Quality Changes of Salmon (*Oncorhynchus gorbuscha*) Muscle during Thermal Processing

FANBIN KONG, JUMING TANG, BARBARA RASCO, CHUCK CRAPO, AND SCOTT SMILEY

ABSTRACT: The objective of this study was to investigate quality changes of salmon fillet muscle during thermal sterilization processes. Small samples (D 30 mm × H 6 mm) from the central dorsal region were heated in an oil bath at 121.1 °C for periods varying from 5 to 120 min. The quality variations along the longitudinal axis of salmon fillets (raw and heated) were examined. The quality properties studied included shear force, color, cook loss, and shrinkage. To minimize the influence of the heterogeneity of the salmon muscle, a multiple thin blade texture device was developed for shear force measurement and a computer vision system was used to facilitate accurate measurements of color and shrinkage. The red muscle was firmer than the white muscle in the raw but not in heated samples. Muscle from the central dorsal region had a lower cook loss and less shrinkage than samples from either the anterior or posterior region following heating. The greatest change in quality occurred within the 1st 10 min of heating at 121.1 °C. Shear force measurements following heating indicated 2 peaks, one corresponding to 5 min and the second for 60 min processing at 121.1 °C. Possible mechanisms were discussed.

Keywords: color, cook loss, salmon, shear force, sterilization

Introduction

About 40% of salmon harvested in the United States is converted into canned or pouched product using conventional retort processes (USDA 2003). A substantial portion of the pink salmon (*Oncorhynchus gorbuscha*) is canned. During retorting, the packaged salmon meat is heated at a high temperature, typically around 120 °C, for various periods from 20 to 90 min, depending on the package size and shape. Knowledge of kinetics for quality changes in salmon muscle during those processes is desired in design of food packages and thermal processes to produce the best possible shelf-stable products.

A wide range of analytical methods has been used to characterize the quality changes that occur to a muscle food during commercial sterilization processes. Color, texture, and cook loss are among the most frequently used quality indicators. Area shrinkage, caused by heat-induced protein denaturation and the resultant shrinkage of the muscle fibers, is also an important cooking quality of muscle foods (Barbera and Tassone 2006).

The instrumental color measurement usually uses the CIE L^*, a^*, b^* scale in which primary parameters are lightness (L^*), redness (a^*), and yellowness (b^*). Conventionally, the color values are measured by a colorimetric or spectrophotometric method, involving reflected light from a sample surface. This method often measures only a small surface area (normally 2 to 5 cm^2), and thus it does not accurately describe the visual color of a heterogeneous product (Louka and others 2004; Briones and Aguilera 2005). Computer vision systems (CVS) developed for color analysis have been used in many areas to determine the color of fruits, vegetables, grains, meats, and seafoods (Louka and others 2004; Yam and Papadakis 2004; Balaban and others 2005; Briones and Aguilera 2005) and have a number of advantages. A CVS system can take measurements over an entire sample area, thus significantly decreasing the variation in color prediction from heterogeneity of a sample. The images can be also used for other purposes, such as area measurement (Barbera and Tassone 2006). However, the use of CVS for salmon muscle color is still limited (Lin and others 2003).

As an indicator of tenderness, shear force of muscle foods has been cited as the most significant factor affecting consumer satisfaction (Sigurgisladottir and others 1999; Jonsson and others 2001). A variety of shearing and cutting devices are commercially available for shear force measurement for muscle, such as the Warner–Bratzler (WB) shearing device, the blade probe, and Kramer shear compression cells. Among these methods, the Kramer shear cell is generally preferred (Dunajski 1979). The Kramer shear cell is a multibladed fixture: the upper part or blade holder holds 10 70-mm-wide and 3.0-mm-thick blades, and the lower part or cell contains the food specimen and slots to guide the blades. The blades shear the specimen when the slots in the cell become engaged. The maximum force required to move the blades through the specimen is used to characterize the texture quality of the sample. The use of a Kramer cell is, however, problematic for fish muscle due to its unique morphological and compositional features compared to red meat such as beef muscle (Dunajski 1979). Fish muscle has smaller muscle fiber dimensions, and the muscle fibers tend to fracture after cooking. The slits in the bottom of a standard Kramer cell are too wide and the blade is too thick, so the testing is in a compression mode rather than shearing. In addition, samples of a relatively large dimension are required for a standard Kramer cell, making it inappropriate for the small sample sizes needed for texture studies with fish fillets in which the muscle morphology and chemical composition changes significantly within a single fillet. Therefore, a fixture with thinner blades would be more suitable (Dunajski 1979), and such a device was developed here. No report on using a similar thin blade device for fish muscle tenderness measurements was found in the literature.

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Chemical composition and muscle structure vary along the length of a fish fillet and from the dorsal to the ventral side, all affecting the quality properties being measured (Sigurgisladottir and others 1999). Therefore, the sampling location is important and should be considered when measuring the quality properties of the fillet. Several studies report on the variation of shear force along a salmon from its head to its tail. The muscle is firmer in the tail than in the head, and this might be related to smaller muscle fiber diameter and higher proportion of insoluble collagen in the tail (Love 1970; Montero and Borderias 1989).

Quality changes occuring during cooking (< 100 °C) have been studied in salmon (Skrede and Storebakken 1986; Bhattacharya and others 1993). Shear force increased as temperature increased, and the higher number of fibers of smaller diameter was found in cooked muscle compared to raw muscle (Skrede and Storebakken 1986). Increasing the processing temperature or time increased the visual lightness, but reduced both the redness and the yellowness of muscle (Bhattacharya and others 1993).

The objectives of this study were to (1) develop a multiple thin blade (MTB) texture fixture to characterize raw and heated fish muscle tenderness; (2) develop CVS to characterize raw and heated muscle color as well as changes in sample area attributable to shrinkage; (3) investigate the variation of quality attributes, including color, shear force, cook loss, and shrinkage, in the raw and heated salmon muscle as related to different locations in a fillet; and (4) investigate the changes in quality characteristics of salmon muscle during thermal processing.

Materials and Methods

Materials

Pacific pink salmon (*O. gorbuscha*) were provided by Ocean Beauty Seafoods Inc. (Seattle, Wash., U.S.A.). These fish were female, from the same catch harvested in August 2005 near Kodiak, Alaska. The fish weighed 1350 ± 100 g and were of similar size (370 ± 10 mm in length and 120 ± 10 mm in width). The fish were gutted, frozen, stored (−31 °C), and shipped to Washington State Univ., Pullman, Wash., U.S.A.

