Meat and Muscle Biology™

Modeling Techniques for Prediction of Safe Cooking Times of Mechanically Tenderized Beef Steaks

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Abstract: Microbial safety issues related to mechanically tenderized beef have become prevalent, resulting in new labeling regulations for mechanically tenderized raw or partially cooked beef products. These products must bear labels to include validated cooking instructions, with specifications for minimum internal temperatures, to ensure that they are fully cooked. However, validation of cooking instructions for individual steak cuts of different sizes and weights is costly and time consuming. The objective of this study was to utilize predictive modeling techniques to determine safe cooking times for various mechanically tenderized steaks, cooked to an internal temperature of 70 to 71°C. A total of 162 steaks of various types (top round, knuckle, strip loin, top sirloin, sirloin cap, tri-tip, ribeye, flap, and flank), thicknesses (1.27, 2.54, and 3.81 cm), and weights (113 to 567 g) were used. Prior to cooking, samples were needle-tenderized, cut, vacuum-packaged, and refrigerated. Steak dimensions (width, thickness, and length) were measured prior to each cooking experiment. Samples were cooked on a flat-top-grill until they reached an internal temperature of 70 to 71°C, and the time taken to reach that temperature was defined as the Experimental Safe Cooking Time (ESCT). A thermocouple, attached to a data logger, recorded the steak-center temperature every 10 s. The time-temperature profiles obtained were used to determine the rate of temperature increase (RTI). Data generated through the experiments was used for model development and determination of predicted safe cooking time (PSCT) for steaks. The thickness, weight, and RTI of the steaks were identified as factors that had a 60% or higher correlation with the ESCT. Prediction accuracy of the regression model was 79%, with no significant differences ($P < 0.01$) between the ESCT and PSCT. This approach could help the meat industry formulate safe cooking times of various steak cuts, without repeating costly validation studies.

Keywords: mechanical tenderization, predictive modeling, safe cooking, steaks
Meat and Muscle Biology 2(1):180–188 (2018) **doi:10.22175/mmb2017.10.0049**
Submitted 10 Oct. 2017 Accepted 18 Apr. 2018

Introduction

Consumers, to a large extent, judge the palatability and quality of meat products based on their tenderness (Umberger et al., 2002; Font-i-Furnols and Guerrero, 2014). This has encouraged the meat industry to focus on enhanced safety and quality of tenderized meat products. Among the various tenderization techniques, conventional aging, mechanical tenderization, brine injections, and enzymatic treatment are the most common (Dikeman et al., 2013). Even though conventional aging is successful with tender cuts such as ribeye and top sirloin, it has not been effective with tough cuts. In this case, mechanical tenderization is considered comparatively better for improving the tenderness of tough cuts (Pietrasik and Shand, 2004). Studies have also identified tenderization as a vital step in reducing cooking time, while increasing the flavor profile and overall palatability of meat (Pietrasik et al., 2010).

The popularity of tenderized beef products, however, has been accompanied by serious food safety con-

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The authors would like to acknowledge the support of Brad Morgan and Performance Food Group (Richmond, VA). We also wish to thank Kyle Flynn for his assistance with meat fabrication.

cerns. Mechanical tenderization, which involves blade- or needle-piercing, could lead to increased transfer of surface pathogenic bacteria such as, *Salmonella enterica* and *Escherichia coli* O157:H7, into the previously sterile deep tissue (Gill et al., 2005; Huang, 2010; Jefferies et al., 2012; Saha et al., 2016). Furthermore, spoilage and pathogenic bacterial population could increase during re-use of a contaminated needle or blade (Greer et al., 2004; Ray et al., 2010; Jefferies et al., 2012). According to reports by the Centers for Disease Control and Prevention, mechanical tenderization of beef products has led to six outbreaks in the U.S., since 2000 (Heiman et al., 2015). In the wake of these outbreaks, a mandatory labeling guideline on safe cooking times and temperatures has been issued for mechanically tenderized and not-ready-to-eat (NRTE) beef products, by the United States Department of Agriculture's Food Safety and Inspection Service (USDA-FSIS, 2015). Fulfillment of this mandate requires validation of safe cooking times. Previous studies have revealed that multiple factors such as shape, type, thickness, weight, and cooking methods of beef steaks could influence the cooking time (Jeremiah et al., 2003; Hildrum et al., 2009). However, determination of safe cooking times and the degree of doneness for individual steak cuts, of various sizes and weights, could get tedious and expensive. Use of thermocouples in the food service sectors such as restaurants, food-trucks, and fast-food joints, to monitor temperature during cooking, is also impractical and seldom done (Obuz, 2004). In this scenario, mathematical modeling could prove to be a powerful and concise way to predict safe cooking times, without undergoing costly cooking experiments.

