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Research article

Physical characteristics and their relationship with surface-physical properties of Thai local beef during sous-vide processing

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Abstract

In Thailand, local beef (*Bos indicus*) is preferred by most consumers since it is cheaper than imported beef; however, it has a tougher texture and requires a longer cooking time to make it palatable. The sous-vide cooking process has been found to improve food characteristics, especially the color and texture of meat. Therefore, sous-vide cooking was tested on Thai local beef using various cooking temperatures (60°C, 70°C or 80°C) for various cooking times (2–36 hr), after which the cooking loss, color and shear force of samples were measured. Cooked samples were also re-heated to simulate the preparation by the consumer and the re-heating loss was measured. Sous-vide cooking significantly ($p<0.05$) reduced cooking loss and lightness and resulted in higher yellowness and less redness compared to a raw sample. However, the lightness of the beef was not significantly ($p>0.05$) different at any of the cooking temperatures and times tested, whereas yellowness and redness depended on the cooking temperatures and times. Increasing the cooking temperature resulted in an increased shear force, while increasing the cooking time resulted in a significantly ($p<0.05$) decreased shear force. Cooking at higher temperatures for longer times significantly ($p<0.05$) increased the sous-vide cooking loss and decreased the re-heating loss. Image analysis of the surface texture showed that muscle fiber was at first clear and firm and then it shrank, with layering clearly visible during cooking. The coefficient of determination for the relationship between the fiber shrinkage area from images and the physical properties of color, cooking loss, re-heating loss and shear force were in the range 0.70–0.98 in all cases.

Introduction

Thai local beef cattle, a *Bos indicus* genotype, originated from India, later spreading across Southeast Asia and has existed in Thailand for many years; the bulls typically weigh 300–350 kg and the cows 200–270 kg (Jaturasitha et al., 2009). There are four native breeds, originating from different regions, that are officially recognized by the Department of Livestock, Ministry of Agriculture, Thailand (Wangkumhang et al., 2015), namely, Kho-Khaolumpoon (Northern Thailand), Kho-Isaan (Northeastern Thailand), Kho-Lan (Central Thailand) and Kho-Chon (Southern Thailand). Their meat is used in many kinds of Thai food since it tends to be cheaper than imported beef and meat from other types of cattle produced in Thailand; however, its texture is tougher and requires a longer cooking time in order to make it more palatable (Sethakul and Oparpatankit, 2005). A processing technique (sous-vide cooking) first vacuum packs the food and then heats it for a specified temperature and time before cooling at 0–3°C in order to control microorganisms (Schellekens,

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1996). Sous-vide cooking is based upon two major principles: first, the packaging prevents moisture loss and evaporative losses of flavor volatiles; and second, vacuum packing induces low oxygen tension in the pack and inhibits the oxidative changes responsible for the development of off-flavors (Church and Parsons, 1993). Sous-vide cooking improved food characteristics such as color and texture (Schafheitle, 1990; Roldàn et al., 2013).

Sous-vide cooking is a favorite traditional French method of food preparation (Tiampo, 2006). It can be defined as cooking in a water bath under controlled conditions of temperature and time inside heat-stable vacuum pouches or containers, followed by a rapid cooling (Pulgar et al., 2012). During sous-vide cooking, heat from a water bath is transferred slowly to the vacuum-packed food. Temperatures are much lower than in conventional cooking methods. Therefore, cooking times are longer to produce palatable meat. Its benefits include good nutrient retention (Creed, 1995; Botinestean et al., 2016) and reduction in microbial levels (Roldán et al., 2013; Singh et al., 2016). Sous-vide cooking is used in restaurants, catering and industrial processing because of its ease and appropriateness for food preparation management (Pulgar et al., 2012). In addition, it can be used for ready-to-cook food because the vacuum packaging associated with the thermal treatment eliminate the microbial risk (Pulgar et al., 2012; Roldán et al., 2013; Oz and Zikirov, 2015) increases the shelf-life (Roldán et al., 2013; Botinestean et al., 2016; Singh et al., 2016) and reduce the risk of food poisoning (Nissen et al., 2002). Low-temperature long-time cooking (LTLT) for the inactivation of microbes in beef at 50–62°C resulted in significant reductions in microorganism counts for mesophiles and psychrotrophs (Dominguez-Hernandez et al, 2018). Roldàn et al. (2013) reported that cooking lamb at 60°C for at least 6 hr was sufficient to reduce microorganism counts for lactic acid bacteria, Gram-positive cocci, Enterobacteriaceae, coliforms, *Bacillus thermosphacta*, *Listeria monocytogenes* and *Salmonella typhimurium* to values lower than 1 colony forming unit/g. However, heat-tolerant microorganisms that can reproduce under storage at refrigeration temperatures, such as *Clostridium perfringens* could survive this cooking process. Smith et al. (1981) tested roast beef inoculated with *Cl. perfringens* (1×10^6 cells/g) and recommended a minimum of 2.3 hr holding time at 60°C in a water bath to ensure both safety and the retention of quality when initial counts were higher than expected.

