with T_{max} values of 67°C and 90°C (Figure 5). The transition at $\sim 60^\circ\text{C}$ was mainly attributed to the denaturation of membrane proteins and intracellular cytoplasmic components, and the transition at $\sim 90^\circ\text{C}$ was due to nuclear skeletal proteins (Lepock et al., 1993). In contrast, only one peak was determined in liver protein isolate, with the peak temperature of 53.6°C to 72.5°C in chicken liver protein isolate (Zou et al., 2017a) and 62°C to 64°C in duck liver protein isolate (Zou et al., 2017b). This is probably because the nucleus takes up a relatively small fraction of the total cell, and sometimes the transitions may not be detectable in liver homogenates (Lepock et al., 1993).

The peak area (residual enthalpy) is correlated with the content of the ordered 3-dimensional structure of proteins; thus, a reduction in peak area implies the loss of protein structures. The residual enthalpy (ΔH) of peaks 1 and 2 in the thermogram of the fresh chicken liver was 0.47 and 0.05 J/g, respectively. The frozen chicken liver showed similar peaks with no difference ($P > 0.05$) in peak temperatures and ΔH of peak 2 (data not shown). However, with a value of 0.36 J/g, ΔH of peak 1 was significantly less ($P < 0.05$) than that of fresh chicken liver, suggesting the freezing damage of protein. Due to the denaturation of protein during heating, peak 1 strongly reduced after heating at 60°C and disappeared at higher temperatures (Figure 5). Peak 2 disappeared after heating at 80°C (Figure 5).

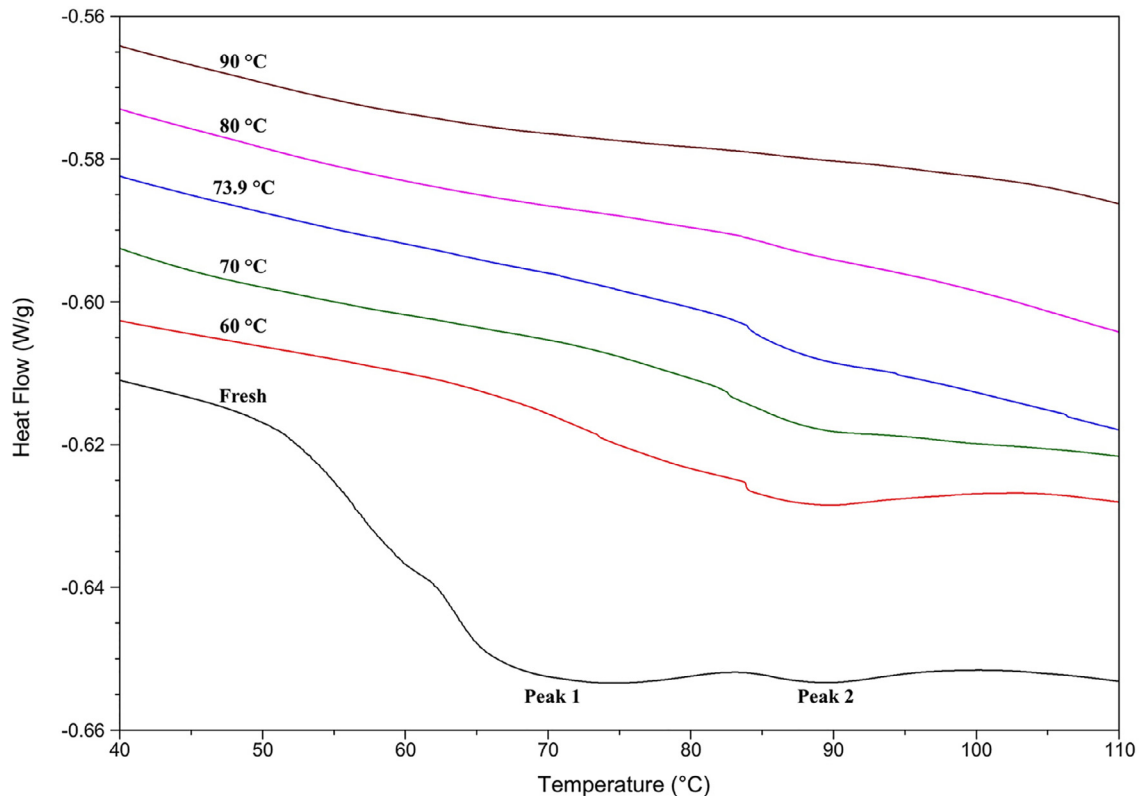


Figure 5. Typical thermograms of fresh chicken liver and fresh livers heated for 15 min at 60, 70, 73.9, 80, and 90°C.