Predictive modeling, which incorporates mathematics, statistics, engineering, chemistry, and biology to study various processing parameters, can provide quick and inexpensive testing of "what if" scenarios in meat processing, thereby reducing production or experimental costs (Datta, 1998; Shimoni and Labuza, 2000; Rust et al., 2008; Lawrence et al., 2010; Ho et al., 2013). Recent use of modeling techniques, to predict the degree of doneness for round and top loin steak cuts, was in good agreement with the experimental data (Obuz et al., 2004). Though there are a few studies predicting beef tenderness and temperature profiles (Liddell and Bailey, 2001; Lawrence et al., 2010; Modzelewska-Kapituła et al., 2012), there are almost none that would predict safe cooking times for mechanically tenderized NRTE beef steaks. The objective of this study was to enhance the applicability of mathematical modeling, using regression techniques, to predict safe cooking times of various steak cuts.

Materials and Methods

Mechanical tenderization

Various beef subprimals (UDSA Choice or higher grades) were delivered to the Robert M. Kerr Food and Agricultural Products Center (FAPC) at the Oklahoma State University (Stillwater, OK) by Performance Food Group (PFG, Richmond, VA). The subprimals were obtained by PFG from multiple beef processing plants in the US and originated from fed cattle, with a yield grade of 3 or higher. Prior to shipping to FAPC, subprimals were wet aged, vacuum packaged, and stored at refrigerated temperature (4 to 5°C). The subprimals were mechanically tenderized by passing once through a needle tenderizer (Ross TC700M-I, Ross Industries, Midland, VA) at the FAPC Meat Pilot Plant. Samples were placed in such a way that the external carcass surface faced downward when passed through the tenderizer. After tenderization, the subprimals (Institutional Meat Purchase Specifications item numbers in Table 1) were cut (as per PFG specifications) to obtain various steak cuts: top round, knuckle, top sirloin, sirloin cap, tri-tip, ribeye, strip loin, flank, and flap. A total of 162 steak cuts were prepared, with weights ranging from 117 to 567 g ($n = 3$ for each weight) and thicknesses of 1.27, 2.54, and 3.81 cm (Tables 2. a-d). Steaks were vacuum packaged (Ultravec 400, Ultrasource, Kansas City, MO) and stored at refrigeration temperatures (4 to 5 ± 0.5°C) until cooking at 45-d postmortem.

Dimensional measurements

Prior to each cooking experiment, steak dimensions (cm) and weights (g) were recorded. Steaks were measured for thickness (cm), width (cm), and length (cm), using the sliding vernier calipers (Starrett 86405180, MSC Industrial, Melville, NY), following the method described

Table 1. Institutional Meat Purchase Specifications item numbers for the subprimals used for steak cuts

Subprimal	IMPS[1] number
Beef round knuckle-cap off	167A
Beef eye of round	171C
Beef ribeye roll-lip on-boneless	112A
Beef chuck-shoulder clod-top blade	114D
Beef round-top inside	168
Beef loin-bottom sirloin butt-flap-boneless	185A
Beef loin-tops sirloin butt-boneless	184
Beef loin-bottom sirloin butt-tri-tip-boneless	185D
Beef loin-bottom sirloin butt-ball tip-boneless	185B
Beef plate-outside skirt	121C
Beef flank-flank steak	193

[1] IMPS = Institutional Meat Purchase Specifications.

Table 2a. Comparison of experimental safe cooking times and predicted safe cooking times of beef top round and knuckle steaks with uniform thickness (cm) and varying weights (g)