Temperatures and cooking times have a large effect on the eating quality of meat (García-Segovia et al., 2007; Roldán et al., 2013). Botinestean et al. (2016) reported that sous-vide cooking at 60°C for 270 min of *M. semitendinosus* beef steaks significantly reduced their Warner-Bratzler shear force values from 32.97 N (control) to 27.80 N. Part of these quality improvements came from changes in the physicochemical characteristics of the muscle proteins that occurred during the heating treatment (García-Segovia et al., 2007; Christensen et al., 2013). Heating can induce denaturation of muscle fiber proteins, leading to myofibrillar and sarcoplasmic protein aggregation during cooling that causes fiber shrinkage (Roldán et al., 2013). Heating can also cause collagen denaturation, leading first to its shrinkage and finally to its solubilization (Hamm, 1977; Astruc et al., 2010; Astruc et al., 2012; Niu et al., 2015). Two phases of toughness have been observed in beef meat associated with increased cooking temperature. The first phase, which occurs at around 40–50°C, is associated with myofibrillar protein denaturation, especially myosin and the second phase occurs at 60–80°C and is associated with collagen shrinkage (Hamm, 1977; Christensen et al., 2000; García-Segovia et al., 2007).

With the use of digital cameras and image analysis, it is now possible to acquire digital images of meat surfaces and to quantify some morphological and physical changes that can be assigned to several food properties and meat tenderness, which in turn can be used to predict the surface texture of meat (Li et al., 2001; Chandraratne et al., 2006). Li et al. (2001) used texture feature images to classify beef samples into tender and tough categories in terms of cooked beef tenderness. Chandraratne et al. (2006) investigated the prediction of the tenderness of cooked lamb meat using image and texture analyses together. This prediction gave the highest coefficient of determination (R^2) of 0.75. Jabri et al. (2010) also used image analysis to study the perimysial connective network tissue and its relationship with tenderness and the composition of bovine meat. They found that intramuscular connective tissue image parameters were a good prediction of beef tenderness, collagen and lipids contents with R^2 values of 0.82–0.91. These studies have shown that surface textural characteristic of food materials can be observed from surface images. Translation of the surface images into numerical data and their interpretation could be useful in relating the physical properties of foods to their various cooking conditions. Therefore, the objective of the current study was to investigate the relationship between the surface texture of cooked meat and its quality to provide a novel non-destructive method that could be used in the catering and food industry.

Materials and Methods

Raw material

Thirty round muscles (at 24 hr postmortem) from Thai local beef animals (*Bos indicus*), aged 18 mth and weighing 200–250 kg, were purchased from Huatakhe market in Bangkok province, Thailand and brought to the laboratory. The exudate from the samples was blotted dry with tissue paper, rather than washing that could have affected the moisture content. The fat and connective tissue were trimmed before cooking.

Sous-vide cooking process

Muscles were sliced into 7 cm × 7 cm × 7 cm pieces, identifying the fiber direction. Samples were vacuum packed into laminated low density polyethylene pouches (dimensions: 150 mm ×230 mm) using a vacuum machine (DZQ-500B; China). Then, the samples were sous-vide cooked under various conditions.

Sous-vide cooking was carried out in a water bath (WNB; Memmert; Germany) at 60°C, 70°C or 80°C for 2 hr, 4 hr, 6 hr, 12 hr, 18 hr, 24 hr, 30 hr or 36 hr. After cooking, the samples were cooled in iced water until the core temperature reached 20°C and then they were stored at room temperature (approximately 25°C) for 30 min and their color, sous-vide cooking loss, re-heating loss, shear force and surface texture were measured. Three cooking runs were carried out for each condition of time and temperature.

