Effects of Freezing on Quality of Cold-smoked Salmon Based on the Measurements of Physiochemical Characteristics

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ABSTRACT: How the quality of cold-smoked Atlantic salmon (*Salmo salar*) is affected by freezing the raw fish as whole fish, as gutted fish, and as fillets before smoking, and by freezing the finished product after smoking was studied. Freezing before smoking resulted in increased product yield and water content, but softer texture and increased K-value. Freezing reduced the content of astaxanthin but increased the lightness and the color intensity of the flesh. Gaping increased when the fish was frozen as fillets before smoking. Freezing only after smoking led to fewer changes in quality than freezing before smoking, whereas refreezing the finished products had little additional effect on quality.

Keywords: cold-smoked salmon, freezing, texture, color, yield

Introduction

COLD-SMOKED SALMON IS A LIGHTLY PRESERVED fish product of considerable economic importance throughout the world; 40% to 50% of Norwegian Atlantic salmon (*Salmo salar*) reaches the final consumer as a cold-smoked product (Borch and Aaker 1997). Fish are smoked in industrialized countries to enhance the flavor and texture, and this form of processing only to a certain degree protects against microbiological, enzymatic, and chemical degradation.

A successful smoked product depends on high yield throughout the process (Rørå and others 1998), on desirable and good quality, and on an acceptable shelf life (Dobbs and others 1992). Product yield is important for the economic output, and both starvation (Lie and Huse 1992; Einen and others 1998) and feed ration level (Einen and others 1999) before harvest have been associated with reduced fillet yield of Atlantic salmon. Furthermore, Rørå and others (1998) showed that smoking yield increased with increasing fat content of the raw material. Cold-smoked salmon is processed in many ways, and the techniques used for salting, drying, and smoking affect both yield and general quality.

The color of the flesh is one of the most important sensory attributes of farmed Atlantic salmon (Simpson 1978; Christiansen and others 1995). Fading of color, or "de-pigmentation," consequently has a severe negative effect on the marketability of the salmon. Smoked salmon is sold on markets that have different preferences for flesh pigmentation, but usually a deep red/orange color is preferred (Moe 1990; Gormley 1992). A relationship between the concentration of carotenoids and red color intensity in raw, boiled, and smoked Atlantic salmon is given by Skrede and Storebakken (1986). Besides initial concentration of carotenoids in the muscle, the color of the smoked product also depends on textural properties, chemical composition, and the liquid-binding ability of the muscle. Soft texture, fillet gaping, and liquid loss are serious problems for the smoking industry. Though some effects of pH and muscle composition can be found, little is known about what initiates these problems in smoked salmon.

Most sizes of farmed Atlantic salmon are now available throughout the year, but smokehouses may choose to freeze their fish either before or after processing for reasons of tradition, price, or logistics. Furthermore, the product might be frozen once or twice in the retail store or the home freezer before consumption. Freezing, frozen storage, and thawing are all processes that can cause changes in the properties of fish flesh; and apart from the primary quality of the flesh, the characteristics of the freezing process, including storage and thawing, affect the quality of the product at consumption. Earlier studies have shown the effects of frozen storage on sensory attributes, color, and chemical composition of salmon (Refsgaard and others 1998; Sheehan and others 1998). The changes have been explained as arising from biochemical changes that occur during long storage periods, and the effects of short-term freezing on salmon quality are not known. Considerable attention has been given to chemical and microbiological quality indicators to predict the shelf life of frozen fish, also in combination with smoking (Truelstrup Hansen and others 1996). However, the ways in which freezing affects other important quality characteristics such as the yield, color, and texture of cold-smoked salmon have been given little attention.

The objective of this study was to evaluate how freezing the fish before and/or after smoking affected central quality characteristics of the finished cold-smoked salmon.

