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4 **Sensory and physical changes in chilled farmed coho**  
5 **salmon (*Oncorhynchus kisutch*): Effect of previous**  
6 **optimized hydrostatic high-pressure conditions**  
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1 **ABSTRACT**

2 The effect of a previous hydrostatic high-pressure (HHP) treatment on sensory  
3 and physical quality of chilled coho salmon (*Oncorhynchus kisutch*) was investigated.  
4 As a first stage, a 2<sup>2</sup> factorial design based on the response surface methodology was  
5 used for optimization of HHP conditions; for it, the effects on color uniformity, white  
6 spots appearance, elasticity and hardness were analyzed. In a second stage, optimized  
7 HHP conditions (135 MPa for 30 s, 170 MPa for 30 s and 200 MPa for 30 s; treatments  
8 T-1, T-2 and T-3, respectively) were applied as previous treatment to chilling, being  
9 sampling carried out on salmon muscle at days 0, 6, 10, 15 and 20. A marked effect on  
10 sensory and physical parameters was detected after HHP treatment and throughout the  
11 chilled storage. According to odor (rancid, putrid), texture (elasticity, gaping, firmness)  
12 and color (L\* value) attributes, fish corresponding to T-1 condition showed to better  
13 maintain quality throughout the chilled storage than fish belonging to T-2 and T-3  
14 conditions; additionally, a quality enhancement (putrid odor, cohesivity, gaping) was  
15 found when compared to control samples. In agreement to the preliminary optimization  
16 study, it is concluded that T-1 condition can provide the most effective HHP pre-  
17 treatment to better maintain sensory and physical properties when salmon muscle is to  
18 be commercialized as a fresh product. Results obtained for the quality evolution of  
19 chilled fish attest the importance of establishing a judicious selection of previous HHP  
20 treatment parameters to minimize undesirable changes related to sensory and physical  
21 characteristics.

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23 **Key Words**: Hydrostatic high-pressure, coho salmon, chilled storage, sensory, physical,  
24 quality, optimization.

25 **Running Title**: Hydrostatic high-pressure and chilled salmon quality.

## **1. INTRODUCTION**

During fish chilled storage, significant losses of sensory and nutritional values have been detected as a result of different damage pathways such as endogenous enzymatic activity, microbial development and lipid oxidation (Whittle et al. 1990). According to an increasing consumer's demand for high quality fresh products, fish technologists and the fish trade have developed different advanced processing systems, these including previous chemical and physical treatments (Ashie et al. 1996; Oms-Oliu et al. 2010) and employment of preservative packaging (Ozen and Floros 2001; Rodríguez et al. 2011).

One such advanced physical treatments is hydrostatic high-pressure (HHP), which has proved to enlarge the shelf life time of marine products, while inactivating microbial development and deteriorative endogenous enzymes (Norton and Sun 2008; Yagiz et al. 2009; Erkan et al. 2011). This technology has demonstrated potential application in the seafood industry for the surimi and kamaboko production (Montero et al. 1998; Uresti et al. 2005), as assisting thawing (Rouillé et al. 2002) and thermal processing (Ramírez et al. 2009) and for the cold-smoked fish preparation (Lakshmanan et al. 2007). However, HHP has been reported to produce different kinds of detrimental effects in fish foods such as cell membranes damage, proteins denaturation, lipid fraction oxidation, browning development and constituents breakdown and aggregation (Ohshima et al. 1993; Ashie and Simpson 1996; Angsupanich and Ledward 1998). As a result, marked quality losses related to the general appearance of the product and a consumer acceptance lowering have shown to be produced.

In recent years, the fishing sector is paying great attention to aquaculture development as a source of marine food products. Among cultivated fish, coho salmon (*Oncorhynchus kisutch*), also called silver salmon, has received great attention because

1 of its increasing production in countries like Chile, Japan and Canada (FAO 2007a) in  
2 parallel to important capture production in countries such as USA, Russian Federation,  
3 Canada and Japan (FAO 2007b). Previous research related to the chilling storage of this  
4 species accounts for the development of different spoilage pathways and quality losses  
5 recently reviewed (Vinagre et al. 2011).