Round						
	Top round			Knuckle		
Thickness, cm	Weight, g	ESCT[1], min	PSCT[2], min	Weight, g	ESCT[1], min	PSCT[2], min
1.27	170	4.27 ± 0.90^{a}	4.10 ± 0.20	170	6.88 ± 0.68^{a}	6.76 ± 0.29
	227	5.23 ± 0.36^{a}	4.83 ± 0.16	198	8.21 ± 0.91^{a}	6.93 ± 0.11
	283	4.38 ± 0.53^{a}	5.75 ± 0.40	283	6.66 ± 0.86^{a}	7.93 ± 0.13
2.54	170	11.94 ± 0.69^{b}	11.15 ± 0.20	113	11.66 ± 0.44^{b}	11.82 ± 0.41
	227	12.33 ± 1.36^{b}	12.73 ± 0.58	170	15.16 ± 0.44^{b}	12.63 ± 0.65
	283	14.16 ± 3.92^{b}	13.48 ± 0.57	255	15.22 ± 1.07^{b}	13.80 ± 0.48
3.81	170	23.11 ± 0.67^{c}	16.93 ± 0.35			
	227	18.05 ± 0.51^{c}	17.01 ± 0.33			
	283	19.50 ± 0.33^{c}	18.02 ± 0.54			

$^{a–c}$Letters provide evidence of significant difference, where different letters represent statistical significance (P < 0.01) between ESCT values for a particular steak cut in the same column.

[1] ESCT = Experimental safe cooking time: cooking time (min) required by a steak to reach an internal temperature of 70 to 71 °C.

[2] PSCT = Predicted safe cooking time: cooking time (min) predicted by the model that would be required by a steak to reach an internal temperature of 70 to 71 °C. The values for ESCT and PSCT are expressed as the mean ± SD for 3 independent cooking experiments of a particular steak cut, with a given weight and thickness.

Table 2b. Comparison of experimental safe cooking times and predicted safe cooking times of beef top sirloin, sirloin cap, and tri-tip steaks with uniform thickness (cm) and varying weights (g)

Loin									
	Top sirloin			Sirloin cap			Tri-tip		
Thickness, cm	Weight, g	ESCT[1], min	PSCT[2], min	Weight, g	ESCT[1], min	PSCT[2], min	Weight, g	ESCT[1], min	PSCT[2], min
1.27	142	4.29 ± 0.09^{a}	4.03 ± 0.10	170	6.55 ± 0.54^{a}	6.16 ± 0.51	170	10.16 ± 0.93^{a}	8.95 ± 0.17
	283	6.43 ± 0.41^{a}	5.75 ± 0.22						
2.54	142	9.38 ± 0.25^{b}	12.38 ± 0.15				198	19.21 ± 0.87^{b}	17.49 ± 0.05
	170	12.60 ± 0.86^{b}	12.50 ± 0.26	198	13.72 ± 0.57^{b}	12.07 ± 0.51			
	198	11.49 ± 0.74^{b}	12.61 ± 0.02						
	255	11.5 ± 0.19^{b}	13.78 ± 0.11						
3.81	170	16.38 ± 0.95^{c}	16.38 ± 0.36	227	14.60 ± 0.69^{b}	16.99 ± 1.40		-	
	198	18.00 ± 0.35^{c}	17.45 ± 0.02						

$^{a–c}$Letters provide evidence of significant difference, where different letters represent statistical significance ($P < 0.01$) between ESCT values for a particular steak cut in the same column.

[1] ESCT = Experimental safe cooking time: cooking time (min) required by a steak to reach an internal temperature of 70 to 71°C.

[2] PSCT = Predicted safe cooking time: cooking time (min) predicted by the model that would be required by a steak to reach an internal temperature of 70 to 71°C. The values for ESCT and PSCT are expressed as the mean ± SD for three independent cooking experiments of a particular steak cut, with a given weight and thickness.

by McDonald and Sun (2001). Measurements for thickness were taken at 3 positions along the length of the steak cut (1 center and 2 edge positions) and averaged before statistical analysis. Length and width measurements were taken at 1 position around the major axis. The steaks were surface-dried using a filter paper (No. 1 Whatman filter, Millipore Sigma, Billerica, MA) and weighed using a digital balance (GX-32K, Grainger, Japan).

Experimental safe cooking times

Experimental safe cooking time (ESCT) was defined as the cooking time required by a steak to reach an internal temperature of 70 to 71°C. Steak cooking temperature was chosen based on the recommendations of USDA-FSIS guidelines for a well-cooked, mechanically tenderized steak (USDA-FSIS, 2015). The steaks were cooked using the method described by Obuz et al. (2004), on a flat-top grill (LG-36–1, Lang Manufacturing, Redmond, WA), with a cook surface area of 1.20 m^2 and preheated to 180°C. A copper constantan thermocouple, attached to a temperature data logger (length: 15.54 cm and diameter 0.125 cm; Omega RDXL4SD, Omega, Stamford, CT) was inserted into the probable geometrical center of the steak sample and temperature recorded every 10

s. Each steak was cooked individually until it reached an internal temperature of 70 to 71°C (American Meat Science Association, 2015; Luchansky et al., 2012; Gill et al., 2013) and flipped once after the first side reached an internal temperature of 35 to 40°C. The flat-top grill temperature was logged simultaneously to ensure that the grill temperature was maintained at 180 ± 3°C throughout the cooking experiment.