Color measurement

Color based on the CIE Lab system (Salueña et al., 2019) was measured across the cross-section of the cooked sample at room temperature (25°C). The L^* value (lightness), $+a^*/-a^*$ value (redness/greenness) and $+b^*/-b^*$value (yellowness/blueness) were measured using a Minolta colorimeter (Minolta Chroma Meter CR-400; Japan). Triplicate readings were taken randomly from three locations on each side of the sample (six measurements for each sample). Three replications of each measurement were taken.

Sous-vide cooking loss

The sous-vide cooking loss was determined by weighing the sample before and after sous-vide cooking and replicating the measurements three times. The percentage of sous-vide cooking loss was calculated using Equation 1:

$$\%\ \text{Sous-vide cooking loss} = \frac{w_2 - w_1}{w_2} \times 100 \quad (1)$$

where w_1 is the weight of the sample after sous-vide cooking and w_2 is the weight of the sample before sous-vide cooking, both measured in grams.

Re-heating loss

Sous-vide cooked products are usually cooked in the factory and are then sold cold so that the product must be warmed up or reheatedbefore serving (Uttaro et al., 2019). To simulate this process, sous-vide cooked samples were cut into 3 cm ×1 cm ×1 cm pieces, packed in polyethylene bags and heated at 75°C for 30 min in a water bath. Samples were then removed from the water bath and cooled to room temperature for 30 min until the temperature was about 25°C. For each sous-vide cooking condition, the percentage of re-heating loss was calculated on three beef pieces by the difference between the weights before and after heating. Analyses were performed on three replicates for each combination of time and temperature based on the measurement on nine different pieces of muscle.

Shear force

The beef samples were cut into 3 cm × 1 cm × 1 cm pieces for shear force measurement using a Warner-Bratzler blade in the texture analyzer (TA-XT plus; UK) with a cross-head speed of 1 mm/s and a 50 kg load cell following the method of Roldán et al. (2013). For each sample, the shear force was measured on seven different pieces perpendicular to the muscle fiber direction and the maximum force (N) required to shear the sample was recorded.

Surface texture characteristics

The characteristics of the surfaces of the cooked beef were observed based on image capture following the procedure described by Supaphon et al. (2014). Each beef sample was placed in a black box (61 cm × 61 cm × 61 cm) with a 15 cm distance between the camera and the sample. The sample was illuminated by two light-emitting diodes lamps (each 5 W with a bulb size of 70 mm × 116 mm). The sous-vide cooked samples were cut in parallel to the muscle fiber direction and images of the muscle surface from each side were acquired in red-green-blue (RGB) format in triplicate using a Fujifilm camera (XT-10; Japan) with an XF60 mm F2.4R macro lens and each image was stored as 4296 × 2664 pixels.

The muscle surface texture of the beef images was analyzed using the ImageJ software (Version 1.51n, National Institutes of Health; USA). The RGB images were converted to black and white format with a gray level threshold of 170, which chosen so that each image was clearly divided into two parts (an extra bundle fiber area and a muscle fiber bundle area). Pixels representing the intensity between 0 and 169 were grouped in the dark zone (space between muscle fiber bundles including connective tissue), whereas pixels with an intensity between 171 and 255 were grouped in the white zone (muscle fiber bundles). The total number of each pixel type was calculated from the black and white images and presented as a percentage of the layer of muscle fiber bundle shrinkage area.

Multiple regression of image parameters and physical properties

A multiple regression model was used to establish and quantify the relationships between image characterization of meat structure (%extra bundle fiber area X_1 and muscle fiber bundle area X_2) and each physical property (color, sous-vide cooking loss, re-heating loss and shear force) using the SPSS software (Version 21; IBM; USA). For each regression model, 70% of the respective data was used to obtain the model itself and 30% of the data was used for validating the model for accuracy as described by Lin et al. (2011). The performance of the final model was evaluated according to the correlation coefficient of determination of calibration (R^2_C) and validation (R^2_{CV}), the standard error of calibration (SEE_C) and validation (SEE_{CV}).

Statistical analyses

The experiments were conducted in triplicate and their means and standard deviations were reported. Data were subjected to analysis of variance and the means were compared using Tukey's test with the SPSS software (Version 21; IBM; USA). A significant difference test at the 95% confidence level ($p<0.05$) was applied to test differences between evaluated parameters.