6 Preliminary studies account for HHP previous treatment to chilled coho salmon.  
7 In them, an inhibitory effect on microbial activity development was proved by pressure  
8 augmentation (Aubourg et al. 2010). However, pressure enhancement also showed to  
9 lead to a lipid oxidation development increase (Aubourg et al. 2010) and to a marked  
10 protein damage in the sarcoplasmic fraction (Ortea et al. 2010). According to the great  
11 importance of sensory and physical properties on consumer acceptance of fresh fish, the  
12 present work was focused on the effect that previous HHP conditions could have on  
13 such properties in this chilled species. For it, optimized HHP conditions were tested and  
14 compared to untreated (control) fish throughout a 20-day storage period.

15

## 16 **2. MATERIALS AND METHODS**

### 17 **2.1. Raw fish and HHP equipment**

18 Thirty coho salmon specimens (50-52 cm length; 2.8-3.0 kg weight) were  
19 obtained from an aquaculture facility (AquaChile, S. A., Puerto Montt, X Región,  
20 Chile) after being harvested for 30 weeks. Individuals were sacrificed in the plant by a  
21 sharp blow to the head, the gills cut, bled in a water-ice mixture, beheaded, gutted (HG  
22 type) and transported to the laboratory during 24 h under slurry ice condition (40% ice  
23 and 60% water; -1.0 °C) at a 1:1 fish to ice ratio. Then, the fish was filleted, cut into  
24 pieces (weight range: 125-150 g) and placed in individual flexible polyethylene bags.

1 HHP treatment of packaged fish pieces was performed in a cylindrical loading  
2 container at room temperature ( $15 \pm 2$  °C) in a 2-L pilot high-pressure unit (Avure  
3 Technologies Incorporated, Kent, WA, USA). In all cases, water was employed as the  
4 pressurizing medium, working at a 17 MPa/s ramp rate. Come up times for 135, 170  
5 and 200 MPa treatments were 8, 10 and 12 s, respectively; decompression time was less  
6 than 5s.

## 7 **2.2. Preliminary HHP study**

9 As a first stage, a preliminary study was undertaken to optimize the HHP  
10 conditions range to be employed as previous treatment to a further chilled storage  
11 experiment. For it, a  $2^2$  factorial design of 2 factors in 4 runs plus a central point run  
12 using the Response Surface Methodology (RSM) was performed in order to identify the  
13 significant sensory variables of the HHP process ( $p < 0.05$ ). Two independent variables  
14 were considered (hydrostatic high-pressure, MPa; holding time, min), being their  
15 values, respectively, in the different experiment runs as follows: 100 and 0.5 (run 1),  
16 200 and 0.5 (run 2), 100 and 0.5 (run 3), 200 and 5.0 (run 4), 150 and 2.75 (run 5). In  
17 each experiment run, responses of salmon sensory descriptors were analyzed as  
18 expressed in section 2.4.

## 19 **2.3. HHP processing followed by chilled storage**

21 According to the preliminary study results, three different HHP conditions (135  
22 MPa for 30 s, 170 MPa for 30 s and 200 MPa for 30 s; treatments T-1, T-2 and T-3,  
23 respectively) were selected and applied to fish; comparison to untreated fish (control,  
24 treatment C) was undertaken. After HHP treatment, packed fish pieces were kept at 0 °C  
25 under chilling conditions (traditional flake ice) in a refrigerated room (4 °C). Sampling

1 was carried out on salmon white muscle at days 0, 6, 10, 15 and 20 of chilled storage.  
2 For all kinds of samples, three different batches (n = 3) were considered and analyzed  
3 separately.