Table 2c. Comparison of experimental safe cooking times and predicted safe cooking times of beef ribeye steaks with uniform thickness (cm) and varying weights (g)

Rib			
Ribeye			
Thickness, cm	Weight, g	ESCT[1], min	PSCT[2], min
1.27	113	2.22 ± 0.69^{a}	4.62 ± 0.60
	170	4.27 ± 0.82^{a}	5.01 ± 0.12
	227	5.49 ± 1.08^{a}	5.36 ± 0.15
2.54	283	10.83 ± 0.33^{b}	16.22 ± 0.06
	340	15.50 ± 1.89^{b}	17.11 ± 0.29
3.81	397	19.50 ± 1.89^{c}	22.10 ± 0.97
	454	21.5 ± 1.45^{c}	23.61 ± 0.21

[a–c] Letters provide evidence of significant difference, where different letters represent statistical significance ($P < 0.01$) between ESCT values for a particular steak cut in the same column.

[1] ESCT = Experimental safe cooking time: cooking time (min) required by a steak to reach an internal temperature of 70 to 71°C.

[2] PSCT = Predicted safe cooking time: cooking time (min) predicted by the model that would be required by a steak to reach an internal temperature of 70 to 71°C. The values for ESCT and PSCT are expressed as the mean ± SD for three independent cooking experiments of a particular steak cut, with a given weight and thickness.

Rate of temperature increase

The rate of temperature increase (RTI), i.e., the rate at which the steak temperature increased with time, was calculated for each steak cut through linear fitting of the time-temperature profiles, obtained from the cooking experiments. The linear fit was statistically validated using regression coefficient (r^2), where a higher r^2 value (> 0.90) was considered the best fit. The following equation was used to obtain the RTI: $\mathbf{y = mx + c}$; where y = time (min), x = temperature (°C), m = rate of temperature increase (°C/min), and c = regression line intercept.

Model building

The model was built using correlation and regression analyses and checked using multicollinearity. Association between the steak parameters (length, width, thickness, and weight), RTI, and ESCT was examined through the Pearson's correlation statistics to identify the most influential factors for ESCT. The factors with a correlation coefficient (σ) of 0.60 or higher (at $P < 0.01$) were considered the primary predictors of interest or the prediction variables (Mason and Perreault, 1991). A relationship was then established between the prediction variables and ESCT, using stepwise regression, to develop a model equation that would provide predicted safe cooking times (PSCT).

Stepwise regression can be performed using any of the following 3 procedures: forward selection, backward elimination, or both (Stoneham et al., 2000). However, in this study, backward elimination was used where all

Table 2d. Comparison of experimental safe cooking times and predicted safe cooking times of beef strip loin, flap, and flanks steaks with uniform thickness (cm) and varying weights (g)

Strip loin				Flap			Flank		
Thickness, cm	Weight, g	ESCT[1], min	PSCT[2], min	Weight, g	ESCT[1], min	PSCT[2], min	Weight, g	ESCT[1], min	PSCT[2], min
1.27	113	5.00 ± 0.86^{a}	4.21 ± 0.32	113	11.22 ± 0.83^{a}	14.17 ± 0.65	170	15.99 ± 0.16^{a}	14.41 ± 0.33
	142	3.78 ± 1.10^{a}	4.41 ± 0.20	142	11.10 ± 0.95^{a}	14.33 ± 0.13	227	17.60 ± 0.10^{a}	15.63 ± 0.41
	170	5.77 ± 0.47^{a}	4.64 ± 0.03	170	18.10 ± 1.44^{b}	14.58 ± 0.11	283	18.22 ± 1.60^{a}	16.23 ± 0.13
				227	19.77 ± 0.50^{b}	15.82 ± 0.32	340	17.11 ± 0.25^{a}	16.57 ± 0.27
2.54	227	17.16 ± 0.57^{b}	19.92 ± 0.16	283	25.55 ± 0.60^{c}	20.98 ± 0.39			
	255	16.72 ± 2.21^{b}	20.31 ± 0.23						
	283	21.72 ± 1.54^{b}	20.31 ± 0.15						
3.81	340	26.10 ± 2.61^{c}	23.58 ± 0.17						
	394	25.46 ± 0.46^{c,d}	25.02 ± 0.54						
	454	27.06 ± 0.92^{c,d}	25.90 ± 0.25						
	567	30.11 ± 0.03^{d}	27.42 ± 0.76						

[a–d] Letters provide evidence of significant difference, where different letters represent statistical significance ($P < 0.01$) between ESCT values for a particular steak cut in the same column.