Results and Discussion

Color change in processed meat

The cooked samples were significantly lighter (L^*), more yellowish (higher b^*) and less reddish (lower a^*), than the raw control (Table 1). The increase in $L^*$of cooked muscles (compared to raw control ones) was probably linked to the muscle fiber shrinkage that led to a decrease in light penetration in the meat and thus produced paler meat (Nikmaram et al., 2011; Roldán et al., 2013). In addition, cooking leads to higher denaturation and aggregation of sarcoplasmic and myofibrillar proteins, which would increase light scattering (Wattanachant et al., 2005; Christensen et al., 2011; Roldán et al., 2013).

Compared to the control samples, the redness decreased after cooking whatever the cooking time and temperature. This loss of redness during cooking was in accordance with the results of García-Segovia et al. (2007) in beef samples and of Roldán et al. (2013) in lamb loins. Overall, increasing the cooking time and temperature did not significantly change the redness, except for samples treated for 6 hr at 60°C and 30–36 hr at 80°C that were usually redder than other cooked samples. The compound largely responsible for the brown-gray color is globin hemichrome (Fe^{3+}), which results in the globin (the protein part of myoglobin) being denatured during heating (Wattanachant et al., 2005). The globin denatures at around 60°C depending on its oxidation status before cooking (Bejerholm et al., 2014).

The lower decrease of redness in the samples cooked for 2 hr or 4 hr at 60°C suggested a lower denaturation of myoglobin because of the shorter time under conditions suitable for denaturation. Compared to samples cooked at 60°C or 70°C, the highest redness of the samples cooked for 30–to 36 hr at 80°C could be linked to the formation of pink, denatured globin ferrohemochrome (Suman and Joseph, 2013). Cooking significantly increased the yellowness (b^*), which may have been due to the denaturation of metmyoglobin and to heme conversion into nicotinamide hemichrome that increased the brown hue (Suman and Joseph, 2013). In fact, myoglobin denatures at around 60°C and probably the larger part of its myoglobin was denatured after 6 hr of cooking at all cooking temperature tested. The increase in b^* could also have been due to Maillard reactions that happen during cooking (Hamm, 1977; Shahidi et al., 2014).

The slight increase in yellowness (b^*) along with increased cooking duration was not significant, except after 30 hr of cooking at 80°C. Overall, the results from the color measurements agreed with previous studies (Christensen et al., 2011; Nikmaram et al., 2011). The most aggressive condition of cooking (30–36 hr at 80°C) promoted increased denaturation of myoglobin and of the Maillard reaction compared to the other cooking conditions tested.

Sous-vide cooking loss

The moisture content of Thai local beef was reported to be approximately 75.5% (Sethakul and Sivapirunthep, 2009). In the current study, sous-vide cooking resulted in water loss whatever the cooking temperature (Fig. 1), which was much higher for 70°C and 80°C than at 60°C. After 2 hr of cooking, samples cooked at 70°C lost more than twice as much water as the samples cooked at 60°C. At 70°C cooking, water loss significantly increased until 6 hr of

Table 1 Color parameters of sous-vide-cooked round beef surface at different temperatures and times, where L^* is lightness, a^* is redness and b^* is yellowness