4

#### 5 **2.4. Sensory analyses**

6 The sensory analysis was conducted according to the Quantitative Descriptive  
7 Analysis (QDA) method by a sensory panel consisting of ten experienced judges (five  
8 females and five males). Panelists were selected and trained according to international  
9 standards in sensory descriptors for raw and processed fish of different quality  
10 conditions (Howgate 1992; ISO 1993; Codex Alimentarius 1999).

11 The following descriptors were analyzed in salmon muscle in the preliminary  
12 HHP study: Salmon color uniformity (original color maintenance), white spots  
13 appearance (formation of such spots), elasticity (recovery capacity after pressure  
14 application) and hardness (resistance of muscle fibers against compression).

15 Concerning the experiment where HHP treatment was followed by a chilled  
16 storage, the following descriptors were analyzed: Rancid odor (presence of off-odors  
17 related to rancidity development), putrid odor (presence of off-odors related to decayed  
18 meat), amine odor (presence of off-odors related to amine formation), elasticity and  
19 cohesivity (binding degree of myotomes in salmon muscle).

20 At each sampling time, fish muscle portions were presented to panelists in  
21 individual trays and were scored individually. The panel members shared samples  
22 tested. The different sensory descriptors were evaluated on non-structured linear scales  
23 with numerical scores from 0 to 10. Scores among panelists were averaged. For  
24 parameters such as salmon color uniformity, elasticity, hardness and cohesivity, score  
25 10 corresponds to the stage where such properties are observed in their maximum value,

1 while score 0 represents the stage where a decrease is no more noticeable. For white  
2 spots appearance, rancid, putrid and amine odors, score 0 represents the stage where  
3 such attributes are not noticeable, while stage 10 corresponds to the stage where no  
4 increase is possible.

5 Additionally, the red color appearance of the fillets was evaluated by the Roche  
6 SalmoFan™ Lineal card; for it, panelists matched the salmon muscle color with a 20-  
7 34-score card system previously established for salmonids pigmented with astaxanthin  
8 (ISO 1993; Codex Alimentarius 1999).

9 Finally, gaping in salmon muscle was analyzed visually by panelists after chilled  
10 storage at days 0, 6, 10, 15 and 20. The number of incisions or slits in the muscle  
11 myotomes of salmon was recorded to obtain the gaping score. Evaluation of gaping  
12 development was performed according to previous research (Andersen et al. 1994).  
13 Thus, scores were attributed as follows: 0 (no gaping; 0 slits), 1 (minor gaping; 1-5  
14 slits), 2 (moderate gaping; 6-10 slits), 3 (intense gaping; 11-15 slits), 4 (severe gaping;  
15 16-20 slits), and 5 (extreme gaping; > 20 slits).

16

## 17 **2.5. Physical analyses**

18 Instrumental color analysis (CIE 1976 L\*, a\*, b\* space) was performed by  
19 employing a tristimulus Hunter Labscan 2.0/45 colorimeter. Measurements were made  
20 directly on the salmon muscle and by employing cuvette. For each sample analysis,  
21 color scores were obtained as mean values of four measurements obtained by rotating  
22 the measuring head 90° between duplicate measurements per position.

23 A shear test was used to evaluate texture in chilled salmon muscle. Firmness and  
24 deformation were determined from a stress-distance curve obtained from a Universal  
25 Testing Machine (LR-5K; Lloyd Instruments Limited, Hampshire, England, UK)

1 including a load cell of 500 N connected to a computer, this including a Dapmat 40-  
2 0465 software data analysis (version 3.05, Lloyd Instruments Limited, Hampshire,  
3 England, UK). A Warner-Bratzler blade (knife edge 60°), 1.2 mm thick, 150 mm width  
4 and cutting at a 1 mm s<sup>-1</sup> speed was employed at 4 °C on a 4 x 4 x 2 cm sample. The  
5 firmness (N) was regarded as the resistance maximum of the muscle fibers against  
6 transversal shearing (maximum force) and was the height of the first peak; deformation  
7 was measured during the upward movement of the blade and was calculated as the  
8 cohesivity (mm) at maximum peak force (Sigurgisladóttir et al. 1999). The average  
9 value of quadruplicate replicates was considered in each sample analysis.