[1] ESCT = Experimental safe cooking time: cooking time (min) required by a steak to reach an internal temperature of 70 to 71°C.

[2] PSCT = Predicted safe cooking time: cooking time (min) predicted by the model that would be required by a steak to reach an internal temperature of 70 to 71°C. The values for ESCT and PSCT are expressed as the mean ± SD for three independent cooking experiments of a particular steak cut, with a given weight and thickness.

the prediction variables were initially included in the regression model equation, followed by the elimination of those that did not contribute to the accuracy of the prediction model. To further increase the accuracy of the model, the squared values of prediction variables were also included and those that did not contribute to the accuracy ($P < 0.01$) were eliminated (Stoneham et al., 2000). This resulted in a final model containing variables that significantly contributed to the prediction accuracy. For a given number of observations (n), the regression model equation was represented as:

$$\mathbf{y_i = \beta_0 + \beta_1 x_{i1} + \beta_2 (x_{i1})^2 + \beta_3 (x_{i2}) + \beta_4 (x_{i2})^2 + \beta_5 x_{i3} + \beta_6 (x_{i3})^2 + \beta_7 x_{i4} + \beta_8 (x_{i4})^2 + \beta_9 x_{i5} + \beta_{10} (x_{i5})^2;}$$

where y = predicted safe cooking time (min); i = 1, 2,.... n; (*n* = number of observations), β_{0-} β_{10} = regression line coefficients, and xi = prediction variable [x1: steak thickness (cm), x2: steak weight (g), x3: steak length (cm), x4: steak width (cm), x5: RTI].

To ensure that there was no inter-correlation between the prediction variables, which could result in false elevation of prediction accuracy, a multicollinearity check was performed using the variance inflation factor (Tu et al., 2005). A prediction variable with a variance inflation factor of less than 10 was considered to have no multicollinearity (Tu et al., 2005).

Prediction model assumptions

Precision and consistency were maintained throughout the experiments. The assumptions made by Obuz et al. (2004), for predicting cooking temperatures of beef muscle types, were followed in this study. The steak cuts were considered to be homogenous and rectangular in shape, and thermal conductivity of the grill surface was considered to be constant throughout the cooking process.

Statistical analysis

Each experiment, where the experimental unit was an individual steak cut of a given weight and thickness, was repeated 3 times. The ESCT was used to determine PSCT and both were expressed as the mean ± standard deviation of the replicate values. Data were analyzed using one-way analysis of variance, where the Tukey-Kramer-honest significant difference test was used to obtain the means of ESCT for a given steak cut of a particular thickness and weight. Significant differences ($P < 0.01$) among means were determined using PROC GLM. Correlation and model building was performed using PROC CORR and PROC REG at $P < 0.01$. All the analyses were performed using SAS v9.3 (SAS Inst. Inc., Cary, NC).

Results and Discussion

Experimental safe cooking times

The ESCT for each steak cut, of a given weight and thickness, are presented in Tables 2a-d. Results revealed that the thickness of steaks was a significant factor ($P = 0.01$) influencing ESCT of a particular steak cut. These results are similar to those obtained by Gill et al. (2013) and Dunn et al. (2000), where the cooking times for different steak cuts were dependent on the thickness of the steak. However, in the current study, certain steak cuts (strip loin and flap) with the same thickness, but varying weights, showed significant differences ($P < 0.01$) in their ESCT (Table 2d). For example, a strip loin of 2.54 cm thickness, with a weight of 227 g and 340 g, exhibited an ESCT of 17 and 26 min, respectively. This indicates that in addition to thickness, the weight of the steak could also influence ESCT. In studies by Otto et al. (2004) and Christensen (2003), increase in the weight of the meat was found to be directly related to increase in cooking loss. Furthermore, Rincon et al. (2015) showed that the drip loss of cooked beef steaks was inversely related to heat transmission. In the current study, a greater steak weight could have led to an increased drip loss, thereby lowering heat transmission and increasing ESCT. Additionally, Obuz et al. (2014) and Rincon et al. (2015) noted increased drip loss in mechanically tenderized steaks because mechanical tenderization could disrupt and open up the muscle structure, allowing moisture to escape from the interior of the meat more easily.