Development of a test cell

To provide uniform heating, a special test cell (WSU Test Cell) was designed to minimize come-up-time (CMT: the time needed for the internal temperature to reach the processing temperature) for meaningful sample sizes for texture and color analyses. Sample dimension, particularly the thickness of sample, is the most important parameter influencing the CMT; the samples were 6 mm in thickness and 30 mm in diameter. The custom-designed cylindrical aluminum test cell is illustrated in Figure 1. The cells had a net inner space of 35 mm in diameter and 6 mm in depth. The top and bottom lids with o-rings provided a hermetic seal. The bottom lid allowed easy removal of fragile heated samples for texture and color measurements. A 0.1-mm-dia copper-constantan thermocouple (Type-T) was inserted through the top lid to measure temperature at the geometrical center of the sample during the heat treatments.

The heating was conducted in a 121.1 °C oil bath using glycerol as the heating medium. During heating, the signals from the thermocouple junctions were transferred to a computer equipped with a DLZe type data logger (DELTA-T Devices, Cambridge, U.K.). The CMT was about 2.5 min.

Sampling position and experimental design

A multilocation sampling technique was employed to examine the influence of sample locations along the length of a salmon fillet, dorsal side only, on the quality attributes measured here. Six fish were used in the sampling. Each fish was cut into 9 sections (location 1 to 9) along the length of the fish (Figure 2). The belly flaps were removed. Each section was sliced into up to 3 6-mm-thick layers depending on the thickness of the fillet (Figure 2). A 30-mm dia cutter was used to take disk-shaped samples from these thin slices. The samples (size: D 30 mm × H 6 mm) from the 3 layers were designated as an inner layer, middle layer, and outer layer and numbered as shown in the Figure 2. The middle and inner layers were primarily composed of white muscle, while the outer layer contained part of the red muscle (Kiessling and others 2006). For the tail sections number 7 to 9, only 2 (outer and inner) or 1 (outer) section could be cut because of limited fillet thickness. For each location, a fish provided 2 replicates, one from each side of the fish. In total, 12 samples were taken from the same location of 6 fish, of which 6 replicates were used for raw color, texture, and moisture measurements, and the other 6 were heated in the 121.1 °C oil bath for 20 min. After heating, the samples were removed rapidly from the oil bath and cooled in ice to 4 °C. The sample temperature dropped to 20 °C within a half minute in ice, so that the thermal effect of the cooling step on the

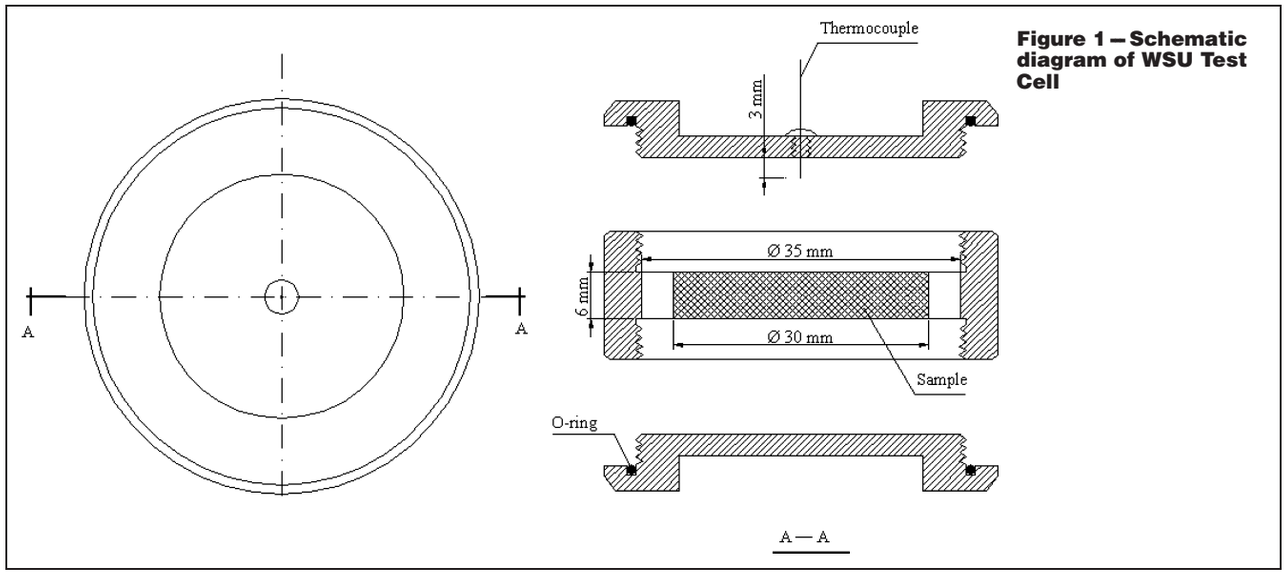

Figure 1 — Schematic diagram of WSU Test Cell

product quality could be neglected. After cooling, the samples were dried with a filter paper, weighed in an analytical balance (Ohaus model Analytical Plus, Ohaus, Pine Brook, N.J., U.S.A.), placed on a sample dish with a cover, and stored in a cooler (4 °C) for further analysis.

To investigate the effect of heating time on the quality changes, the muscles (red muscle and tissue along the lateral line removed) near the dorsal fin (inner and middle layer samples of section 3, 4, 5, 6) of 4 fish were sampled. In total, 60 samples were obtained, pooled, and heated at 121.1 °C for 0, 2.5, 5, 10, 15, 20, 30, 60, and 120 min. Six replicates were used for each time level. The heated samples were cooled and stored as stated earlier.

Cook loss and moisture

The weights of raw and heated samples were recorded to calculate cook loss. Percentage of total cooking loss was calculated as:

$$\text{Cook loss} = \frac{\text{weight of raw sample} - \text{weight of cooked sample}}{\text{weight of raw sample}} \times 100\% \quad (1)$$

To determine moisture content, 3 to 5 g raw and cooked samples were dried in a vacuum oven at 65 °C to constant weight (Hart and Fisher 1971).

