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Endpoint Temperature and Tenderness Variability in Pork and Beef Cooked Using Sous-Vide Style Immersion Heaters and Grills

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Abstract: The objective was to determine endpoint temperature and Warner-Bratzler shear force (WBSF) variability (range, coefficient of variation) differences in both pork and beef cooked using grilling and sous vide. Four 2.54-cm steaks were cut from 10 beef eye-of-round (*semitendinosus*) Choice-grade muscles ($n = 40$) and aged for 21 d. Four 2.54-cm chops were cut from 51 pork loins ($n = 204$) sourced from standard commercial pigs and aged for 7 d. Steaks and chops were randomly allotted within whole muscle to 4 treatments: grilled to 63°C, sous vide to 63°C, grilled to 71°C, and sous vide to 71°C. Four cores measuring 1.25 cm in diameter were excised parallel to the muscle fibers of each chop and steak respectively, and analyzed for WBSF. Temperature accuracy was defined as how close thermometer readings were to the targeted cooked temperature. Temperature precision was defined as how similar 2 thermometer readings within a single cut were to each other. WBSF accuracy was defined as how close individual core values were to the cut average. WBSF precision was defined as how similar individual core values were to each other. In both pork and beef, sous vide was more accurate ($P < 0.01$) and precise ($P < 0.01$) in achieving target endpoint temperature at both 63°C and 71°C. At 63°C, chops cooked using sous vide were more tender than grilled ($P < 0.01$), but at 71°C, chops cooked using sous vide were less tender than grilled ($P < 0.01$). Steaks cooked to 71°C using sous vide had the lowest core coefficient of variation, whereas other treatments were not different. Cooking method had no effect on average WBSF within target endpoint temperature. Overall, these data indicate that sous vide is more precise and accurate in reaching target temperature but may decrease tenderness when used at 71°C in pork.

Key words: beef, endpoint temperature, grilling, pork, sous vide, variability
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Introduction

Sous-vide cooking, in combination with pre- or post-searing, is gaining popularity in both restaurant and household settings (Baldwin, 2012). Beginning as a method to extend the shelf life of minimally processed foods (Baldwin, 2012), sous vide is expanding into other uses because of its anecdotally superior temperature control and reproducibility. In sous-vide cooking, a water bath is held at a constant desired endpoint temperature and packaged food is submerged in this water. Therefore, food can be cooked and held at a desired temperature without fear of overcooking, unlike with other techniques such as grilling or baking. However, the use of sous-vide cooking in meat quality research has been limited.

Grilling is the most common cooking method used in meat quality research, both for its relatively short cooking time and inexpensiveness when used repeatedly (Kerth et al., 2003). However, even when executed properly, grilling can be imprecise and lead to variability in endpoint cooking temperature and a lack of repeatability (Berry and Dikeman, 1994; Wheeler et al., 1998; Lawrence et al., 2001; Yancey et al., 2011). This may be due to a variety of factors associated with open-hearth grilling. When grilling with temperature monitoring, a thermometer must be inserted into the exact center of the meat to provide an accurate reading of internal temperature (AMSA, 2016). This can be challenging depending on the cut of meat, the thermocouple or thermometer used, and placement of samples on the grill. Additionally, meat can be heated unevenly on a grill. Cuts are only cooked one side at a time and must be flipped to evenly cook both sides. Grills can have hot and cold spots, resulting in uneven heating of the cut lengthwise. Grilling also requires attentive observation to prevent overcooking. Uneven cooking may generate temperature variation within a particular cut or between cuts within an experiment and could contribute to variation in cooked meat quality properties like tenderness, in which endpoint cooking temperature is influential (Rincker et al., 2008; Moeller et al., 2010a, 2010b; Klehm et al., 2018).

Conceptually, sous-vide cooking minimizes these sources of variation. No thermocouple is required during cooking, meat is heated evenly through all sides at once, and meat cannot exceed the set water temperature regardless of cooking time. These conceptual advantages would indicate that sous-vide cooking may be useful in research applications. Although water baths have been used in meat science research previously (Channon et al., 2003; Ngapo, et al., 2012; Jose et al., 2013; Channon et al., 2014, 2016), validation of sous vide as a cooking method in the context of meat science research is limited (Bryan et al., 2019). Therefore, the objective of this study was to evaluate differences in the variation of endpoint temperature and tenderness in pork chops and beef steaks cooked to different degrees of doneness using sous-vide and open-hearth electric grilling.