Temperature (°C)	Cooking time (hr)	L^*	a^*	b^*
60	control	40.33 ± 3.19^{a}	19.38 ± 1.42^{d}	1.52 ± 1.11^{a}
	2	60.90 ± 3.57^{b}	18.72 ± 1.30^{d}	7.32 ± 1.66^{bc}
	4	61.51 ± 1.51^{b}	17.92 ± 1.40^{cd}	7.30 ± 0.68^{bc}
	6	58.97 ± 1.61^{b}	16.81 ± 0.53^{c}	7.91 ± 0.72^{c}
	12	61.93 ± 0.41^{b}	14.44 ± 0.25^{b}	6.03 ± 0.19^{b}
	18	63.64 ± 1.55^{b}	13.21 ± 0.86^{ab}	5.94 ± 0.48^{b}
	24	58.79 ± 5.00^{b}	13.24 ± 0.40^{ab}	6.56 ± 0.47^{bc}
	30	61.50 ± 2.07^{b}	13.00 ± 0.49^{ab}	7.15 ± 0.55^{bc}
	36	63.33 ± 1.31^{b}	11.81 ± 0.84^{a}	7.20 ± 0.66^{bc}
70	control	40.33 ± 3.19^{a}	19.38 ± 1.42^{b}	1.52 ± 1.11^{a}
	2	57.19 ± 4.98^{b}	12.82 ± 0.73^{a}	6.72 ± 0.96^{bc}
	4	61.23 ± 3.57^{b}	12.12 ± 0.90^{a}	6.05 ± 0.77^{b}
	6	60.74 ± 4.26^{b}	11.95 ± 0.36^{a}	6.27 ± 0.74^{b}
	12	61.85 ± 1.85^{b}	12.90 ± 0.61^{a}	5.91 ± 0.49^{b}
	18	60.71 ± 2.81^{b}	12.88 ± 0.43^{a}	6.05 ± 0.66^{b}
	24	61.35 ± 2.25^{b}	12.67 ± 0.47^{a}	6.83 ± 0.92^{bc}
	30	60.61 ± 3.78^{b}	12.58 ± 0.69^{a}	8.11 ± 1.18^{cd}
	36	60.07 ± 2.94^{b}	12.56 ± 0.69^{a}	8.68 ± 1.24^{d}
80	control	40.33 ± 3.19^{a}	19.38 ± 1.42^{d}	1.52 ± 1.11^{a}
	2	61.01 ± 4.46^{b}	11.73 ± 0.90^{a}	6.32 ± 0.66^{b}
	4	59.86 ± 6.11^{b}	12.40 ± 0.60^{ab}	6.28 ± 0.38^{b}
	6	60.47 ± 4.70^{b}	12.12 ± 0.60^{a}	6.36 ± 0.48^{b}
	12	61.62 ± 4.09^{b}	13.00 ± 0.46^{abc}	6.89 ± 1.10^{bc}
	18	59.44 ± 2.60^{b}	13.46 ± 0.08^{abc}	7.59 ± 1.81^{bc}
	24	57.11 ± 3.30^{b}	13.49 ± 0.49^{abc}	9.83 ± 2.33^{de}
	30	59.09 ± 5.26^{b}	14.35 ± 0.76^{c}	9.37 ± 1.93^{de}
	36	57.21 ± 2.90^{b}	14.02 ± 0.76^{bc}	11.36 ± 3.81^{d}

Data are presented as mean ± SD. Different lowercase superscript letters within the same column indicate significant differences ($p<0.05$).

cooking, but cooking for longer than 6 hr did not change the water loss. The maximum amount of water loss was reached after only 2 hr at 80°C after which the water loss did not change.

Christensen et al. (2011) reported that in conventional cooking (not sous-vide), cooking loss increased with cooking temperature in the first phase of heating, but after a period of cooking (depending on the size of the meat pieces), increasing the cooking time did not continue to increase the cooking. Locker and Daines (1974) cooked beef meat at 80°C and showed that water was released during the first 90 min, but after 90 min the increase in water loss stopped. In the present study, cooking loss significantly increased from 60°C to 70°C or 60°C to 80°C but not from 70°C to 80°C. However, in sous-vide cooking, water remains in contact with the meat, trapped inside the plastic throughout cooking and cooling. Probably most of the free water had been extracted after cooking for 6 hr at 70°C and for 2 hr at 80°C.

Compared to 60°C, the large decrease in water holding capacity for sous-vide cooked meat at 70°C and 80°C was probably due to the shrinkage of muscle fibers because of connective tissue contraction and perhaps also because of new cross linkages in the coagulated myofibrillar system as described by Hamm (1977) and Roldán et al. (2013).

Re-heating loss

The temperature and time of sous-vide cooking significantly affected the re-heating loss of beef (Fig. 2), with 60°C sous-vide cooking producing higher cooking losses than at 70°C or 80°C and significantly decreasing the cooking loss with increasing time. The 60°C sous-vide cooked samples initially had a higher water content than the samples cooked at 70°C or 80°C since the latter two lost a lot of juice during cooking. This effect was consistent with Kongpeam et al. (2015) who found that sous-vide-cooked flank steak, which had higher sous-vide loss values, displayed lower re-heating losses. Increasing the cooking temperature to higher than 60°C has been shown to cause changes in the protein structure, particularly increasing the proportion of denatured proteins and causing severe shrinkage of myofibrillar and connective materials leading to released water from the muscle (Ranken, 2000; Baldwin, 2012).

Shear force

The shear force of raw meat (control sample) was 46.52 N, which was consistent with that reported by Rinaldi et al. (2014). In the current study, all samples had higher shear force values compared to the raw control sample, which was consistent with a previous study on the effects of cooking on meat texture (Christensen et al., 2000).