Cooking Recommendations for Chicken Livers

Safety FSIS suggests cooking all categories of meats (e. g., cooked, fermented, salt-cured, dried) to achieve a minimum 6.5-log reduction (6.5D) of *Salmonella* and a minimum of 7D of *Salmonella* in poultry products (FSIS, 2005). The published *D*-values of *Salmonella* in different types of meat range between 4.1 and 68 min at 55°C, 0.28 and 16 min at 60°C, less than 2 min at 65°C, and less than 0.25 min at 70°C (Silva and Gibbs, 2012). However, no such information is available on the thermal resistance of *Salmonella* in chicken liver. Based on the cooking conditions recommended by FSIS and using the highest *D*-values of *Salmonella* in chicken meat as reported by Murphy et al. (2000), we estimated the heating time to achieve a 7D of *Salmonella* at various temperatures (Table 5). The minimum holding time was determined as 25.5 s after the internal temperature (cold spot) reached 73.9°C, which is more than the current FSIS recommendation for cooking chicken livers. The possible explanation is the *D*-values reported by Murphy et al. (2000) were obtained using a cocktail of *Salmonella*, which included *Salmonella* Senftenberg, a serotype reported to exhibit high thermal resistance (Mazzotta, 2000). Chicken livers can be contaminated with different *Salmonella* serotypes, including *Salmonella* Enteritidis and *Salmonella* Heidelberg (Lamier et al., 2018). Inter- and intraserotype differences may exist in the thermal resistance of *Salmonella* in chicken liver. The equivalent heating conditions obtained using high thermal resistance *Salmonella*

should be adequate for cooking chicken livers thoroughly (Table 5). Besides, CUT was added to the total cooking time to ensure the internal tissue (cold spot) receives enough heating, as pathogens may exist in the internal tissue of chicken livers (Whyte et al., 2006; Firlieyanti et al., 2016). In the current study, the CUT was short as the small pieces of livers were uniformly heated in the aluminum heating cells using a water bath. However, heating whole lobes of livers with uneven surfaces in a restaurant or domestic kitchen may require longer CUT. Different cooking methods also lead to different CUT; for example, the uneven heat application in pan-frying may result in longer CUT compared to boiling (Hutchison et al., 2015). The CUT varies with food sizes, package geometry, and the heating method; it should be determined for individual products.

Quality Consumers have always preferred juicy meat; the higher the juiciness, the higher the acceptability score (Aaslyng et al., 2007). The cooking loss is negatively correlated with consumer juiciness rating (Lucherik et al., 2017). As discussed above, fresh chicken livers showed lower cooking loss than frozen livers when the same cooking conditions were applied. Thus, from the perspective of raw material selection, fresh chicken livers showed advantages over frozen livers by the potential of providing more juicy cooked livers. Hadi (2020) also reported that frozen chicken livers generally have fewer acceptances in comparison with fresh livers.

The kinetics of quality changes obtained in the current study could be used to make cooking recommendations to avoid undesired quality losses and retain desired quality based on consumers' preferences. Table 5 shows the total

Table 5. Minimum process time estimation for pasteurization of poultry meat products to achieve a 7-log reduction of *Salmonella* at various target temperatures at the cold spot and corresponding quality changes and typical images of fresh chicken livers after suggested cooking.

Target temperature	D -value ¹	Suggested cooking time	Cooking time (min)	Cooking loss (%)	Shear resistance (N/g)	Δh° (surface)	Typical images after suggested cooking	
							Surface	Middle
60.0°C	5.9 min	41.3 min + $CUT_{60^\circ C}^2$	44.1	14.2	2.3	25.9		
70.0°C	14.4 s	100.8 s + $CUT_{70^\circ C}$	4.61	8.8	4.7	16.6		
73.9°C	3.6 s	25.5 s + $CUT_{73.9^\circ C}$	3.51	7.5	5.5	19.9		
80.0°C	0.4 s	3.0 s + $CUT_{80^\circ C}$	3.36	7.9	5.2	25.1		
90.0°C	0.01 s	0.1 s + $CUT_{90^\circ C}$	3.67	13.4	7.0	31.3		

¹ D -value at 60 and 70°C were extracted from [Murphy et al. \(2000\)](#), whereas D -values at 73.9–90°C were estimated using [Eq. \(9\)](#) with a z -value of 6.53°C ([Murphy et al., 2000](#)).