Materials and Methods

Experimental design

Pork loins (51 total, North American Meat Processors #410) were sourced from the University of Illinois Meat Science Laboratory (Urbana, IL) at approximately 1 d postmortem. Beginning at the area of the 10th rib and working posteriorly, 4 boneless, 2.54-cm-thick chops were cut from each loin for a total of 204 chops. Chops were vacuum packaged and allowed to age at 4°C for 7 additional days. After aging, chops were frozen at −20°C until further analysis. Beef eye-of-round (10 total, North American Meat Processors #171C) muscles were obtained from an outside vendor at approximately 14 d postmortem. Beginning in the center of the muscle and working distally, four 2.54-cm-thick steaks were cut for a total of 40 steaks. Steaks were vacuum packaged and allowed to age at 4°C for 21 additional days, then frozen at −20°C until further analysis. Steaks and chops were randomly allotted within whole muscle to 1 of 4 treatments: grilled to 63°C, sous vide to 63°C, grilled to 71°C, or sous vide to 71°C. The term "cuts" will be used when referencing both pork chops and beef steaks.

Endpoint temperature and cook loss

For pork chops, all chops originating from the same loin were cooked on the same day. Cooking of pork chops took place over 7 d (approximately 8 loins per day). All steaks were cooked on a single day. Chops and steaks were allowed to thaw at 4°C for a minimum of 12 h prior to cooking and then removed from packages and weighed for an initial raw weight.

Cuts allotted to sous vide were vacuum packaged again prior to cooking. The nonforming side of the packaging was 356 mm thick with a 3-mil absolute pressure gauge, and the forming side was 363 mm thick with a 7-mil absolute pressure gauge (Schmidt Equipment and Supply, St. Louis, MO). Two 22-L plastic containers were filled with approximately 18 L of hot (approximately 47°C) water. Each tub was fitted with an Anova precision immersion cooker (Anova Applied Electronics, Inc., San Francisco, CA) set to either 63°C or 71°C. Once the water reached the set temperature, the cuts were placed in their assigned tub and cooked for 90 min, similar to Bryan et al. (2019). No more than 10 chops or steaks were cooked at any one time.

For cuts allotted to grilling, a thermocouple (Type T, Omega Engineering, Norwalk, CT) connected to a digital scanning thermometer (model 92000-00, Barnant Co., Barrington, IL) was placed in the geometric center of each cut prior to cooking to allow real-time monitoring of internal temperature. Grilled cuts were placed on a Farberware open-hearth grill that was preheated for a minimum of 10 min to a grate temperature between 163°C and 197°C (model 455N, Walter Kidde, Bronx, NY). When the internal temperature reached approximately half of the target endpoint temperature (63°C or 71°C), cuts were flipped to their other side. When the target endpoint temperature was reached (approximately 20 min cook time), cuts were removed from the grill.

For both cooking methods, immediately after the completion of cooking, 2 handheld thermometers (Javelin handheld thermometer, Lavatools, Los Angeles, CA) were placed in the medial and lateral ends of the cuts to determine actual final temperature. Therefore, grilled cuts had 3 recorded temperatures: center (while cooking) and medial and lateral (post cooking). Sous-vide cuts had 2 recorded temperatures: medial and lateral (post cooking). The highest temperature observed on the each of the thermometers was recorded as the final cooked temperature for that location. Chops and steaks were then allowed to cool at ambient temperature (25°C) to approximately 22°C before being weighed to obtain cooked weight. Cook loss was calculated using the following equation:

$$\text{Cook loss,\%} = ([\text{Initial weight,g} - \text{Cooked weight,g}]/\text{Initial weight,g}) \times 100$$

Warner-Bratzler shear force

After cuts were cooled, 4 cores measuring 1.25 cm in diameter were removed parallel to the orientation of the muscle fibers. Cores were sheared using a Texture Analyzer TA.HD*Plus* (Texture Technologies Corp., Hamilton, MA/Stable Micro Systems, Godalming, UK) with a blade speed of 3.33 mm/s and a load cell capacity of 100 kg. AMSA sensory guidelines for Warner-Bratzler shear force (WBSF) were followed (AMSA, 2016). Peak values from each core were recorded.