The shear force values significantly increased with cooking temperature from 60°C to 80°C after 2 hr of cooking (Fig. 3) confirming the findings of Christensen et al. (2000). Kongpeam et al. (2015) also found that increasing the sous-vide cooking temperature of flank steak of local Thai beef from 55°C to 65°C increased the firmness and toughness. Tornberg et al. (1997) characterized the evolution of muscle fibers and connective tissue of bovine muscle biceps femoris and observed a lateral and longitudinal shrinkage of muscle fibers from cooking at 40°C, but this shrinkage increased with higher temperatures tested (up to 80°C). In the current study, the shrinkage of connective tissue started at 60°C and increased significantly up to 80°C. These phenomena were generally associated with water loss and increased hardness as confirmed by Hamm (1977).

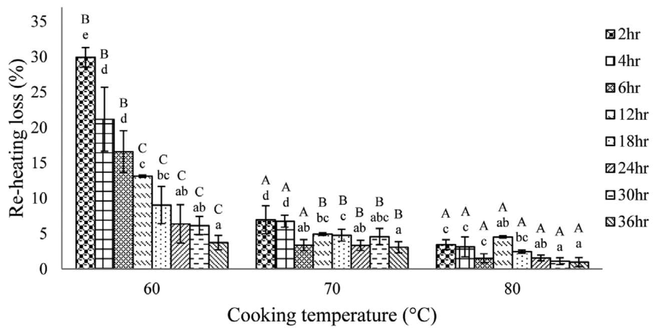

Fig. 2 Percentage of re-heating loss of sous-vide beef at 60°C, 70°C or 80°C for 2–36 hr, where uppercase letters above bars indicate a significant difference ($p<0.05$) between cooking temperatures (same cooking time) and lowercase letters indicate a significant difference ($p<0.05$) between cooking times (same cooking temperature)

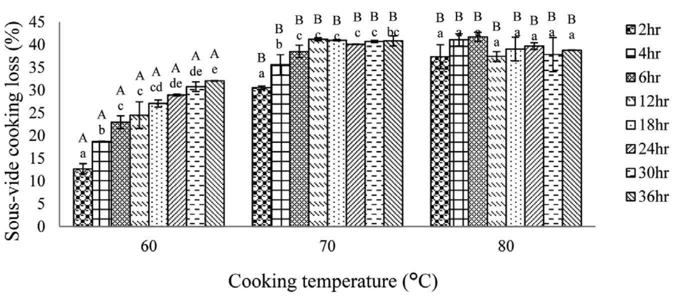

Fig. 1 Percentage of sous-vide cooking loss of beef at 60°C, 70°C and 80°C for 2–36 hr, where uppercase letters above bars indicate a significant difference ($p<0.05$) between cooking temperatures (same cooking time) and lowercase letters indicate a significant difference ($p<0.05$) between cooking times (same cooking temperature)

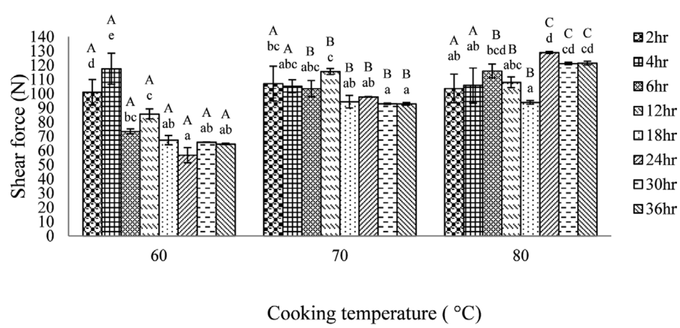

Fig. 3 Effect of sous-vide cooking on shear force of beef, where uppercase letters above bars indicate a significant difference ($p<0.05$) between cooking temperatures (same cooking time) and lowercase letters indicate a significant difference ($p<0.05$) between cooking times (same cooking temperature

Rochdi et al. (2000) showed that the shear force decreased with solubilization of collagen into gelatin, which depended on the rate of crosslink in the collagen and in older animals, the high crosslink rate requires a temperature above 80°C to properly solubilize the collagen. They also showed that the collagen solubilization was rapid during the first hour of cooking at 90°C but was much slower for longer cooking times.