Rate of temperature increase

The RTI was determined through linear fitting of the time-temperature profiles, obtained from the cooking experiments (Fig. 1a-i), and the best fit criterion was set at a regression coefficient (r^2) of 0.9 or higher. For all the steak cuts, there was a significant difference in RTI due to the thickness of the steak. The difference in RTI is in agreement with previous studies done in other meat products such as patties and bologna (Houšová and Topinka, 1985; Mangalassary et al., 2004), where the thickness of the product led to a decrease in RTI. Mangalassary et al. (2004) also suggested that marbling (intramuscular fat content) and moisture movement could significantly contribute to lower RTI in thicker meat products. Marbling in meat adds to the insulating effect (Woodams and Nowrey, 1968; Mangalassary et al., 2004) while moisture movement results in a decrease in heat transfer, causing a delay in temperature increase, thereby decreasing RTI (Ikediala et al., 1996; Shilton, Mallikarjunan, and Sheridan, 2002).

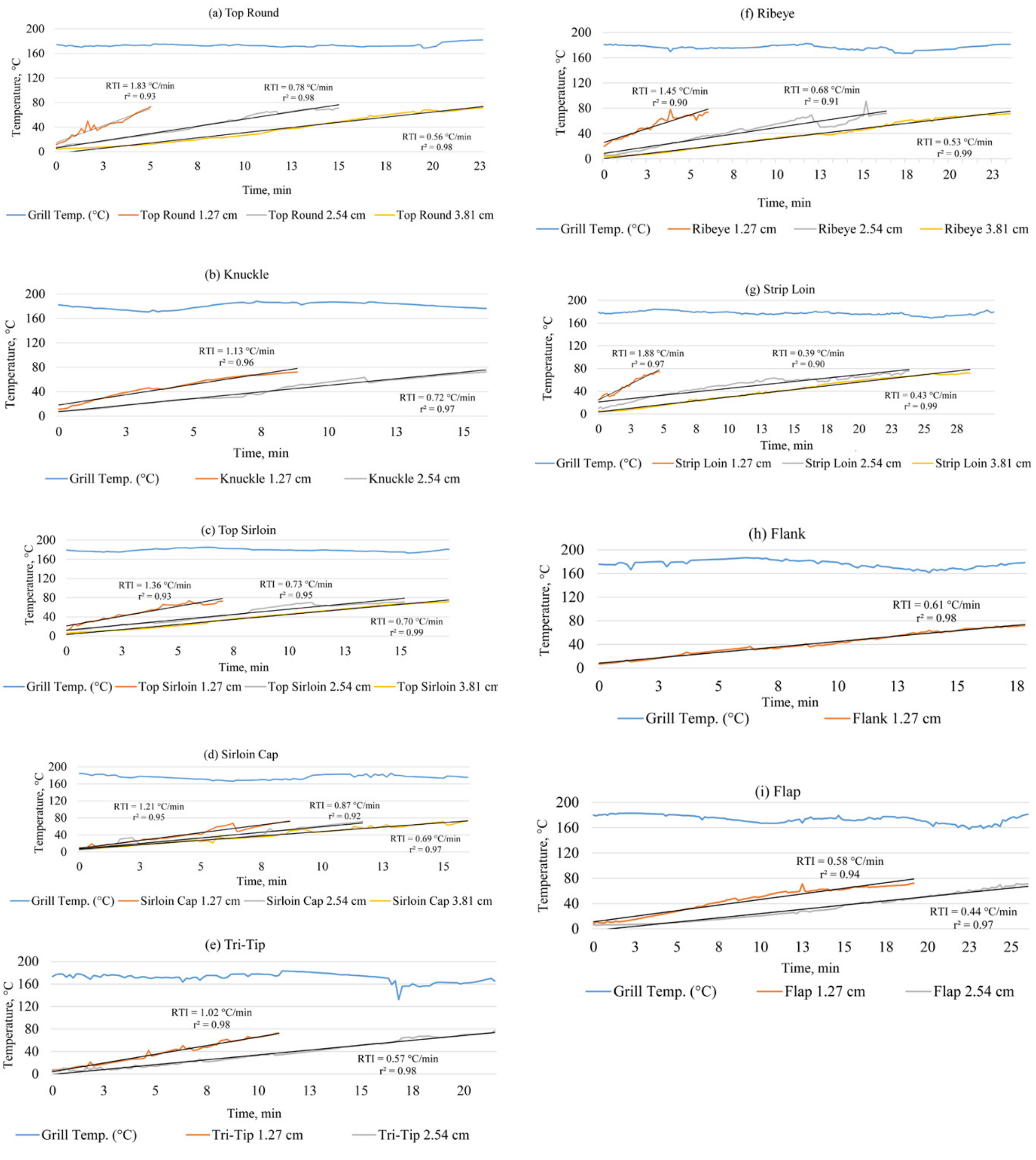

Figure 1. a-b. Rate of temperature increase (°C/min) during cooking of beef (a) top round and (b) knuckle steaks of varying thickness (cm). c-e Rate of temperature increase (°C/min) during cooking of beef (c) top sirloin, (d) sirloin cap and (e) tri-tip steaks of varying thickness (cm). f. Rate of temperature increase (°C/min) during cooking of beef (f) ribeye steaks of varying thickness (cm). g–i. Rate of temperature increase (°C/min) during cooking of beef (g) strip loin, (h) flank and (i) flap steaks of varying thickness (cm).

Prediction model

The results of correlation analyses are shown in Table 3. Results indicated that the thickness, weight, and RTI of the steaks were highly correlated with the ESCT. The length and width of the steaks were found to have no significant correlation with ESCT at $P < 0.01$. Significant prediction variables (weight, thickness, and RTI) and their squared values, identified through correlation, were included in the regression model. The model was found to have a prediction accuracy of 79% (r^2