Calculations and statistical analysis

A power analysis prior to the experiment was conducted to determine the number of samples needed to detect a 0.5 kg difference in WBSF. Parameters for the test included an alpha of 0.05, standard deviation based on prior literature of 0.369, and a power of 0.80. Such analysis indicated that 10 samples per treatment were required to detect this difference. A post hoc power analysis using the same parameters and given the standard deviation of the present experiment for beef (standard deviation of 0.17) and pork (standard deviation of 0.10) indicates that an effect size (difference) of 0.225 and 0.081 kg was detectable for beef and pork, respectively.

Several calculations were made from the endpoint temperature values obtained from the 2 handheld thermometers used on the medial and lateral sides of the cuts (Table 1). The average final cooked temperature was the average of the medial and lateral temperature measurements. To determine precision of temperature, the difference between these 2 values (temperature range) was calculated. To determine temperature accuracy, the difference between the average cooked temperature and the target cooked temperature (63°C or 71°C) was used. Similarly, calculations were made with the individual WBSF values of the cores. These values were averaged and reported as average WBSF. The difference between the highest and lowest core values for a particular chop or steak was reported as WBSF range. Finally, the coefficient of variation (CV) of WBSF core values was calculated as the standard deviation divided by the average WBSF value.

Beef and pork data were analyzed separately. Data were analyzed using the MIXED procedure in SAS (9.4, SAS Institute Inc., Cary, NC) as a 2-way analysis of variance with the main effects of cooking method, target endpoint temperature, and their interaction. Whole muscle and cooking day (for pork only) were included as random variables. Normality of residuals was tested using the UNIVARIATE procedure. Homogeneity of variances was tested using the GLM procedure. Least-squares means were separated using

Table 1. Variable abbreviations and definitions

Variable	Definition
Temperature Variables	
Cooked temperature 1	Final endpoint temperature from probe #1 (TEMP1)
Cooked temperature 2	Final endpoint temperature from probe #2 (TEMP2)
Average cooked temperature	(TEMP1 + TEMP2) / 2
Temperature range	|TEMP1 – TEMP2|
Temperature accuracy	Average temperature – Target temperature
Tenderness Variables	
Average WBSF	Peak values of all cores averaged
Maximum WBSF core	Highest peak value recorded for a particular chop
Minimum WBSF core	Lowest peak value recorded for a particular chop
WBSF range	WBSF maximum – WBSF minimum
WBSF CV	Coefficient of variation of WBSF core values

CV = coefficient of variation; WBSF = Warner-Bratzler shear force.

the probability of difference (PDIFF) option in the MIXED procedure of SAS. Means were considered significantly different at $P \leq 0.05$.

Results

Endpoint temperature variability

Pork. The 2 cooked temperatures obtained using handheld thermometers from each cut are displayed in Figure 1 with a graphical depiction of the target endpoint temperature (±2°C) for each cut and temperature combination. The value of ±2°C was chosen because this was the tolerance reported by the manufacturer. Cuts that fell within this range were considered accurately cooked to their target endpoint temperature. Of chops cooked to 63°C, 98% of those cooked using sous vide fell within this range, whereas only 4% of grilled chops did. When cooked to 71°C, 98% of sous-vide chops were within range, whereas only 2% of grilled chops were within range. However, the average endpoint cooked temperature (Table 2) of each treatment fell within the arbitrary ±2°C range specified. Average cooked temperature was affected by cooking method, target temperature, and their interaction. In pork chops cooked to a target of 63°C, average cooked temperature was greater ($P < 0.05$) for grilled chops (64.85°C) compared with sous-vide chops (62.08°C). However, for pork chops cooked to 71°C, average cooked temperature did not differ between methods. Target temperature did not affect the accuracy or precision of cooked temperature for pork chops. Precision and accuracy of cooked temperature were improved with sous-vide cooking. Temperature range was reduced ($P < 0.05$) by over 3.8°C in sous-vide cooked chops compared with grilled chops. Temperature accuracy was improved ($P < 0.05$) by approximately 7.5°C in sous-vide cooked chops compared with grilled chops (Table 2).