²The values of CUT are shown in [Table 1](#).

cooking time (come-up time plus holding time) at different cooking temperatures to achieve a 7-log reduction of *Salmonella* inactivation in the chicken liver samples used in this study. The corresponding cooking loss and shear resistance in fresh chicken livers were estimated using kinetic parameters in Table 3. Typical images (surface and middle) after the suggested cooking times and corresponding measured hue angle changes are also shown in Table 5. It is clear from Table 5 that increasing the cooking temperature from 60°C to 70–80°C sharply reduces the total cooking time, from 41 min to less than 5 min. Moreover, the corresponding cooking loss is reduced from 14% to ~8%. The 60°C cooking softened the liver texture, that is, reducing the shear resistance of the liver samples to 2.3 N/g, while heating at 70°C to 80°C allowed the texture of the cooked chicken livers to remain the same as that of the fresh liver, with a shear resistance of 4.7 to 5.5 N/g. But elevating the cooking temperature to 90°C tightened the liver texture and cause considerable cooking loss and color change. This is likely because holding at high temperature induced more changes, and also, the higher-temperature cooking required relatively longer CUT (Table 1) during which quality changes took place. In terms of color changes, the smaller Δh° , the pinker the livers. As shown by the sample images in Table 5, cooking at 60°C for 44 min resulted in a complete loss of the structure along with a loss of the pink color in the chicken liver samples. Cooking at 80°C led to visible discoloration, similar to that of 60°C cooking, while 90°C cooking resulted in a sharp darkening in the livers, as also indicated by the large Δh° . In contrast, cooking at 70°C and 73.9°C best preserved the pink color and the internal structures.

The recommended cooking conditions of chicken livers may vary based on consumers' desire, how it is consumed, and the method of preparation. For example, consumers prefer fried meat to have crispy exteriors and moist and juicy interiors (Das et al., 2013). Cooking temperatures of 73.9°C to 80°C are suggested, as the heating could provide livers with relative lower cooking loss and toughening in texture (compared to the raw livers shown in Table 2) in extended holding. The heat transfer during cooking leads to a longer holding time at the cooking temperatures on the surface than inside, so it is possible to develop a firm outside and tender and juicy inside in the extended heating. In the case of liver pâté, cooking temperatures of 70°C 73.9°C are recommended. The typical texture of liver pâté may vary from smooth to dense or coarse based on consumers' preference and mixture with other food ingredients (Porto-Fett et al., 2019). Long-time cooking at 60°C, also referred to as sous vide cooking, resulted in a silky texture; the long-time cooking to achieve safety also caused extensive cooking losses. Cooking at 70°C to 80°C for 5 min can give the liver samples a smooth and spreadable texture while achieving a 7-log reduction in *Salmonella*. Further increase in the cooking times at these temperatures would lead to dense and coarse texture (Figure 4). Consumers tend to prefer pinker liver products (Jones et al., 2016). Thus, the cooking temperatures of 70°C and 73.9°C are recommended.

CONCLUSIONS

Heating caused the cooking loss, area shrinkage, color, and texture changes in chicken livers. Freezing to -18°C reduced the water holding capacity of chicken livers and resulted in more cooking loss and area shrinkage after heating. Cooking loss and area shrinkage increased with increasing cooking temperature and time, following the first-order fractional model. Shear resistance increased with time and temperature during heating at 73.9°C to 90°C. However, heating at 60°C resulted in a decrease in shear resistance. The color of chicken livers changed from red hue toward yellow hue in cooking, with Δh° increasing with cooking time at 60°C to 80°C and a relatively stable value of 30° at 90°C. This study provides an understanding of kinetics for chicken liver quality changes during heating. Cooking livers to an internal temperature of 70°C to 73.9°C following appropriate holding to achieve a 7-log reduction in *Salmonella* is recommended to produce microbial safe ready-to-eat chicken livers with desired texture and pink color.

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DISCLOSURES

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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