The current results for meat samples from an 18-month-old rustic breed of cattle showed that when the cooking temperature did not exceed 80°C, there was already high collagen crosslinking, which could explain why the shear force did not change much from 6 hr cooking and longer. Rinaldi et al. (2014) suggested that using long sous-vide cooking times at low temperature caused the denaturation of myofibrillar proteins and meat toughening.

Surface texture imaging

The images of the round beef muscle surface after sous-vide cooking at different temperatures and times (Fig. 4) exhibited distinct characteristics. Firm and clear muscle bundle fibers and inter bundles spaces were observed. The onset of these changes differed in time depending on the cooking temperature. Cooking at 60°C for 2–36 hr slightly changed the surface texture, but muscle bundle fibers were clear and firm for up to 6–18 hr. After 24 hr cooking, the muscle fiber layer was clearly observed with similar trends for cooking at 70°C or 80°C for which the muscle fibers were clear and firm after 12 and 6 hr cooking, respectively. The muscle fiber layers then started to appear after 18 hr and 12 hr for 70°C and 80°C, respectively.

The images showed the appearance of gaps in between the muscle fiber bundles depending on cooking temperature and time. At 60°C, the number of gaps and their size clearly increased from 24 hr. Gaps appeared at 18 hr for samples cooked at 70°C and at 6 hr for samples cooked 80°C, with a larger hole size after 24–36 hr cooking. These results reflected muscle fiber bundle lateral shrinkage that was moderate for samples cooked at 60°C and increased at 70°C and 80°C.

The connective tissue of the perimysium was seen (when zooming in on the images) for samples cooked at 60°C and 70°C whatever the cooking time, and for samples cooked for 6–18 hr at 80°C. Collagen contraction was probably the largest participant in fiber bundle shrinkage. Connective tissue was less visible on samples cooked at 80°C for 24–36 hr, with more degraded muscle bundle fibers apparent. This decrease in the perimysium density suggested a partial solubilization of collagen, after protracted cooking at 80°C, which weakened the links between fiber bundles. Moreover, after cooking for 24 hr at 80°C, the color of the meat became brown, which could have been due to changes in the myoglobin molecules or to Maillard reaction products or both. The appearance of fiber layering at the onset of the second phase was due to surface muscle fiber shrinkage and layering due to water loss during cooking, which were consistent with the sous-vide cooking loss (Fig. 1). Water loss after sous-vide cooking was approximately 34% with the loss tending to be from the muscle bundle fibers, which occurred slowly at 60°C, but was more rapid at 70°C and 80°C, confirming the results of Astruc et al. (2010). Astruc et al. (2012) and Pulgar et al. (2012) reported that during heat processing, some of the proteins are denatured and then form complexes and aggregates and the muscle fibers shrink and become layered. such activity could be an indication of high compression due to the collagen shrinking and water being released from the muscle fibers (Kapitula et al., 2015).

This compression effect might be due to the shrinkage of endomysial collagen, which gelatinized at 80°C (Baldwin, 2012; García-Segovia et al., 2007). The current results showed that both the control and cooked meat samples displayed changes in their structure when their water content was reduced, with damage to the cell membrane, shrinkage in muscular fibers both transversally and longitudinally, aggregation and gelling of sarcoplasmic proteins, and shrinkage and solubilization of connective tissues. Kapitula et al. (2015) reported that these effects collectively resulted in the appearance of granular fibers.

Surface-physical properties relationship of Thai beef

Data analyzed from round beef images showed the percentage of layer of muscle from image analysis protein (X_1) and the percentage of muscle from image analysis (X_2) were highly correlated with the percentage of sous-vide cooking loss, with values for R^2_C of 0.98 and SEE_C of 3.61 (Table 2). The multiple regression produced validation results with R^2_{CV} values of 0.81, 0.78, 0.81, 0.94, 0.85 and 0.77 for L^*, a^*, b^*, percentage of sous-vide cooking loss, percentage before-heating loss and shear force, respectively (Table 2).