Materials and Methods

Fish material

Gutted Atlantic salmon were obtained from a feed ration experiment of duration 110 d at AKVAFORSK's Research Station (Ekkilsøy, Norway). Einen and others (1999) have described the details of this experiment. The experimental fish were kept in 6 net pens in seawater and fed 3 different ration levels, namely 0%, 75%, and 100% of voluntary feed intake, with 2 net pens per ration level. The fish were fed a commercial diet (ROYAL 2 + manufactured by T. Skretting) containing 955 g/kg dry matter, 456 g/kg protein, 323 g/kg fat, 3 g/kg crude fiber, 103 g/kg carbohydrate, 51 mg/kg astaxanthin, and 25.0 MJ/kg gross energy. The ration levels (RLs) are denoted by RL = 0, RL = 75, and RL = 100, respectively. Fifteen fish were sampled from each of the 6 net pens for use in the experiment with different freeze/thaw treatments.

Freeze treatments

The salmon were treated in 3 groups. Fish in the first group were filleted and smoked fresh; fish in the second group were filleted, frozen as plastic-packed fillets, thawed, and then smoked; whereas fish in the third group were frozen as whole, gutted fish packed in plastic, thawed, filleted, and then smoked. The smoked fillets were cold-stored for 1 wk before analysis (left-side fillets), or frozen, thawed, and then cold-stored for 1 wk before analysis (right-side fillets). The experiment thus covered 36 experimental groups with 5 smoked fillets in each group: 6 different freeze/thaw treatments × 3 feed ration level × 2 net pens per ration level.

Whole fish or fillets to be frozen were packed individually in plastic bags, frozen by cold air in a climate chamber that could be regulated from –50 °C to + 50 °C ± 0.5 °C, and stored at –30 °C for 6 d before thawing and subsequent smoking. Freezing and thawing was recorded by temperature sensors in the center of 2 fish per treatment. A core temperature of –30 °C was reached in both whole and fillet frozen fish after 30 h, but the fillets frozen fish reached a core temperature of –10 °C after 8 h, whereas the whole-frozen fish reached the same temperature after 16 h. When thawing, the fillets passed –25 °C after 6 h, whereas the whole fillets used 26 h to reach the same temperature; both groups were completely thawed after 36 h. After smoking, the left-side fillets were frozen in vacuum packs in a freezing room at a constant temperature of –20 °C and stored frozen for 7 to 14 d before being thawed (at 4 °C) and analyzed.

Filleting and smoking

Two of the groups were sent in a refrigerated truck directly to the smokehouse, whereas the third group was sent to the laboratory of AKVAFORSK, Ås, Norway. The iced, gutted fish were there frozen on the third day after slaughter. The 2 fish groups that were sent directly to the smokehouse were stored on ice at 0 to 3 °C for 5 d after slaughtering before processing. One of these 2 groups was filleted by machine and trimmed according to standard B (NSA 1996), which includes skin but where visible dorsal and ventral fat depots, bones, and peritoneum are removed before the fillets were frozen. The other group was machine-filleted, hand-trimmed, and salted by automatic injection brining using a 25% wt/wt brine and an injection pressure of 1 bar. The fillets were then cold-smoked for 2.5 h at 23 °C and at a relative humidity of 69% in a smoke oven supplied with smoke generated from beech wood, and then chilled to 4 °C and vacuum-packed. After thawing, the whole-frozen and filleted-frozen fish were smoked and packed in exactly the same manner, using the same experienced trimmer for all the fish.

Yield and liquid-holding capacity

Both round weight and gutted weight were recorded at slaughter, and fillet weight was recorded after brine injection and after smoking. After smoking, all fish were packed with a 10- × 10-cm absorbent pad having a dry weight of 4.2 g (NKL, Oslo, Norway) between the skin side of the fish and the vacuum pack. The absorbent pad absorbed all liquid leakage from the smoked salmon during storage and during freezing. The vacuum packs were opened and the wet absorbent pad was weighed. The absorbent pad was then dried at 60 °C for 24 h to distinguish between water and other material. Loss in the vacuum pack was multiplied by 2, divided by the round weight, and expressed as percentage loss.

Pooled samples of muscle from 5 smoked fillets, taken directly under the dorsal fin, were collected from each of the 36 experimental groups, finely chopped, and analyzed for liquid-holding capacity. The samples (15 g) were weighed and placed in a tube with a weighted filter paper (V_1) (Schleicher & Schuell GmbH, Dassel, Germany). The tubes were centrifuged at 500 × *g* for 10 min at 10 °C, as described by Hermansson (1986), and the wet paper was weighted (V_2) before drying at 50 °C to constant weight (V_3). The percentage liquid loss was calculated on a wet weight basis as $100 \times (V_1 - V_2) \times S^{-1}$, where S = weight of muscle sample, water loss as $100 \times (V_2 - V_3) \times S^{-1}$, and fat loss as $100 \times (V_3 - V_1) \times S^{-1}$, respectively.