Beef. For steaks cooked to 63°C, 100% of sous-vide steaks fell within the target range of ±2°C, whereas only 30% of grilled steaks were considered accurate (Figure 1). When cooked to 71°C, again, 100% of sous-vide steaks were accurate, whereas 0% of grilled steaks fell within the ±2°C range. However, both grilled and sous-vide cooking to 63°C resulted in average cooked temperature within this ±2°C. However, at 71°C, only the average of sous-vide cooked steaks fell within this range. Average cooked temperature did not differ between methods ($P = 0.12$). In contrast to pork

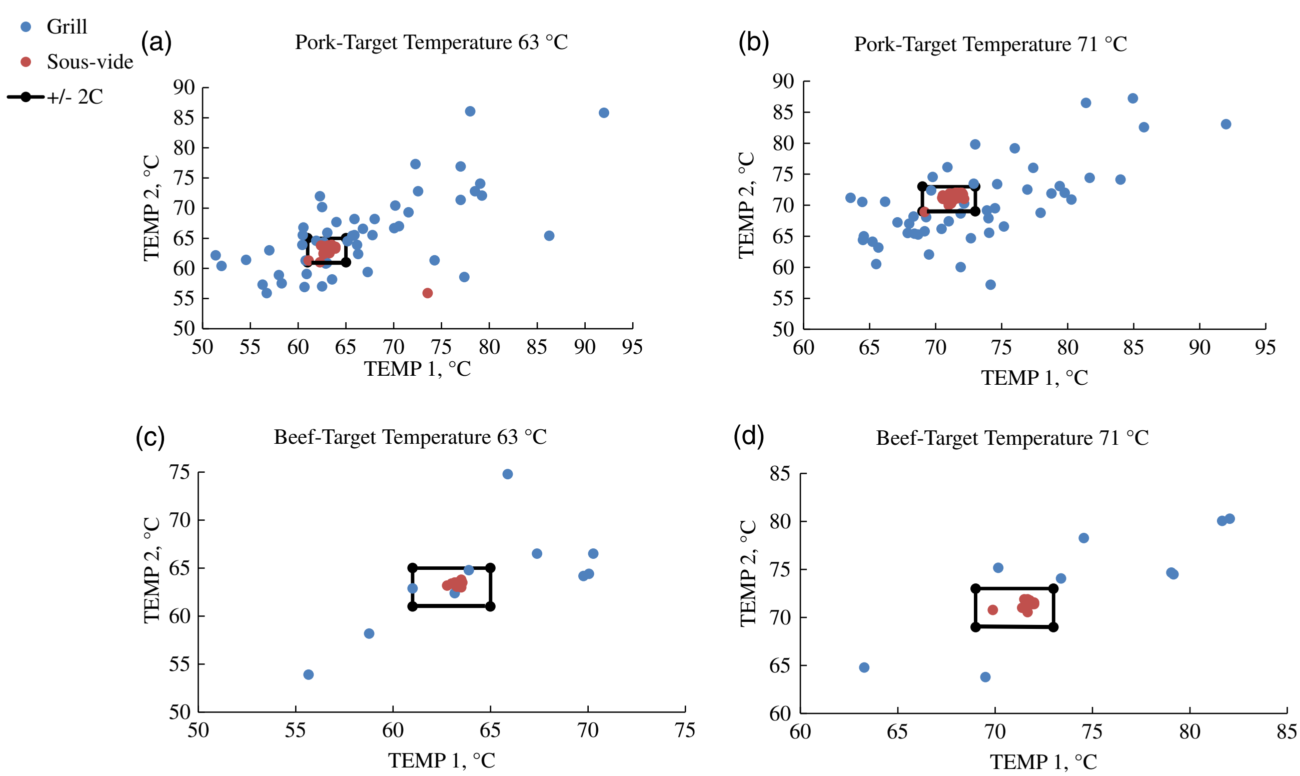

Figure 1. Effect of cooking method on the accuracy of actual endpoint temperature in (A) pork loin chops targeting 63°C, (B) pork loin chops targeting 71°C, (C) beef *semitendinosus* steaks targeting 63°C, and (D) beef *semitendinosus* steaks targeting 71°C. Box indicates ±2°C of the target temperature along both the *x* and *y* axis. TEMP 1 = Final endpoint temperature from probe #1. TEMP 2 = Final endpoint temperature from probe #2.