## 11 **2.6. Statistical analyses**

12 Concerning the preliminary HHP study, RSM was performed to optimize both  
13 variables (hydrostatic high-pressure and holding time) by means of sensory descriptors  
14 analysis. For it, a multifactor ANOVA (panelists, specimens and HHP treatment) was  
15 conducted on the design responses for each descriptor. The requirements for  
16 optimization were significant differences among HHP treatments, but not among  
17 panelists. Multiple regression equations were fitted for the descriptors that fulfilled this  
18 requirement to obtain the response surfaces; for it, non-significant terms were discarded.  
19 A multiple response optimization was performed to assess the combination of  
20 experimental factors that simultaneously optimize several responses; as a result,  
21 maximization of the desirability function was obtained, this function ranging from 0 to  
22 1 (Derringer and Suich 1980). The Statgraphics plus statistical graphics software  
23 Corporation, Manugistics Inc., Rockville, USA, was used for data analysis (Manugistics  
24 Inc. and Statistical).



1 Data were analyzed according to a first-order model, called main effect model.  
2 In it, equations of the fitted models for HHP variables (hydrostatic high-pressure and  
3 holding time) were obtained taking into account the interaction between both of them.  
4 The response for each sensory attribute was calculated according to the following  
5 equation (Myers and Montgomery 1995):

$$Y = \beta_0 + \beta_1 X_1 + \beta_2 X_2 + \beta_{12} X_1 X_2,$$

6  
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9 where Y is the estimated response for the first-order model;  $\beta_0$ ,  $\beta_1$ ,  $\beta_2$  and  $\beta_{12}$  are the  
10 regression coefficients for intercept, linear and interaction terms, respectively;  $X_1$  and  $X_2$   
11 are the main effects of the two independent variables; and  $X_1 X_2$  is the interaction  
12 between both variables.

13 Data concerning the HHP processing followed by chilled storage were analyzed  
14 by multifactor analysis of variance ANOVA (Tukey test), taking into account possible  
15 differences among specimens, panelists, HHP treatments and chilled storage times.  
16 Statistical program used was Statgraphics plus statistical graphics software Corporation,  
17 Manugistics Inc., Rockville, USA (Manugistics Inc. and Statistical). A confidence  
18 interval at the 95% level was used in all cases.

19

## 20 **3. RESULTS AND DISCUSSION**

### 21 **3.1. Preliminary HHP study**

22 Table 1 indicates the results of fitting a multiple linear regression model to  
23 describe the relationship between independent variables (hydrostatic high-pressure and  
24 holding time) and sensory descriptors (color uniformity, white spots appearance,  
25 elasticity and hardness) of salmon muscle. The only response variable that presented a

1 first-order model including interaction between both variables (hydrostatic high-  
2 pressure and holding time) was hardness ( $p < 0.05$ ); its determination coefficient ( $R^2$ )  
3 indicated that the fitted model could explain 99.973 % of the variability in hardness.  
4 Meantime, a good determination coefficient was also obtained in the case of elasticity  
5 ( $R^2 = 97.477$ ). Regression coefficients were removed from Table 1 in cases where  $p$ -  
6 values obtained from the ANOVA analysis were found higher or equal to 0.05 and were  
7 not considered statistically significant at the 95% or higher confidence level.