Chemical analysis

Dry matter content was determined on an individual basis following heating at 105 °C for 24 h, whereas the rest of the chemical analyses were performed on pooled homogenates of the 5 fillets in each group. Protein content was analyzed as Kjeldahl- N*6.25 (Kjeltec Autoanalyser, Tecator, Sweden) and fat by ethyl-acetate extraction (NSA 1994).

The K-value was determined using the test strips Fresh Tester FTP II (Transia, Netherlands), which is a simple enzymatic colorimetric method. This method gives the K-value as 100% × (Inosine + Hypoxanthine)/(IMP + Inosine + Hypoxanthine) as defined by Karube and others (1984). Salt was measured with a Chloride Analyser 926 (Corning, Halstead, U.K.).

Color analysis

Instrumental color analyses (CIE 1976 $L^*a^*b^*$) were performed using a Minolta Chroma Meter CR-200 (Minolta, Osaka, Japan) with light source D. Four measurements were carried out directly on each fillet. L^* describes the lightness of the sample, a^* the intensity of red color ($a^* > 0$), and b* the intensity of yellow color (b* > 0). The color intensity (c) was calculated as $c = (a^{*2} + b^{*2})^{1/2}$. Furthermore, the hue angle (h_{ab}) was calculated as $h_{ab} = \tan^{-1}(b^*/a^*)$, where $h_{ab} = 0°$ for a red hue and $h_{ab} = 90°$ for a yellow hue. Astaxanthin from pooled samples was determined by high-performance liquid chromatography using Hewlett Packard Series 1050 Instrument (Palo Alto, Calif., U.S.A.) as described by Bjerkeng and others (1997). All samples were analyzed isocratically on a Spherisorb S5CN-4800 nitrile column (Hichrom Ltd., Theale, Berkshire, UK; 250-mm length; 4.6-mm internal dia; 5-μm particle size) using 20% acetone in hexane as mobil phase.

Texture analysis

Fillet gaping was evaluated according to a scale from 0 to 5 of gaping severity (Andersen and others 1994) on which score 0 describes fish with no gaping and score 5 describes fish with extreme gaping with the fillet falling apart. Two judges with several years experience in gaping evaluation performed the scoring.

Fillet texture was measured by compression using a Texture Analyser, TA-XT2 (Stable Micro Systems, Surrey, England) with a 12.5-mm cylindrical probe. Texture profile analyses were performed using a test speed of 2 mm/s and 60% penetration on the fillets and 90% penetration on 2-cm-thick cutlets. The force needed to create a break in the muscle was denoted as the breakpoint value. Four measurements were taken from each fillet and from each cutlet, and the mean was used in further calculation.

Statistical analysis

The effects of ration level, with the net pen as the unit of observation, and the effects of freezing before and after smoking were analyzed by ANOVA. Means were ranked by the Student-Newman-Keuls test with the significance level set at 5%. Principal component analysis (PCA) was performed including all the variables measured on an individual basis. The variables were weighed by 1/SD when used in the PCA analysis. Numbers in the text are given as mean ± SD.

Results

PCA ANALYSIS OF ALL DATA SHOWED THAT THE main principal component (PC1), explaining 31% of the variation, grouped the fillets according to the degree of freezing (Figure 1a). The fresh smoked fillets were totally separated from the other groups, whereas

Table 1—Yield and liquid-holding capacity of Atlantic salmon fillets frozen before and/or after smoking