Table 3. Selection of variables, to be included in the prediction model, based on correlation coefficient between the steak variables and the experimental safe cooking times

Steak variables	Correlation coefficient[1]	95% Confidence interval[2]	*P*-value
Weight	+0.61	0.49 – 0.69	0.0001
Length	-0.07	-0.22 – 0.84	0.3700
Width	-0.18	-0.33 – (-0.03)	0.0200
Thickness	+0.68	0.59 – 0.75	0.0001
RTI[3]	-0.78	-0.83 – (-0.71)	0.0001

[1] Correlation was checked between steak parameters and ESCT ($P < 0.01$) to determine the variables to be included in the final prediction model; (+) and (-) signs before correlation coefficient values indicate positive and negative correlation with ESCT, respectively.

[2] Confidence interval for each correlation coefficient indicates that 95% of the coefficient values will be included in that range.

[3] RTI = Rate of temperature increase (°C/min): the rate at which the steak temperature increased with time while cooking.

~ 0.79). Removal of the squared values of weight and thickness from the model did not result in a change in prediction accuracy. However, it was found that removal of the squared value of RTI reduced the prediction accuracy from 79 to 74% and also reduced the significance of the overall model. The squared value of RTI was therefore included in the final prediction model. The final model is represented in the following equation:

$$\text{PSCT} = 23.03 + 0.014 \times \text{Weight} + 1.34 \times \text{Thickness} + (-25.62) \times \text{RTI} + 7.52 \times (\text{RTI})^2$$

A regression coefficient (r^2) of 0.79 indicated that the model explained 79% of the variation in PSCT for different steak cuts ($P < 0.01$). In the present study, the prediction variables in the final model had variance inflation factor values ranging from 1.33 to 1.87, far less than the threshold value of 10, which assured that the variables were highly independent of each other, providing true value for prediction accuracy. These results are comparable with the previously studied cooking time prediction model, for beef round and top loin (Obuz et al., 2004), where high r^2 values (0.98) indicated that regression equations could be successfully used to predict cooking times and temperature profiles of these steak cuts.