Multiple thin blade texture fixture and shear force measurement

A multiple thin blade (MTB) texture fixture similar to a Kramer shear test cell was developed to measure shear force of small salmon samples. Similar to a standard Kramer shear cell (Catalog Number 2830-018, Instron Corporation, Norwood, Mass., U.S.A.), the MTB consisted of the upper part and lower part: the upper part had thin 10 blades and the lower part was the support base with slots. Compared to a commercial Kramer shear cell, the new MTB used thinner blades (0.5 mm against 3 mm), shorter blade length (40 mm against 107 mm), and smaller blade width (50 mm against 70 mm) as well as narrower slits (1.2 mm against approximately 3.3 mm) in the base. The spacing between 2 adjacent blades was 5 mm. The cell was fitted to a Texture Analyser TA-XT2 (Stable Micro Systems Ltd., Surrey, U.K.) equipped with a load cell of 5 kg. Before shear force measurement, the raw and heated samples were allowed to equilibrate to room temperature (approximately 22 °C), which took approximately half an hour. The samples were placed on the support base in a way so that the blades were perpendicular to muscle fibers. The traveling speed was 1 mm/s. The force-time graphs were recorded by a computer and analyzed using the Texture Expert for Windows (version 1.15, Stable Micro Systems Ltd.). The shear force was measured as the peak height in the force-time profile.

A study was conducted to compare the performance of MTB and a flat, blunted blade in characterizing texture of salmon fillets. The blade probe had a thickness of 3.0 mm and width of 70 mm. This method was commonly used in the literature for measuring texture of salmon fillets (Sigurgisladottir and others 1999; Casas and others 2006). The blade was fitted to a Texture Analyser TA-XT2 equipped with a load cell of 5 kg. The measurement was made with a loading speed of 1 mm/s. Outer layer samples were used in the comparative study. Paired samples (from each side of the same fish) were divided into 2 groups. The tests were conducted in 4 replicates. The texture of 1 group of the samples was measured with MTB while the other was measured with the blade probe.

Computer vision system and color/area determination

A CVS was used to capture color images of fresh and cooked samples for color and area analyses. The CVS included 3 parts: a lighting system; a Nikon D70 Digital camera, with 6.1 megapixel solution and 18 to 70 mm DX Zoom Nikkor Lens; and a Pentium IV desktop computer with image-processing software to be described later. The lighting systems consisted of a translucent diffusion shooting tent and 4 fluorescent bulbs (60 Hz 26 W) as lighting source. This system is described in detail in Pandit and others (2007). Samples were placed in a black plate on the bottom of the shooting tent. The 4 fluorescent bulbs were mounted on the 2 sides of the shooting tent, 25 cm above and at an angle of 45° to the food sample plane. The digital camera was mounted downward on the top of the tent, 50 cm above the sample plane. The lights were turned on at least 15 min before the pictures were taken. A Roche *Salmo*Fan™ color wheel, comprising 15 color cards, each with an individual number ranging from gray pink to deep red and frequently used for color assessment of Atlantic salmon flesh, was used to verify the experimental settings prior to actual measurements. Color images were downloaded into the computer for analysis.

The color parameters (CIE L^*, a^*, and b^*) were derived using Adobe Photoshop CS2 software (version 8.0, Adobe Systems Inc., San Jose, Calif., U.S.A.). The procedures involved using a magic wand tool to select sample area, and a histogram tool to indicate the average lightness, redness, and yellowness values for the selected area. In CIE LAB, L^* ranges from 0 to 100, a^* and b^* from −127 to +128; however, in Photoshop, these color values are encoded between 0 and 255. The color values from Photoshop (referred as L, a, b) were converted to standard scaling values using formula (Briones and Aguilera 2005):

$$L^* = \frac{L}{2.5} \quad (2)$$

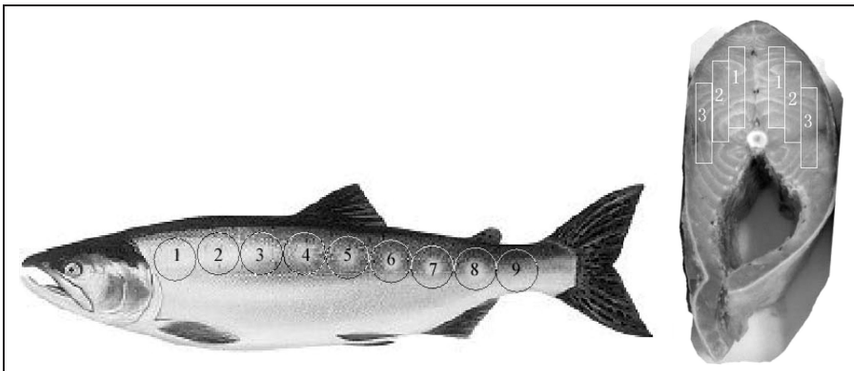

Figure 2—Example of sampling locations for the study of quality variation along the salmon length (left: the sampling sections 1 to 9; right: the sampling layers on the transverse section)

$$a^* = \frac{240a}{255} - 120 \quad (3)$$

$$b^* = \frac{240b}{255} - 120 \quad (4)$$

A comparative study was conducted by using a Minolta Spectrophotometer (Model CM-2002) and the CVS to measure color cards in the Roche *Salmo*Fan.

For sample area determination, the Vision IMAQ Builder image-processing software Version 6.1 (National Instruments, Austin, Tex., U.S.A.) was used. The area of sample image was determined using the "area measurement" menu. The shrinkage ratio was calculated as:

$$\text{Area shrinkage ratio} = \frac{\text{area of raw sample} - \text{area of cooked sample}}{\text{area of raw sample}} \times 100\% \quad (5)$$

Statistical analysis

The data of quality attributes of raw and heated samples from different locations of the fillets were compared by using analysis of variance (ANOVA) in the general linear models procedure of the SAS System for Windows V8.01 (SAS 1996). Differences between group means were analyzed by Duncan's multiple-range test. Statistical significance was set at a 0.05 probability level. The coefficient of variation (CV) was calculated as a percent of the standard deviation to the mean value (SD/mean × 100), and was used to compare the precision of the shear force measurements by different means.