Table 2. Effect of cooking method and target endpoint temperature on endpoint temperature precision and accuracy in pork loin chops and beef *semitendinosus* steaks

	63°C		71°C			*P* Values		
	Grill	Sous vide	Grill	Sous vide	SEM	Method	Temperature	Method × Temperature
Pork Chops[1], ***n***	51	51	51	51				
Average cooked temperature, °C	64.85[a]	62.08[b]	70.41[c]	70.20[c]	0.87	0.02	< 0.01	0.04
Temperature range[2], °C	4.05[a]	0.23[b]	4.16[a]	0.21[b]	0.55	< 0.01	0.88	0.91
Temperature accuracy[3], °C	9.46[a]	1.57[b]	8.90[a]	1.69[b]	1.43	< 0.01	0.84	0.76
Beef Steaks[1], ***n***	10	10	10	10				
Average cooked temperature, °C	64.22[a]	63.32[a]	74.29[b]	71.46[b]	1.16	0.12	< 0.01	0.41
Temperature range[2], °C	3.08[a]	0.26[b]	2.97[a]	0.48[b]	0.54	< 0.01	0.92	0.76
Temperature accuracy[3], °C	4.04[a]	0.34[b]	5.64[a]	0.64[b]	0.60	< 0.01	0.12	0.28

[1]Least-squares means in the same row containing differing superscripts are statistically different ($P < 0.05$).

[2]Mean difference between 2 measurements of endpoint temperature made in each chop.

[3]Mean difference between average cooked temperature and target temperature.

chops, the interaction of target temperature and cooking method was not significant for average cooking temperature ($P = 0.41$). However, similar to pork, precision and accuracy of cooked temperature were improved with sous-vide cooking at both target temperatures. Temperature range was reduced ($P < 0.01$) by at least 2.5°C in sous-vide steaks compared with grilled steaks. Temperature accuracy was improved ($P < 0.01$) by at least 3.7°C in sous-vide steaks compared with grilled steaks. Targeted temperature did not affect the accuracy or precision of cooked temperature for beef steaks (Table 2).

Warner-Bratzler shear force and cook loss

Pork. Average WBSF was affected ($P < 0.01$) by target temperature and the interaction of cooking method and target temperature. In pork chops cooked to 63°C, sous-vide chops required 0.29 kg less force ($P < 0.01$) to shear than grilled chops (Table 3). Conversely, sous-vide chops required 0.57 kg more force ($P < 0.01$) than grilled chops when cooked to 71°C. Overall, chops targeting 71°C required more force ($P < 0.01$) to shear than those targeting 63°C, regardless of cooking method. Shear force value variability was measured in 2 ways: (1) the range between the greatest and least WBSF values and (2) the CV of the 4 individual core values. Although WBSF range was not affected by cooking method, it was increased by 0.18 kg in chops cooked to 71°C compared with those cooked to 63°C ($P = 0.04$). However, CV of WBSF core values was unaffected by both temperature and method. Cook loss was affected ($P < 0.01$) by cooking method, target temperature, and their interaction. Chops cooked to 63°C did not differ ($P > 0.05$) in cook loss between cooking methods. However, in chops targeting 71°C, sous-vide chops cook loss was increased by 7.03 units ($P < 0.01$) compared with grilled chops (Table 3). Overall, cook loss was increased ($P < 0.05$) at 71°C compared with 63°C.

Beef. Average WBSF values did not differ ($P \geq 0.49$) between cooking methods at either target endpoint temperature in beef steaks (Table 3). Within a steak, WBSF range was affected by temperature ($P < 0.01$) and tended to be reduced ($P = 0.10$) in sous-vide steaks compared with grilled steaks. On average, WBSF range of cores was greater ($P = 0.01$) for steaks cooked to 63°C than 71°C (2.50 vs. 1.66 kg). CV of WBSF cores was affected by method ($P = 0.03$) and temperature ($P < 0.01$). Among steaks cooked to 63°C, CV did not differ between methods. In steaks cooked to 71°C, sous vide reduced the CV of WBSF cores compared with grilling. Cook loss was affected ($P < 0.01$) by both cooking method and endpoint temperature. In steaks cooked using sous vide, cook loss was increased by 4.76 and 7.36 units ($P < 0.01$) compared with grilled steaks when cooked targeting 63°C and 71°C, respectively (Table 3).