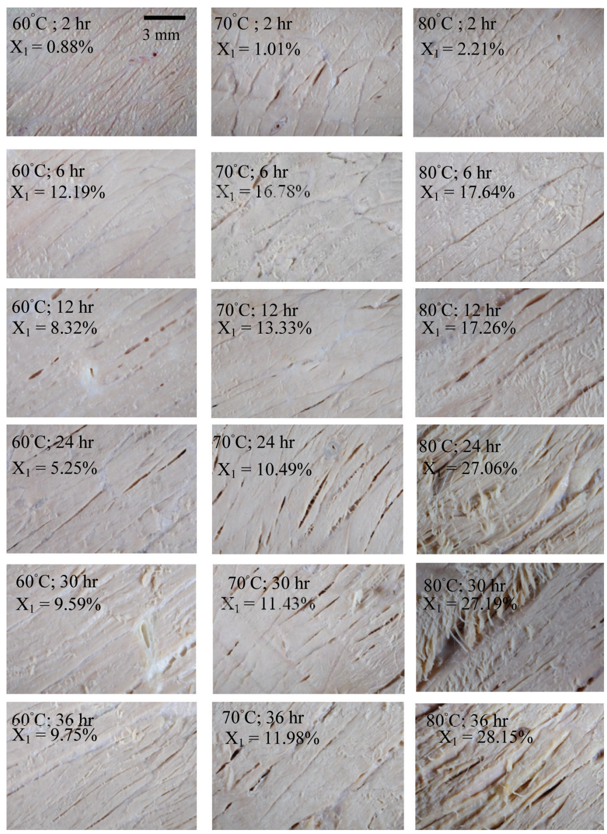

Fig. 4 Image analysis of cut surface of beef after sous-vide cooking at 60°C, 70°C or 80°C for 2 hr, 4 hr, 6 hr, 12 hr, 18 hr, 24 hr, 30 hr or 36 hr

Table 2 Multiple regression models between surface image characteristics and physical properties of cooked meat
X_1 = %extra bundle fiber area; X_2=% muscle fiber bundle area; R^2_C and R^2_{CV} = correlation coefficient of calibration set and cross validation set, respectively; SEE_C and SEE_{CV} = standard error of calibration set and cross validation set, respectively.
Result of multiple linear regressions showing R^2 values and SEE values.
Significance tested at (p<0.05).

Variable	Equation	Calibration		Validation	
		R_C^2	SEE_C	R_{cv}^2	SEE_{CV}
L*	$42.090 + 6.584X_1 + 0.294\ X_1^2 - 5.021\times10^{-5}(X_1X_2)^2 + 3.268\times10^{-8}(X_1X_2)^3$	0.90	2.41	0.81	2.01
a*	$19.151 - 1.342X_1 + 0.047\ X_1^2 + 7.533\times10^{-6}(X_1X_2)^2 + 4.338\times10^{-9}(X_1X_2)^3$	0.79	1.22	0.78	1.58
b*	$1.673 + 0.744X_1 + 0.112\ X_1^2 - 9.082\times10^{-6}(X_1X_2)^2 - 7.494\times10^{-9}(X_1X_2)^3$	0.85	1.32	0.81	1.27
Sous-vide cooking loss (%)	$99.820 - 27.606X_1 + 1.145X_1^2 + 2.420\times10^{-4}(X_1X_2)^2 - 1.432\times10\text{-}7(X_1X_2)^3$	0.98	3.61	0.94	5.78
Re-heating loss (%)	$34.232 -5.631X_1 + 0.084X_1 + 3.118\times10^{-5}(X_1X_2)^2 - 8.487\times10\text{-}9(X_1X_2)^3$	0.92	3.66	0.85	1.54
Shear force (N)	$215.803 - 3.282\times10^{-5}\ (X_1X_2)^2 + 1.708\times10^{-6}(X_1^5) - 1.982\times10^{-8}(X_2)^5 + 1.000\times10^{-3}(X_1X_2)^6$	0.72	15.23	0.70	7.06

Sous-vide cooking affected the cooking loss and lightness and produced higher yellowness, with less redness of beef compared to the raw sample. However, lightness of beef was not significantly different at any of the cooking temperatures and times tested; however, yellowness and redness were dependent on the cooking temperature and time. Increasing the cooking temperature resulted in increasing shear force. Cooking at higher temperatures for longer times significantly increased the sous-vide cooking loss and decreased the re-heating loss. There were good correlations between physical properties and surface image characteristics (R^2 values 0.70–0.98) indicating that surface textural characteristic of cooked meat could be translated into numerical data. Their interpretation could be used to quantify the physical properties of cooked beef providing a novel method that could form a basis of a non-destructive method of measuring meat quality in the catering and food industries. Future studies could include organoleptic analysis of sous-vide cooked Thai beef and how it correlates with the physical measurements and imaging.

Conflict of Interest

The authors declare that there are no conflicts of interest.

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