Results and Discussion

Comparison between measuring methods

Color. Figure 3 shows the correlations between L^*, a^*, b^* values obtained by the CVS and spectrophotometer measuring and the color cards in the Roche *Salmo*Fan. High correlation coefficients were observed between the 2 methods for the all 3 parameters ($R^2 = 0.998$, 0.976, and 0.972 for CIE L^*, a^*, and b^*, respectively). CVS has some special advantages over colorimeter/spectrophotometers. The use of a colorimeter/spectrophotometer requires a fairly large flat sample area for accurate measurement; but this is not a limiting factor for a CVS. This is particularly true in our study. The samples used were only about 7 cm^2, which is too small for multiple measurements with a spectrophotometric colorimeter. After heating, the sample surface was oily and sticky, and the muscle fibers tended to fall apart when applying a slight force. All those characteristics in samples make CVS a better choice for color measurement. With CVS, the color values were obtained from the whole sample area under a controlled and reproducible environment. In addition, sample images could be stored electronically for other analyses, for example, subset colors and area. But to use CVS to obtain consistent and reliable results, it is important to use a standardized illumination for each measurement (Briones and Aguilera 2005), along with a reference color with known values to verify the accuracy of the system.

Shear force. The results of a comparative study on the 2 texture fixtures show a high correlation ($R^2 = 0.932$) between MTB and single blade probe methods, indicating that both methods can be used to evaluate shear force of raw and cooked salmon. CV is an important measure of the consistence of the results and reflects the sensitivity of the test method. Table 1 compares the CV values for the 2 methods on the outer layer samples. The single-blade probe method had generally higher CV (4.98% to 36.06%) than MTB (0.05% to 10.74%), indicating the latter is a much more sensitive and consistent method. Compared to standard Kramer shear/compression cell, the denser, thinner blades in the MTB resulted in a higher effective total contact length of the blades on sample over a limited sample area. For small samples, MTB effectively improved the accuracy and reduced the deviation caused by texture heterogeneity. Moreover, the small slit width in the base prevented the cooked fish muscles from falling apart, allowing for measurement of much smaller samples than a standard Kramer cell. The thin blades also reduced compression when cutting through the samples, leading to results that better correlate with actual shear force measurements (Dunajski 1979).

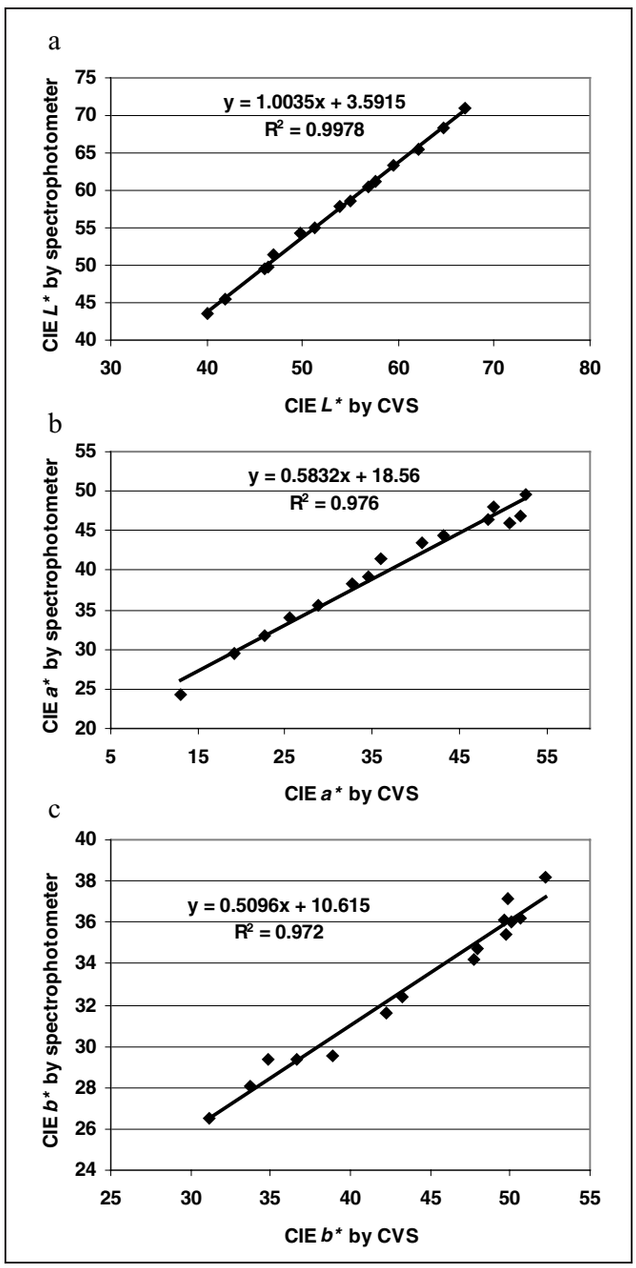

Figure 3—Relationships between color values of Roche *Salmo*Fan color cards measured by the CVS and a CM-2002 spectrophotometer: (a) CIE L^*, (b) CIE a^*, (c) CIE b^*

Quality variation along the longitudinal axis of raw and heated salmon muscle

Color. Significant changes occurred in the CIE L^*, a^*, and b^* values when salmon muscle was heated at 121 °C for 20 min. Heating denatures myoglobin and oxidizes carotenoid pigments (Haard 1992), changing the muscle color from red to pale pink as reflected by an increase in lightness, and decreases in redness and yellowness. In general, no significant difference was found among samples taken from different locations in either the raw or heated fillet. The average values of L^*, a^*, and b^* for the raw samples are 55.19 ± 0.91; 26.27 ± 0.77, and 42.46 ± 1.16, respectively; after 20 min heating, these values became 83.03 ± 1.24, 4.10 ± 0.60, and 24.78 ± 0.58, respectively.

Salmon muscle redness contributes significantly to the overall enjoyment of raw and cooked salmonid flesh (Bjerkeng 2000) and reflects the total carotenoid pigment content (Bjerkeng 2000; Johnston and others 2000). A longitudinal variation in carotenoid content has been reported in literature, with more astaxanthin being deposited in the caudal compared to the anterior part for farm raised Atlantic salmon (Bjerkeng 2000). Although color differences were anticipated from the heat treatments used in this study, little difference in color was expected between different locations of a fish. Pink salmon has a low average carotenoid content. Variations in color that are commonly observed in more highly pigmented *Oncorhynhus* species such as chinook (*O. tschawytscha*) or sockeye (*O. nerka*) were not detectable here, and no measurable differences were observed in redness along the length of the fillets. Furthermore, female salmon muscle loses color during spawning as carotenoid pigment and lipid are mobilized from the flesh and deposited to the eggs.