Treatment before smoking	Fresh		Fillet frozen		Whole frozen			ANOVA[a]		
Treatment after smoking	Fresh	Frozen	Fresh	Frozen	Fresh	Frozen	Root MSE	P_{before}	P_{after}	$P_{Interaction}$
Gutted weight (g)	4314	—	4380	—	4474	—	876.9	0.495	—	—
Yield after brining (%)	63.3	—	64.4	—	65.1	—	2.83	0.002	—	—
Yield after smoking (%)	54.4	—	57.5	—	58.1	—	3.01	0.001	—	—
Loss in vacuum pack (%)	0.2	0.2	0.2	0.2	0.2	0.2	0.09	0.921	0.263	0.562
Liquid loss from salmon muscle (%)	4.4	5.3	2.8	3.4	2.9	4.7	1.81	0.001	0.001	0.164
(%) of which was water	36.8	36.1	34.8	34.1	34.5	34.7	1.23	0.001	0.036	0.059

[a]Results from ANOVA where root MSE is the square root of the mean square error, and P_{before}, P_{after}, and $P_{Interaction}$ denote the significance levels for effects of freezing before and after smoking and the interaction, respectively.

the fresh refrozen fillets were grouped closer to the rest of the material, but still clearly separated. The second principal component (PC2), explaining 24% of the variation, separated the fillets according to feed ration level. The starved fish (RL = 0) were clearly separated from the other ration level groups (RL = 75 and RL = 100). The third principal component, explaining 15% of the variation, separated the fillets according to refreezing after smoking (Figure 1b). The plots indicate the relative importance of the pre-slaughter treatment of the fish material and freezing before and/or after smoking on the ultimate quality of the smoked fillets.

Yield and liquid-holding capacity

Different feeding intensities before slaughter gave a range in round weight from 2660 g to 6240 g. However, the fish were selected so there were no significant differences in average weights between the different freezing treatments (Table 1). The mean yield after brine injection was 64.2% ± 2.9% and after smoking was 56.6% ± 3.3%. The yield after brine injection was significantly higher when using whole-frozen fish than it was when using fresh or frozen fillets before smoking ($P < 0.05$). The yield after smoking was significantly different between all 3 freezing treatments used before smoking. There were no significant differences due to freezing before or after smoking in the amounts of liquid absorbed in the vacuum packs (Table 1). However, there was a significant interaction between feed ration level and treatment before smoking. The liquid loss was higher at RL = 0 than it was at RL = 75% and at 100% when the fish were frozen as fillets before smoking, but the liquid loss was lower at RL = 0 than it was at RL = 75% when the fish were frozen whole or kept fresh before smoking (Figure 1a). The mean weight of liquid loss from salmon muscle after centrifugation was 3.9% ± 2.0%, and 35.2% of this was water (Table 1). The liquid loss was higher in the fresh smoked group (4.8% ± 2.0%) than it was in the whole-frozen group (3.8% ± 1.7%) and in the fillet-frozen group (3.1 ± 2.0%). The amount of water lost was approximately 2% higher in the fresh smoked groups than it was in the other groups (Table 1). Fillets frozen after smoking lost more liquid in the form of fat (4.4% ± 1.6% liquid loss, 35% of which was water) than those only cold-stored (3.4% ± 1.5% liquid loss, 35.5% of which was water).

Chemical composition

The mean protein content of the fish material was 19.4% (range, 18.2% to 20.8%), and