Discussion

The principal assertion made by sous-vide advocates is that food cannot be overcooked. Because of this feature, sous-vide cooking should theoretically reduce the variability within a group of cuts cooked to the same target temperature. Although this is an enticing concept for meat science researchers, there is little objective evidence to support or refute this claim (Baldwin, 2012). One of the objectives of this study was to investigate the effect of cooking method on cooked temperature accuracy and precision around 2 target temperatures.

Table 3. Effect of cooking method and target endpoint temperature on WBSF and cook loss in pork loin chops and beef *semitendinosus* steaks

	63°C		71°C			*P* Values		
	Grill	Sous vide	Grill	Sous vide	SEM	Method	Temperature	Method × Temperature
Pork Chops[1], *n*	51	51	51	51				
Average WBSF, kg	2.97[a]	2.68[b]	3.10[c]	3.67[d]	0.10	0.06	< 0.01	< 0.01
WBSF range[2], kg	1.51[ab]	1.40[a]	1.55[ab]	1.72[b]	0.13	0.77	0.04	0.12
WBSF CV	18.63	18.55	18.55	18.34	0.01	0.88	0.88	0.95
Cook loss, %	17.37[a]	18.20[a]	21.30[b]	28.33[c]	0.58	< 0.01	< 0.01	< 0.01
Beef Steaks[1], *n*	10	10	10	10				
Average WBSF, kg	3.47	3.5	3.59	3.8	0.17	0.49	0.22	0.60
WBSF range[2], kg	2.67[a]	2.33[a]	1.98[ab]	1.34[b]	0.29	0.10	0.01	0.60
WBSF CV	28.24[a]	24.36[a]	21.19[a]	13.53[b]	0.02	0.03	< 0.01	0.45
Cook loss, %	25.69[a]	30.45[b]	31.36[b]	38.72[c]	0.81	< 0.01	< 0.01	0.12

[1]LS means in the same row containing differing superscripts are statistically different ($P < 0.05$).

[2]Difference between WBSF maximum and minimum value within a cut.

CV = coefficient of variation; LS = least-squares; WBSF = Warner-Bratzler shear force.

Our hypothesis was that sous-vide cooking would lead to increased precision and accuracy of cooked temperature. At both 63°C and 71°C, sous-vide chops and steaks had improved cooked temperature precision and accuracy compared with grilled cuts. Additionally, a greater proportion of cuts achieved the target temperature when cooked by sous vide compared with grilled (in pork, 98% compared with 3%; in beef, 100% compared with 15%, on average). These data support the prior assertions that sous-vide cooking results in greater temperature control (Baldwin, 2012).

Differences in target cooked temperatures result in differences in tenderness, with elevated internal temperatures resulting in greater WBSF values in both beef and pork (Rincker et al., 2008; Lucherk et al., 2016; Klehm et al., 2018; Drey et al., 2019). In the present study, increasing the target temperature 8°C (from 63°C to 71°C) resulted in an average 0.56-kg increase in WBSF value in pork. The second objective of the study was to determine whether improved accuracy and precision of cooked temperature affected WBSF values and variability. It was hypothesized that increased temperature variability would result in increased WBSF variability, as measured by WBSF range and CV. However, WBSF range was not different between methods in both pork and beef, meaning that tenderness varied similarly between cuts cooked to the same internal cooking temperature. In pork, sous-vide cooking had reduced temperature variability but not reduced WBSF range or CV when compared with grilling. In beef, the CV of WBSF cores was reduced in sous vide compared with grilling overall but not to the same magnitude to which temperature range was reduced. The average temperature range was reduced 88% in sous-vide steaks when compared with grilling, whereas the CV of WBSF cores was only reduced 24%. This is not to say that variation was not observed within chops or steaks, only that this variation did not differ between cooking methods. These results suggest that variation in temperature within a cut does not elicit a meaningful difference in the range of WBSF values within a cut.