Shear force. Figure 4 shows the variation of shear force properties with locations in the raw salmon fillet as measured by MTB. The shear force of outer layer samples was significantly ($P < 0.05$) higher than the samples in the inner and middle layer, while the shear force of the samples from inner and middle layers was generally not significantly different from each other. Because the main difference between the outer and inner/middle layer samples is the red muscle being part of the outer layer (Kiessling and others 2006), this result suggests that the red muscle is firmer than white muscle. When shearing outer layer of the samples, it was observed that the red muscle fibers required much higher force to cut than did the white muscle. For the outer layer, the shear force significantly increased from head (42 N) to the tail (111 N), suggesting that the red muscle in the head area was more tender than in the tail.

The variation of tenderness along the salmon fillet has been related to the varying contents of fat, moisture, and collagen, as well as muscle fiber dimensions and muscle fiber density (Dunajski 1979; Hatae and others 1990; Jonsson and others 2001). The tail area contains the lowest lipid content (Hughes and Robb 2001), and lower lipid content usually leads to a firmer texture (Dunajski 1979). Higher collagen content also contributes to firmer texture. Montero and Borderias (1989) observed higher shear strength values in trout (*Salmo irideus* Gibb) near the tail, which has a higher proportion of insoluble collagen compared to other parts of the musculature. Muscle cell dimensions and arrangement vary throughout the fillet and this affects texture. Larger numbers of smaller diameter muscle fibers are present in the tail compared to other parts of a same fish (Love 1970). This study confirms previous reports that the tail muscle is firmer than head (Sigurgisladottir and others 1999; Jonsson and others 2001; Casas and others 2006). Our test result suggests that red muscle might play a major role in the firmness of the raw fillet; and its morphological and compositional variation along the fillet is responsible for the difference in shear forces between head and tail. This can be seen clearly in Figure 4, from the changes of shear force in different layers of section 6 and 7: the shear force in the outer layer increased significantly, while that of the inner and middle layer did not show significant difference compared to the anterior sections. The above observations might partly be the result of the smaller diameter of red muscle fibers (25 to 45 μm) compared to white fibers (50 to 100 μm) (Kiessling and others 2006). Our results also support the findings of Kanoh and others (1988) that the lower fiber diameter red muscle of yellowfin tuna had a firmer texture than other types of muscle fibers.

Figure 5 shows the shear force along salmon fillets after heating at 121.1 °C for 20 min. The shear force for each section is a mean of samples from different layers. Heating increased the shear force needed to break muscle fibers. The shear force of raw flesh was mostly in the range of 22 to 50 N (Figure 4). After heating, the shear force increased to 100 to 113 N (Figure 5). Heat-induced toughening of fish muscle is a result of heat denaturation of myofibrillar and sarcoplasmic proteins (Harris and Shorthose 1988; Hatae and others 1990). Protein denaturation leads to a reduced water-holding capacity and shrunken muscle fibers, and subsequently a harder and more compact tissue texture. The heated muscle is characterized with higher number of fibers of smaller diameter than raw muscle (Skrede and Storebakken 1986; Hatae and others 1990). In addition, heat-coagulated sarcoplasmic proteins dispersed between muscle fibers might contribute to firmness by impeding the sliding of the muscle fibers over each other (Hatae and others 1990).

Table 1—Comparison between the shear force results measured by multiple thin blade (MTB) fixture and blunt blade[a]

	MTB		Blunt blade	
Section	Mean shear force (N)	CV	Mean shear force (N)	CV
1	39.79	5.67	10.09	20.71
2	36.96	7.47	9.22	7.22
3	37.93	3.90	10.23	4.98
4	46.21	9.10	9.08	10.34
5	45.83	4.93	10.99	23.00
6	62.77	0.71	12.45	14.36
7	75.00	0.05	14.11	36.06
8	82.20	1.12	17.01	18.09
9	103.50	10.74	19.21	5.51

[a]The samples were outer layer from anterior to posterior (sections 1 to 9). The shear force value is a mean of 4 replicates.

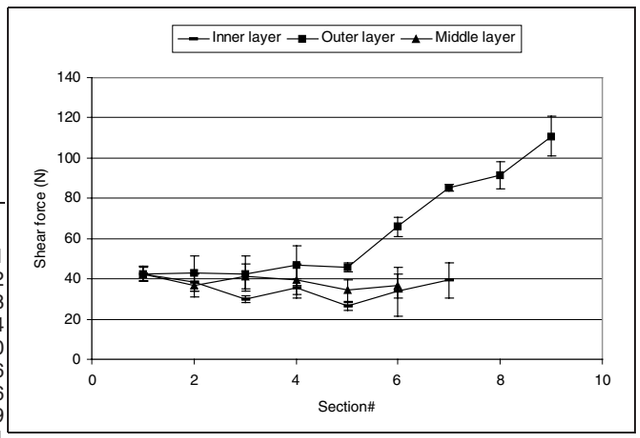

Figure 4—Shear force distribution at different locations along raw salmon fillet as shown in Figure 2. Bars indicate the standard deviation from 6 determinations.

Our results also indicate that the outer layer in a cooked sample has a similar tenderness as the middle and inner layers, in contrast to the raw fillet in which the tail and the outer layer are firmer (Figure 4). This might have resulted from the liquefaction of collagen and shrinkage of myofibrils. During heating, collagen liquefies readily, with the muscle fibers remaining as the sole element of resistance to shear in cooked fish meat from head to tail (Dunajski 1979). Sigurgisladottir and others (2000) found that freezing-induced protein denaturation in salmon caused the smaller diameter muscle fibers to shrink to a lesser extent than larger diameter fibers. Heat–induced protein denaturation might have a similar effect. That is, the white muscle fibers could shrink to a larger extent than the red muscle fibers. This would result in the difference between the fiber diameter and fiber density of denatured red muscle and that of white muscle fibers diminishing, subsequently reducing the differences in the texture between the 2 types of muscle.