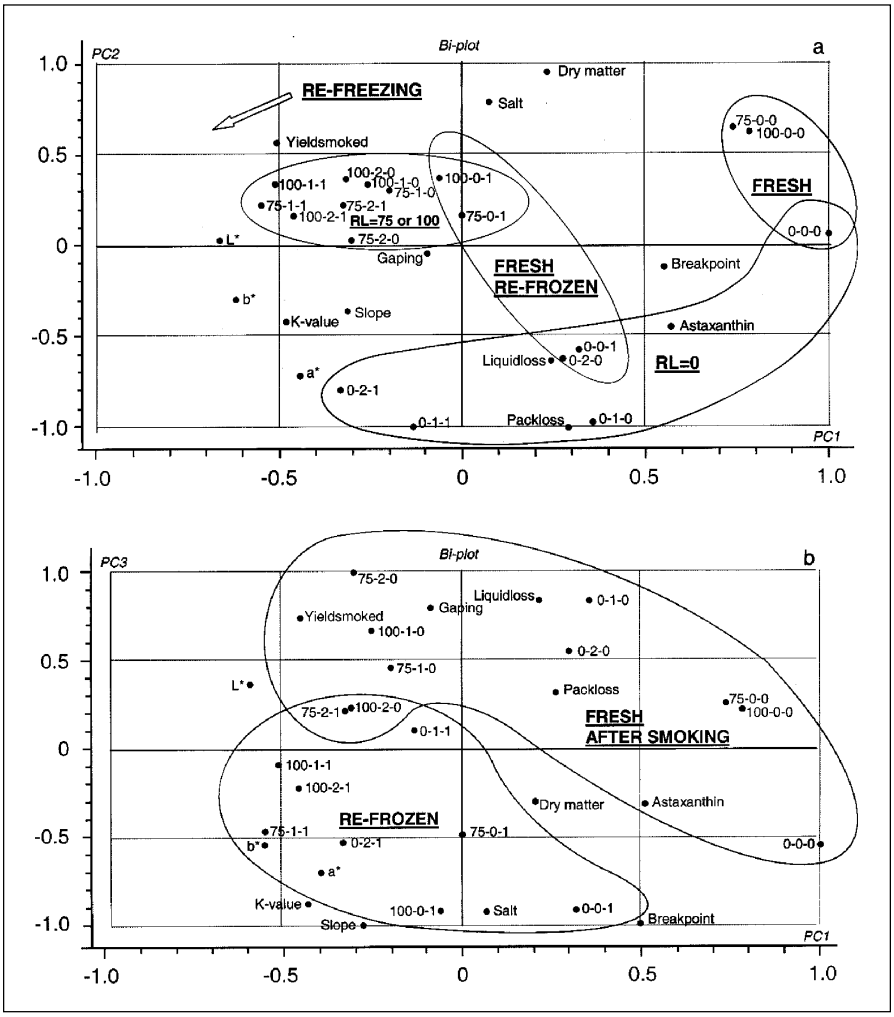

Figure 1—Principal component analysis (PCA) biplots of (a) PC1 (31%) and PC2 (24%), and (b) PC1 and PC3 (15%) of 36 groups of smoked Atlantic salmon. The first denotation gives the feed ration level (0%, 75%, 100%); the second gives the treatment before smoking (0 = fresh, 1 = fillet frozen, 2 = whole frozen); and the third gives the treatment after smoking (0 = fresh, 1 = frozen). Packloss = loss in vacuum packs.

Table 2—Composition of fillets frozen before and/or after smoking (n = 30)

Treatment before smoking	Fresh		Fillet frozen		Whole frozen			ANOVA[a]		
Treatment after smoking	Fresh	Frozen	Fresh	Frozen	Fresh	Frozen	Root MSE	P_{before}	P_{after}	$P_{Interaction}$
K-value (%)	59.3	72.5	66.5	75.0	67.2	75.0	6.04	0.001	0.001	0.034
Salt content (%)	3.1	3.1	2.6	2.9	2.7	2.9	0.24	0.001	0.001	0.115
Dry matter content (%)	36.8	36.1	34.8	34.1	34.5	34.7	1.23	0.001	0.036	0.059

[a]Results from ANOVA where root MSE is the square root of the mean square error, and P_{before}, P_{after}, and $P_{Interaction}$ denote the significance levels for effects of freezing before and after smoking and the interaction, respectively.

the mean fat content was 12.7% (range, 10.8% to 14.6%).

Fish smoked fresh had a lower K-value (65.9%) than whole-frozen fish (71.1%) and fillet-frozen fish (70.9%) (Table 2). There were significant interactions both between feed ration level and freezing before smoking, and between freezing before and after smoking. Fish at RL = 100 had a lower K-value than fish at RL = 75 and RL = 0 when smoked fresh, but this was not the case when the fish were frozen (as fillet or whole) before smoking (Figure 1a). Freezing after smoking increased the K-value from 64.3% to 74.2% (Table 2).

The smoked fillets in this study were brine injected, and the analyzed salt content varied from 2.1% to 3.3% with an average of 2.9%. There were significant differences in average salt content for freeze treatments (Table 2). The salt content depended on the treatment before smoking, and fish smoked fresh had a higher salt content (3.1%) than whole-frozen fish (2.8%) and fillet-frozen fish (2.8%). Fish refrozen after smoking had a higher salt content (3.0%) than those not frozen (2.8%). Fish smoked fresh also had a higher dry matter content (36.5%) than whole-frozen fish (34.6%) and fillet-frozen fish (34.4%). Fillets frozen after smoking had a significantly lower dry matter content than fish that were not refrozen.