Experimental versus predicted safe cooking time

The relationship between PSCT and ESCT is illustrated in Fig. 2. A high positive linear relationship was found between the predicted and the experimental values ($P = 0.001$). The model predicted safe cooking times for each steak cut with 79% accuracy. The difference between the PSCT and ESCT values ranged between -5.39 to 6 min, where 37% of PSCT values were either equal to or higher than the ESCT (Tables 2a-d). However, some PSCT values were underpredicted and the difference ranged between 0.22 to 6 min, where only 4 steak cuts (flap and top-round) showed a difference of 3.52, 3.95, 4.57, and 6 min between the ESCT and PSCT values (Tables 2a and 2d). These differences could be due to the limited number

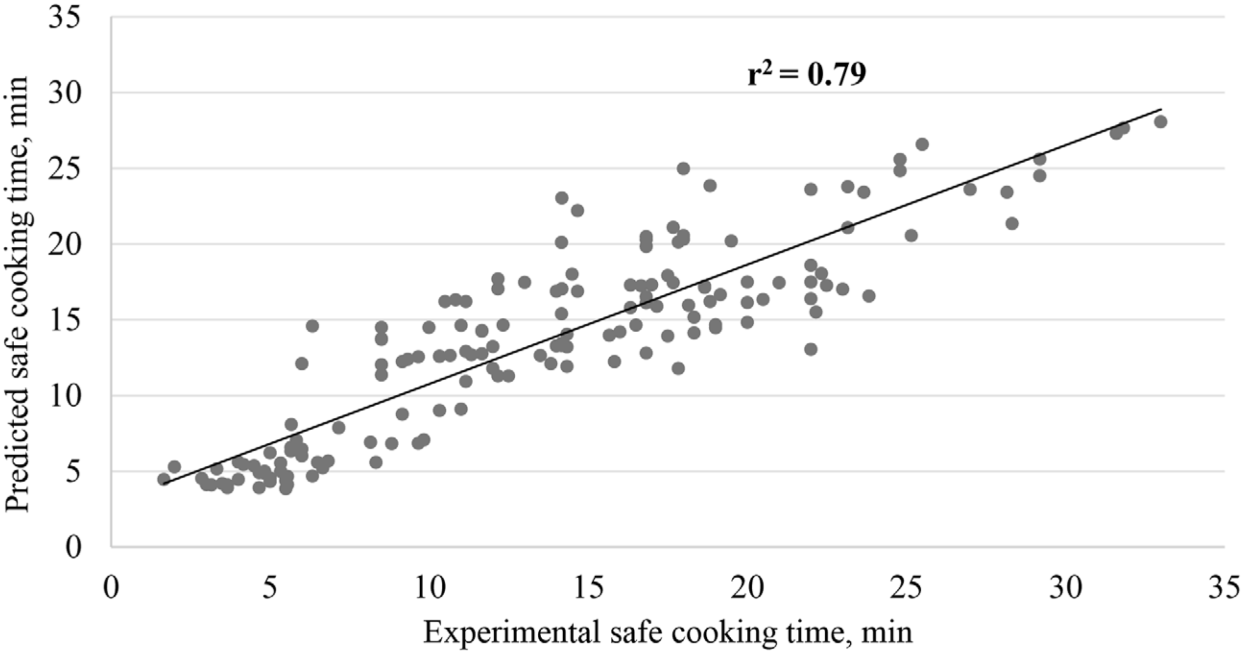

Figure 2. Linear relationship between experimental and predicted safe cooking times for different steak cuts, indicated by regression coefficient (r^2).

of variables (thickness, weight, and RTI) used to develop the prediction model. Although the model predicted safe cooking times for each steak cut with 79% accuracy, it could be further increased in future with studies that include more variables, such as collagen, intramuscular fat, and moisture content, that could influence ESCT.

Conclusions

Experimental safe cooking times and RTI were found to be dependent on the thickness and type of steak cuts. However, for model building, correlation analyses revealed that the thickness, weight and RTI were highly correlated with ESCT. Furthermore, variance inflation factor showed that these factors were not inter-correlated which prevented the false elevation of model accuracy. The regression model built with these factors was robust in predicting cooking time to attain a safe internal temperature for various steak cuts. Overall, no significant differences ($P < 0.01$) were observed between the ESCT and PSCT. However, the model accuracy of 79% may have led to some differences in values obtained for PSCT when compared to ESCT. The inclusion of more data and factors affecting cooking time would help elevate model accuracy and minimize differences between the PSCT and ESCT. This study could help the meat industry formulate safe cooking times of various steak cuts inexpensively, without repeating costly validation studies. It would also benefit the small- and mid-sized processors/retailers in generating instant labels. This application could improve beef safety, which would build consumer confidence in mechanically tenderized beef products, ultimately benefiting the meat industry.

Conflict of Interest

The authors declare that there is no conflict of interest.

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