Variability in WBSF within a single chop or steak has been reported previously. In pork loin chops cooked to 82°C using an electric oven, the range of slice tenderness values within a chop was approximately 0.44 kg (Alsmeyer et al., 1965a), whereas others who pan-fried pork loin chops to 65°C reported a range in WBSF values of up to approximately 0.41 kg within a chop (Hansen et al., 2004). These are less than the ranges of core values reported in the current study, which were on average 1.46 kg for chops targeting 63°C and 1.64 kg for chops targeting 71°C. In beef loin steaks cooked to 60°C, the range of WBSF values within a steak was approximately 0.27 kg (Alsmeyer et al., 1965b), whereas others who cooked strip loin steaks to 71°C in a convection oven reported a range of WBSF values within a steak of approximately 3.01 kg (Zuckerman et al., 2002). The current study was between these 2 levels of variation, with WBSF core values ranging, on average, between 2.50 kg in steaks targeting 63°C and 1.66 kg in steaks targeting 71°C.

Additionally, WBSF can vary between cuts taken from the same muscle in both beef (0.58 kg range in WBSF) and pork (0.37 kg range in WBSF) (Derington et al., 2011; Redifer et al., 2020). In this study, cuts originating from a single primal cut from an animal were randomly allotted to each treatment. Thus, variation in WBSF between 2 cuts from the same whole muscle may also contribute to the differences between cooking methods within a single muscle. However, with the random allotment of cuts to treatments, these "location" effects within a muscle would be randomly distributed and not confounded with treatment differences.

In order to use grilling and sous vide interchangeably in meat science research, it would be ideal if, within a target cooked temperature, WBSF were not different between cooking methods. However, within this study, cooking method did result in differences of WBSF within the target temperature in pork. Furthermore, this result was not consistent, meaning that sous-vide cooking did not consistently result in increased or decreased WBSF in all scenarios. For example, pork chops cooked using sous vide were more tender than grilled chops at 63°C but tougher at 71°C. Meanwhile, beef steaks were virtually identical in average WBSF values when cooked to 63°C, but numerically, sous-vide steaks were tougher when cooked to 71°C. This underscores the need to clarify the cooking method used in meat science research because the apparatus can impact outcomes.

One possible explanation for differences in WBSF between cooking methods is differences in cook loss. Sous-vide cooking increased cook loss in pork chops targeting 71°C and in beef steaks targeting either endpoint temperature. This is consistent with previous reports (Bryan et al., 2019). However, the cook loss reported here is not dissimilar to previous literature in pork (Lonergan et al., 2007; Arkfeld et al., 2015; Harsh et al., 2017) and beef (Hearne et al., 1978; Palka and Daun, 1999; Obuz and Dikeman, 2003; Yancey et al., 2011). This demonstrates that reasonable differences in cook loss can be detected using sous vide for both beef and pork regardless of degree of doneness.

In conclusion, sous-vide cooking in a research setting improves the accuracy and precision target endpoint temperature, partially because of the inaccuracy of temperature measurement during grilling. When grilling, a cut is removed from the heat when a single temperature reading at a single location reaches the desired endpoint. Not only may this measurement not be indicative of temperatures throughout the cut, but internal temperature may continue to rise once the cut is removed from the grill, leading to inaccuracy in reaching the desired degree of doneness. Although more time-consuming than grilling, sous vide reduces the attentiveness required by technicians during the cooking process because of its fixed temperature. Another appealing component to sous vide is its commercial availability compared with open-hearth grills. This method may prove useful to meat science researchers looking to reduce external temperature variability introduced via cooking methods. However, caution must be used because sous vide does not necessarily result in similar WBSF and cook loss values compared with other cooking methods. Additionally, if used for sensory analysis, it must be considered that sous vide is typically accompanied by searing either prior to or after cooking. Finally, although sous vide is gaining popularity in the private sector, open-hearth grilling is most similar to systems used by consumers in residence. Overall, it remains critical in meat science research to detail the exact methods used in each experiment and use that information when comparing studies.

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