Cook loss and shrinkage. Figure 6 shows variations in cook loss for samples taken over the length of the fillet after heating at 121 °C for 20 min. The cook loss ranged from 14% to 22%. The head (section 1, 2) and tail (section 9) had significantly higher cook loss than the middle sections ($P < 0.05$). Our measurements indicate that more than 85% of the cook loss was water, with lipids and solids including collagen or gelatin and muscle fragments and coagulated sarcoplasmic proteins. As a comparison, Ofstad and others (1993) found 84% of liquid was water when salmon muscle was heated at 70 °C. Expulsion of water from the myofibrils occurred as they shrank due to denaturation of myosin (Ofstad and others 1993; Palka and Daun 1999). Higher fat content and the higher stability of the myosin/actomyosin fractions are important for better liquid-holding capacity (Ofstad and others 1993).

Figure 7 shows the moisture distribution along the length of raw salmon fillet. Significantly ($P < 0.05$) higher moisture (> 75.8%, wet basis) exists in the head (section 1, 2) and tail (section 8, 9). The muscle in proximity to the dorsal fin had lower moisture content, which is in agreement with findings of other researchers (Kasai and others 1997; Bell and others 1998). It is well known that the fat and moisture concentrations exhibit an inverse relationship in salmon fillets (Hughes and Robb 2001; Huang and others 2002; Azumaya and others 2003), and high moisture and lower fat are related to higher cook loss (Ofstad and others 1993).

The shrinkage ratio values for samples taken along the length of a fillet after heating at 121.1 °C for 20 min are shown in Figure 8. Overall it ranged from 17% to 25%, with samples from the head show-

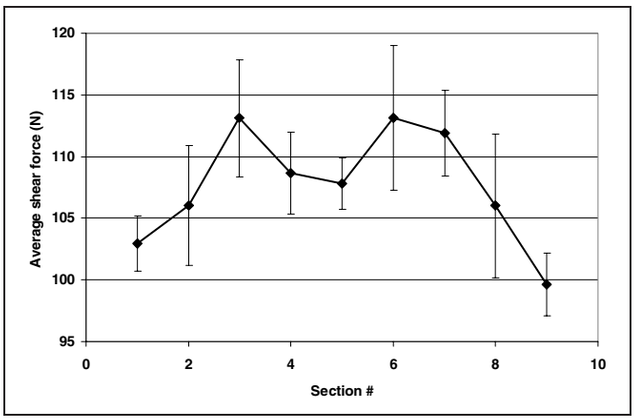

Figure 5—Shear force distribution of heated salmon muscle along the length of a pink salmon fillet (121 °C, 20 min). The shear force value is a mean of all layers (inner, middle, and outer). Bars indicate the standard deviation from 6 to 18 determinations depending on the muscle thickness.

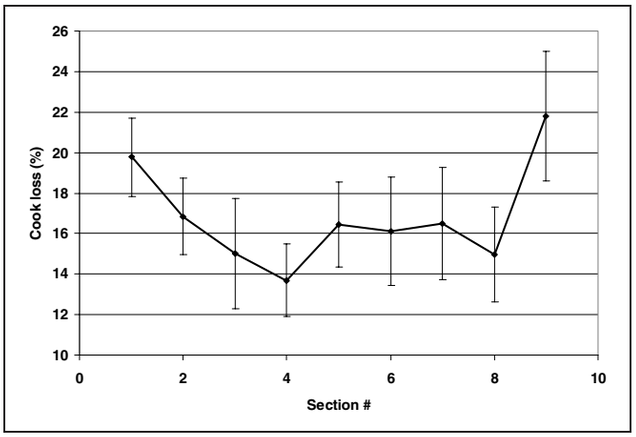

Figure 6—Changes of heating-induced cook loss along the length of a pink salmon fillet length (121 °C, 20 min). Bars indicate the standard deviation from 6 to 18 determinations depending on the muscle thickness.

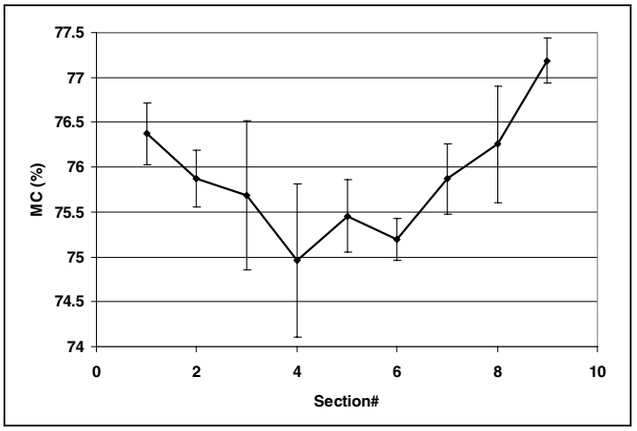

Figure 7—Moisture distribution along salmon fillet length. The moisture value is a mean of all layers (inner, middle, and outer). Bars indicate the standard deviation from 6 determinations.

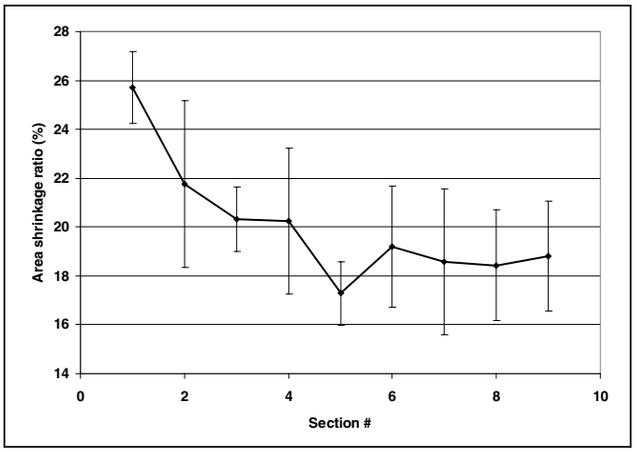

Figure 8—Changes of area shrinkage ratio along the length of a pink salmon fillet length after heating at 121 °C for 20 min. The ratio value is a mean of all layers (inner, middle, and outer). Bars indicate the standard deviation from 6 to 18 determinations depending on the muscle thickness.

ing a significantly higher shrinkage value ($P < 0.05$) than the other areas. Cook loss is positively correlated with shrinkage (Palka and Daun 1999; Barbera and Tassone 2006). In addition, the percentage of red muscle increased from head to tail areas, and the front half of the fillet contains mostly white muscle (Love 1970). As stated earlier, the white muscle fibers might shrink to a larger extent than the red muscle fibers. Therefore, the severe area shrinkage in the head region might be also related to greater shrinkage of white muscle.