Color characteristics

Freezing before smoking had a significant effect on all color characteristics. Astaxanthin content was reduced from fresh smoked to fillet-frozen and whole-frozen fish (Table 3). There was no significant difference between fish frozen whole and fish frozen as fillets before smoking. There was also an interaction effect with pre-slaughter treatment showing that starved fish, having the highest astaxanthin content when smoked as fresh, ended with astaxanthin content in line with the 2 other ration levels (RL = 75 and 100) when the fish was frozen before smoking. There was on average significant lower astaxanthin in fillets that were frozen after smoking (5.6 mg/kg) compared with fillets stored fresh after smoking (6.1 mg/kg).

The CIE (1976) color values for lightness (L^*), redness (a^*), and yellowness (b^*) increased significantly due to freezing before and after smoking (Table 3). The color intensity (c) also increased significantly after the freezing treatments, whereas the hue (h_{ab}) did not change significantly. Freezing before smoking had a significant effect on L^*: fish frozen whole (50.8) and fish frozen as fillets (49.0) had higher L^* values than fillets that were smoked fresh (45.6). Freezing before smoking, either as whole fish or as fillets, also increased significantly the a^* and b^* values (Table 3). Furthermore, the freezing of fillets after smoking increased the average a^* value from 8.7 to 10.5 and the b^* value from 24.0 to 28.1 in fillets that were either stored fresh or frozen after smoking, respectively. The relative increases in a^* and b^* values were much larger than the increase in L^*, indicating a more reddish and a more yellowish color impression of the fillets frozen before or after smoking.

Gaping and texture evaluation

Gaping scores were generally low with a mean of 0.9 (on a scale from 0 to 5) for all the smoked fillets. Fish frozen as fillets before smoking had a higher gaping score (1.3) than fish smoked fresh (0.7) and than fish whole-frozen before smoking (0.6) (Table 4). Freezing the fillets after smoking did not significantly affect the gaping scores. There was an interaction between feed ration levels and freeze treatment before smoking: the higher gaping scores were less pronounced at RL = 75 than they were at RL = 0 and at RL = 100 for fish frozen as fillets before smoking compared with those that were frozen whole or kept fresh until smoking.

The breakpoint measured on fillets (on average, 10.7N) showed significant effects of both freezing before and after smoking (Table 4), whereas the breakpoint measured on cutlets (on average, 5.2N) was not significantly affected by freezing after smoking. However, for the breakpoint measured on cutlets, there were significant interaction effects between freezing before and after smoking (Table 4).

Discussion

A previous study (Einen and others 1999) of the same group of Atlantic salmon documented several changes in the raw fillet characteristics with reduced feed ration (lower contents of fat, water-soluble protein, and astaxanthin; higher content of collagen and higher pH). The study also showed that reduced feed ration affected the sensory quality of smoked fillets (increased hardness and redness, and reduced fattiness and juiciness). The results presented here show that freezing before and/or after smoking also affects the yield and quality of smoked salmon. The interactions between fish raw material for smoking and freezing (before and/or after smoking) stress the importance of husbandry and feeding practices.

The higher yields and higher water content (that is, lower dry matter) of the frozen fillets indicate increased uptake of brine into the muscle due to freezing. Freezing and drying cause major changes in muscle pH and the ionic strength, which profoundly influence the swelling of myofibrils and thus the ability of the muscle to bind water (Wilding and others 1986; Fennema 1990). The nature of the changes depends on the freezing method used. Although the prefrozen groups contained more water, there was no indication of a looser bondage of this water when the fillets were stored in vacuum packs. It is generally accepted that myosin, in particular, undergoes aggregation reactions during frozen storage and that these reactions lead to muscle toughening and drip loss during thawing (Mackie 1993). The frozen storage periods were short in the experiments reported here, probably negligible, whereas the freezing and thawing were relatively slow and the flesh was exposed to the critical temperatures of –1 °C to –6 °C for a relatively long period. Generally, slow thawing (at 5 °C) will give higher liquid loss than fast thawing (at 25 °C in water) (Bilinski and others 1977; Nilsson and Ekstrand 1995). Only extracellular water will be freed by the low-pressure method used in the present study (Offer and Trinick 1983), and loss of cellular water must involve movement of water from intracellular to extracellular locations. The greater loss of liquid during the centrifugation test from fillets frozen after smoking than from those ana-