Reproducibility of quality measurements is affected by sampling technique because of the heterogeneity within a salmon fillet. Color, shear force, cook loss, and shrinkage changed with the locations from which samples were taken on a salmon fillet, with the sample areas closest to the dorsal fin (inner and middle layers of section number 3 to 6) having more consistent quality properties. Because results from samples taken in the dorsal region were more reproducible, only the dorsal samples were used for studies on the influence of heating time. These results are summarized in the next section.

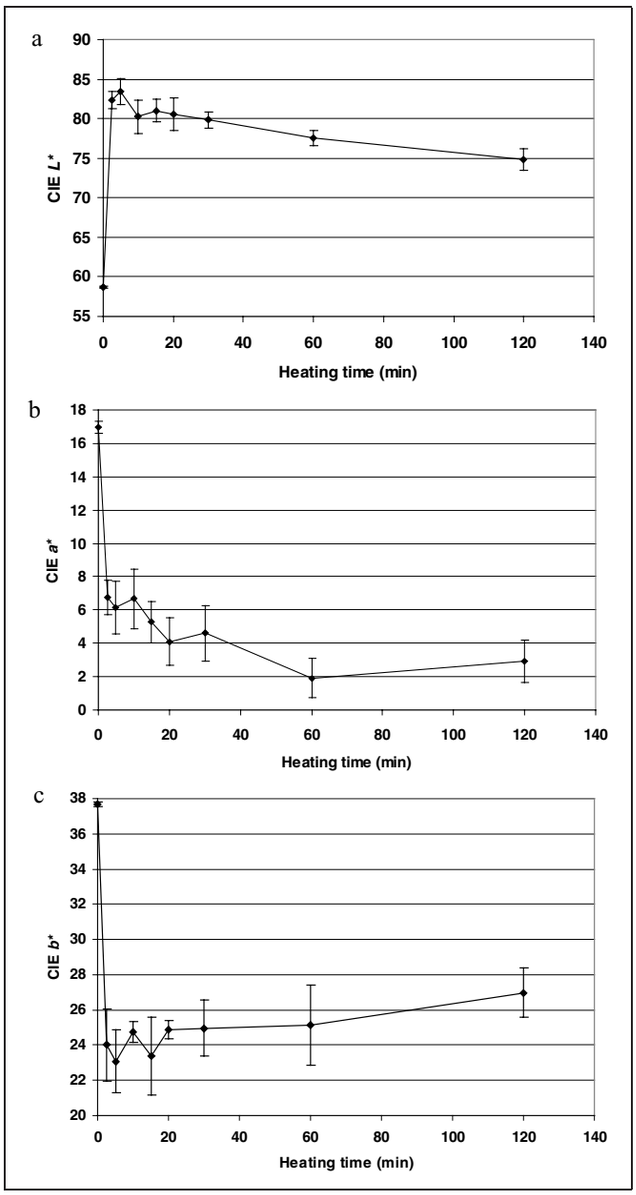

Figure 9—Progressive changes of muscle color with time at 121.1 °C: (a) CIE *L*∗, (b) CIE *a*∗, (c) CIE *b*∗. Bars indicate the standard deviation from 6 determinations.

Progressive changes of salmon quality properties with heating time at 121.1 °C

Color. Figure 9 shows the changes of muscle lightness, redness, and yellowness with heating time at 121.1 °C as measured by CVS. After heating, the color quickly faded from the original pale pink to whitish within 10 min: the lightness increased from originally 58 to a maximum 83, yellowness decreased from originally 38 to a minimum 23, and the redness dramatically decreased from originally 17 to 7. The rapid color change resulted from the denaturation of myoglobin and oxidation of carotenoid pigments at 121 °C. More than 36% of astaxanthin is destroyed during canning (Haard 1992). As the heating time increased, the color gradually changed to yellow and brown, which was reflected by consistent decrease in lightness and increase in yellowness, and a slight increased redness. The browning is mainly due to Maillard reactions (Haard 1992). Moreover, protein–lipid reactions may contribute to the color change that involves the oxidation of the highly unsaturated fatty acids in the salmon and the reaction of peroxide decomposition products with proteins (Haard 1992). Figure 9 shows that browning caused lightness to decrease and yellowness to increase consistently, following zero-order kinetics, which is in agreement with previous reports (Bhattacharya and others 1994).

Cook loss and area change. Figure 10 shows the changes of cook loss and area shrinkage ratio with time at 121.1 °C. At the end of 2-h heating, the area shrinkage ratio and the cook loss increased to 25% and 20%, respectively. Although both area shrinkage and cook loss consistently increased with heating time, most of the increase occurred within the first 10 min, in which area shrinkage ratio reached 18% and the cook loss reached 14%, both accounting for 70% of the total changes. As a comparison, rabbit meat showed 81% of total cooking losses in 20 min when heated at 80 °C (Combes and others 2004). Figure 10 shows a strong correlation between cook loss and area shrinkage ratio. The significant shortening in sarcomere length has been positively correlated to cook loss during heating on beef and pork (Palka and Daun 1999; Barbera and Tassone 2006).

Shear Force. Figure 11 shows a progressive change of shear force after heating for various times at 121.1 °C as measured using the MTB device. 2 peaks were observed: the 1st peak was after about 5-min heating time, when the shear force rapidly increased from 38 N in the raw samples to a maximum of 165 N; after that, the shear force quickly decreased to reach a minimum of 120 N at 20 min, then increased again to a second peak at 130 N about 1-h heating time. The shear force subsequently decreased consistently and reached 100 N after 2-h heating.