Table 3—Color characteristics of fillets frozen before and/or after smoking (*n* = 30)

Treatment before smoking	Fresh		Fillet frozen		Whole frozen			ANOVA[a]		
Treatment after smoking	Fresh	Frozen	Fresh	Frozen	Fresh	Frozen	Root MSE	P_{before}	P_{after}	$P_{Interaction}$
Astaxanthin (mg/kg)	7.0	5.9	5.7	5.3	5.8	5.4	0.90	0.001	0.001	0.061
Instrumental color measurements (CIE 1976)										
Lightness (L^*)	44.3	46.8	47.9	49.9	50.1	51.6	1.84	0.001	0.001	0.336
Redness (a^*)	7.6	10.1	9.4	11.0	9.2	10.5	1.43	0.001	0.001	0.080
Yellowness (b^*)	21.4	26.9	25.6	29.3	25.1	28.1	1.80	0.001	0.001	0.006
Color intensity (c)	22.7	28.7	27.3	31.3	26.7	30.0	1.93	0.001	0.001	0.004
Hue (h_{ab})	70.5	69.5	69.9	69.5	69.9	69.5	2.55	0.899	0.134	0.824

[a]Results from ANOVA where root MSE is the square root of the mean square error, and P_{before}, P_{after}, and $P_{Interaction}$ denote the significance levels for effects of freezing before and after smoking and the interaction, respectively.

Table 4—Gaping score and instrumental texture measurements of fillets frozen before and/or after smoking (*n* = 30)

Treatment before smoking	Fresh		Fillet frozen		Whole frozen			ANOVA[a]		
Treatment after smoking	Fresh	Frozen	Fresh	Frozen	Fresh	Frozen	Root MSE	P_{before}	P_{after}	$P_{Interaction}$
Gaping score (0 to 5)	0.7	0.7	1.6	1.1	0.7	0.5	0.97	0.001	0.166	0.406
Breakpoint (N)										
Fillet	11.9	11.9	9.3	10.4	9.4	11.2	1.24	0.001	0.007	0.069
Cutlet	6.5	6.1	5.0	4.8	3.9	4.6	0.44	0.001	0.787	0.006

[a]Results from analyses of variance (ANOVA) where root MSE is the square root of the mean square error, and P_{before}, P_{after}, and $P_{Interaction}$ denote the significance levels for effects of freezing before and after smoking and the interaction, respectively.

lyzed when fresh is probably due to general muscle degradation and not to freeze-denaturation of proteins.

Adenosine 5-triphosphate (ATP) degeneration occurs rapidly at subzero temperatures down to –6 °C and will accelerate at temperatures just below 0 °C (Cappeln and others 1999). This finding agrees with our observations concerning the effects of freezing on the K-value. The ATP degeneration is due to both an increase in enzyme activity and to increased concentrations of soluble reactants or catalysts in the unfrozen water phase (Dyer 1968; Behnke and others 1973). The K-value does not account for bacterial growth and the risk of food-borne pathogens, which are the limiting factors for the shelf life of cold-smoked salmon (Rørvik and Yndestad 1991; Jemmi 1993), and thus the impact of freezing before and after smoking on the shelf life and freshness requires further documentation of microbiological parameters.