Some research has been conducted on the texture changes in fish muscle that occur during cooking (Kanoh and others 1988; Bhattacharya and others 1993); however, to our knowledge, no studies have followed a time course during heat sterilization of fish tissue or have reported a 2-peak shear force pattern such as that observed in our study. This may in part because the previous research has focused on lower temperature heating. For example, Bhattacharya and others (1993) studied the textural changes of Pacific chum salmon subjected to hydrothermal treatment (60 to 100 °C) for 40 min, and they found that at higher temperatures (80 to 100 °C) the hardness reached a peak within 10 min. In addition, the MTB shear force measurement method used in this study might be more sensitive and reveal minor textural changes. Notably, 2 peaks have been observed in texture changes involving the heating of beef (Harris and Shorthose 1988) and rabbit muscle (Combes and others 2004) during a heating process. For example, when rabbit

meat was slowly heated from 50 to 90 °C, the shear force as measured by WB probe significantly increased at 50 °C, then dramatically decreased to a minimum at 60 to 65 °C, and increased again reaching a maximum shear value at 80 to 90 °C (Combes and others 2004). This observation has been explained by texture changes due to collagen solubilization and denaturation of myofibrillar proteins (actin/myosin hardening) (Harris and Shorthose 1988). Specifically, the initial texture toughening is thought to be caused by denaturation and thermal shrinkage of connective tissue with collagen solubilization leading to decreases between 50 and 65 °C. The 2nd peak is probably due to hardening of the myofibrillar structure (Harris and Shorthose 1988).

The special features of fish muscle structure and the high temperature used in sterilization differentiate our study from previous ones, and thus the main mechanisms for textural changes might be different. Fish muscle contains very low amounts of connective tissue (2% to 3%) compared to that of terrestrial mammals (10% to 15%). Also, the collagen is much less heat stable than mammalian collagen (Dunajski 1979), so the influence of connective tissue on changes in texture following heating is likely to be smaller. The denaturation and melting temperatures of collagen are near 20 and 40 °C, respectively, and the denaturation of actin and the other sarcoplasmic proteins occurs at 60 to 80 °C (Ofstad and others 1993).

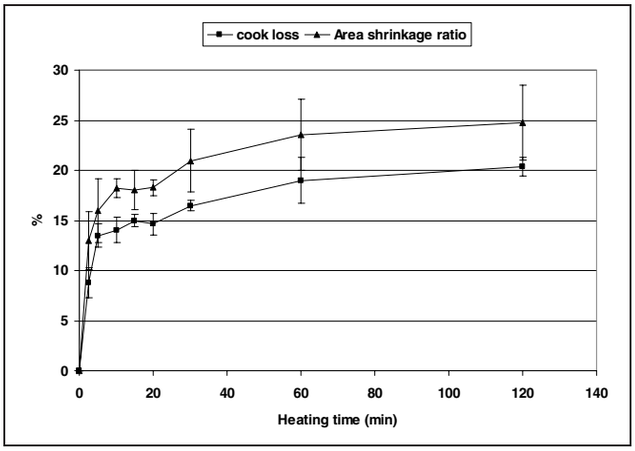

Figure 10—Progressive changes of cook loss and area shrinkage ratio of salmon fillet with time at 121.1 °C. Bars indicate the standard deviation from 6 determinations.

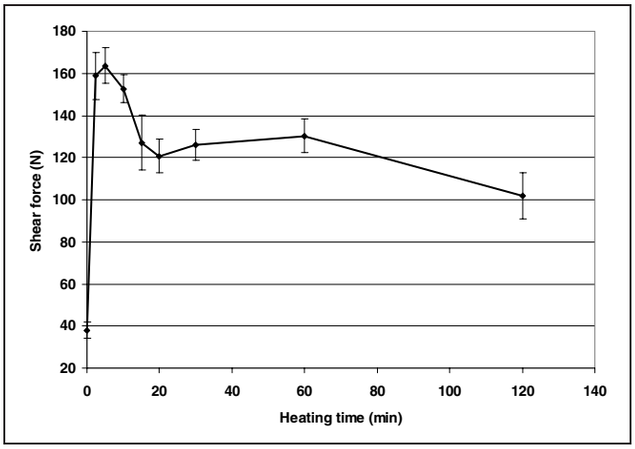

Figure 11—Progressive change of shear force with time at 121.1 °C for salmon muscle. Bars indicate the standard deviation from 6 determinations.

Therefore, the rapid heating to 121.1 °C in our study might denature the proteins rapidly, and the resultant thermal shrinkage of proteins, solubilization, and gelation of collagen, and dehydration might occur almost simultaneously. The 2-peak feature in the shear force profile might have resulted from the following: in the first 5 min, the hardening effect caused by protein denaturation and dehydration was stronger than the tenderization caused by collagen solubilization, the net effect being an increase in toughening. At 5 min, most of the proteins had been denatured, thus collagen solubilization and gelation would become dominant with the net effect being tenderization. After 20-min heating, collagen liquefaction would have been almost completed; the continual dehydration and shrinkage of actin/myosin, protein aggregation in which covalent bonding might be involved, and the increased formation of 0-coagulated sarcoplasmic proteinaeous aggregates between myofibrils might be the main factors leading to an increase in toughness (Dunajski 1979; Hatae and others 1990; Gill and others 1992). At 60 min, the sarcoplasmic protein aggregates mixed with gelatin were able to hold water and/or plug the intracellular capillaries, thus reducing the amount of liquid being released (Ofstad and others 1993); the cook loss and the area shrinkage ratio thereafter did not significantly increase (Figure 10). After 1 h of heating, the tissue gradually became softer due to heat-induced muscle decomposition and fragmentation. However, more detailed study on the changes of collagen content and microstructure, including sarcomere length, fiber diameter, and density, would be helpful to fully understand the mechanisms involved.

Conclusions

The new MTB texture device provided reliable measurements for salmon muscle tenderness. The CVS served as a suitable mean for measuring the color and area changes of salmon muscle following heat treatments. Unlike shear force, color did not differ significantly along the length of raw salmon fillet. The content of red muscle in tissue samples influenced the force needed to shear raw salmon, but this effect diminished with heating. The tissue near the dorsal fin had less cook losses and shrinkage during heating, and yielded more reproducible results than tissue samples taken from the head and tail muscles, indicating that differences in morphology and chemical composition will have a significant effect on heating effects. When salmon muscle was heated at 121.1 °C for 2 h, the area shrinkage ratio and the cook loss increased to reach 25% and 20%, respectively. Most changes occurred within the 1st 10-min heating: the muscle color changed to the whitest, the shear force increased to the maximum, and 70% of total cook loss and shrinkage took place. The shear force profile had 2 peaks, with the 1st peak in the 5 min and 2nd peak at 1-h heating time, indicating that longer heating does not necessarily decrease muscle toughness.

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