Astaxanthin levels were reduced by freezing both before and after smoking (both on a wet weight basis and dry matter basis). Similarly, carotenoids are degraded in frozen stored rainbow trout muscle (Chen and others 1984; Pozo and others 1988; Anderson and others 1990; Ingemansson and others 1993), and in salmon (Lusk and others 1964; Sheehan and others 1998). However, Christiansen and others (1995) found only minor decreases in pigment concentration of salmon frozen stored for 180 d at –18 °C, whereas No and Storebakken (1991) and Scott and others (1994) found that the pigments were stable during frozen storage. The pigments of salmonids are sensitive to light, heat, and oxygen (Burton and Ingold 1984; Burton 1989; Krinsky 1989), and they can function as antioxidants. Jensen and others (1988) claimed that astaxanthin protects against the very early stages of lipid oxidation, whereas α-tocopherol is more important as an antioxidant at more advanced stages of lipid oxidation. Thus, raw material characteristics, individual antioxidant status, freezing and thawing time, temperature, and storage and package conditions will all affect the pigment stability during freezing. The relative loss of astaxanthin was higher in the RL = 0 group, indicating that muscle structure also might have an effect on pigment stability.

Sheehan and others (1998) reported that carotenoid concentration was not significantly reduced in Atlantic salmon muscle due to smoking. They found only small, insignificant reductions in fish fed on astaxanthin (from 9.4 to 8.5 mg/kg) and in fish fed on canthaxanthin (from 10.6 to 9.3 mg/kg). In contrast, Choubert and others (1992) found that the smoking process induced an increase in carotenoid concentration in rainbow trout muscle. The fillets in the rainbow trout study lost 12% of the raw material muscle water weight, which might explain the increase in carotenoid concentration during smoking. We have shown that the astaxanthin content was reduced by freezing on a dry matter basis, and that the reduction cannot be fully explained by differences in water content of the raw material, indicating that astaxanthin is broken down.

The level of astaxanthin was lower in fillets frozen at any stage of the process, but the instrumental color readings showed that the fillets had a higher color intensity. This agrees with results presented by No and Storebakken (1991), who reported that frozen storage resulted in extensive color changes of rainbow trout fillets, causing them to become lighter, more red, and more yellow. We found that harder texture was correlated with a darker color (a lower value of L^*) ($r = -0.56$, $P = 0.001$). This supports the theory of Francis and Clydesdale (1975), which states that visual color differences are due to changes in light absorption and light scattering, which can be caused by freeze-denaturation.

Fillet gaping is the term used to describe the phenomenon in which the connective tissue of the fish fails to hold the muscle blocks together. Slits appear across the surface of the fillets, making mechanical skinning and slicing difficult. Gaping scores were low in the samples we studied, but they were significantly higher in the smoked fillets that had been frozen as fillets before smoking. However, the effect of fillet freezing was lower in the RL = 75 group, indicating a greater connective tissue strength in this group. Gaping has often been associated with low final pH (Lavèty and others 1988; Andersen and others 1994) and with the strength of the connective tissue (Lavèty and others 1988; Mackie 1993). Freezing and thawing cause changes in the salt concentra-

tion and in the pH of the muscle (Sigurgisladottir and others 2000). However, we suggest that the increased gaping that we observed in the fillet-frozen group is related to the mechanical stress that the deboned fillets are subjected to during freezing. The amount of damage occurring during freezing depends on the amount of ice crystal formation, and rapid freezing is generally recommended (Nicholson 1973). The amount of gaping arising during freezing depended on the amount of gaping appearing in the raw material before freezing. Smoked fillet seemed more resistant to further gaping during freezing, and this may have been due to the binding effects of salt and to the surface drying during smoking.

Freezing before smoking resulted in a softer texture, which is in accordance with data from Dunajski (1979). These groups also had a lower dry matter content, but the correlation between texture and dry matter content was low, indicating that the texture softening was related to muscle degeneration. Freezing and thawing affects the membrane structure of the muscle cells (Fennema 1990), and refreezing resulted in a significant difference in texture when measuring on the surface of the fillets but not on the cutlets.

Conclusions

FREEZING BEFORE AND/OR AFTER SMOKING affected the yield and the quality of cold smoked salmon. Product yield increased when the raw material for smoking was frozen and thawed before it was smoked, due to increased water content in the final product. Despite the fact that the pigment concentration of astaxathin in the fillets decreased during freezing, the color intensity (c) and the lightness (L^*) of the fillets increased.

Our results show that the effects of freezing on smoked fillet yield and quality also depend on the treatment of the raw material before slaughter, in this case feed ration level. The effects of freezing may be different if other salting methods than brine injection and other smoking conditions than those used in the present study are used.

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