8         Figure 1 (A-D) shows the response surfaces obtained for each of the sensory  
9 descriptors as a function of the processing variables. It could be observed that both the  
10 hydrostatic high-pressure (100 to 200 MPa) and the holding time (0 to 5 min) had a  
11 significant effect on the sensory properties of the salmon muscle ( $p < 0.05$ ). Thus,  
12 salmon color uniformity decreased (Figure 1A) when the pressure variable augmented,  
13 whereas holding time did not provide a significant effect, according to regression  
14 coefficients shown in Table 1. The combination of factor levels which minimizes the  
15 salmon color uniformity changes over the indicated region was 100 MPa and 30 s, with  
16 9.354 as optimum value. Meantime, white spots appearance (Figure 1B) indicated an  
17 increased value with holding time, being the pressure effect not significant (Table 1).  
18 100 MPa and 30 s was the combination of factor levels which minimized white spots  
19 appearance (1.026 as optimum value). Both hydrostatic high-pressure and holding time  
20 variables proved a significant effect on elasticity (Figure 1C); thus, an enlargement in  
21 both variables led to an elasticity decrease of salmon muscle, according to coefficients  
22 included in Table 1. The combination of factor levels which optimized the elasticity  
23 response was 100 MPa and 30 s, this showing 9.348 as optimum value. Finally,  
24 hardness (Figure 1D) decreased with both pressure value and holding time but increased  
25 as a result of the interaction between both variables (Table 1).

1           Figure 2 provides the evaluation of the desirability function at each point of the  
2 experimental design, according to the optimization process based on the combination of  
3 the sensory descriptors responses.

4           Figure 2A indicates the estimated response surface of the relationship among  
5 the desirability response variable, the hydrostatic high pressure and the holding time by  
6 means of a three-dimensional response surface and the contour plot. Addition of the  
7 interaction term (+ 0.006 hydrostatic high-pressure  $\times$  holding time) introduced a  
8 curvature in the response function (Myers and Montgomery 1995). For each value of  
9 pressure and holding time, a corresponding value of the desirability response was  
10 obtained, this producing a surface which lies above the pressure-holding time plane  
11 (Myers and Montgomery 1995). The optimization process indicated an optimum value  
12 for desirability of 0.75. The contour of the estimated response surface in two  
13 dimensions (hydrostatic high-pressure and holding time; Figure 2B) indicates that the  
14 optimum values of the process variables which minimize color and elasticity changes,  
15 hold hardness at a 5-point score in a 10-point scale and minimize the appearance of  
16 white spots are 135.6 MPa and 30 s, respectively.

17           As a result, this HHP condition (135 MPa and 30 s) was chosen for being  
18 employed as a previous treatment in the present research where salmon quality changes  
19 during chilled storage were to be investigated. Two other HHP conditions where the  
20 holding time was maintained (30 s) but the pressure was intensified (170 and 200 MPa,  
21 respectively) were also selected as previous treatment. Such pressure range chosen  
22 (135-200 MPa) agrees to pressure conditions previously recommended for farmed  
23 turbot (*Scophthalmus maximus*) fillets as not contributing to important modifications  
24 (Chevalier et al., 2001).

25

## **3.2. HHP treatment and chilled storage study**

### **3.2.1. Odor development assessment**

Rancid odor development showed a progressive enlargement in all kinds of samples throughout the chilling time (Table 2). At time 0, very low values were detected; however, compared to control fish, an increased value was obtained as a result of the different HHP treatments, whatever the treatment employed was. Later on (6-20-day period), lower mean values were obtained for fish previously treated under T-1 condition; differences were found significant when comparison was achieved with the counterpart samples corresponding to T-2 and T-3 treatments. An increased lipid oxidation evolution in T-2- and T-3-fish samples was already observed in a previous parallel study where primary, secondary and tertiary lipid oxidation indices were analyzed (Aubourg et al. 2010).

In general, HHP treatment has been reported to enlarge the lipid oxidation progress of fish muscle during a further refrigerated storage (Lakshmanan et al. 2007; Yagiz et al. 2007). However, isolated extracted lipids have demonstrated to be relatively stable against oxidation under HHP conditions and during further storage; additionally, the prooxidant effect of HHP treatment on muscle lipids was shown to be eliminated if a previous water washing of the muscle was applied or if a complexation compound (EDTA, for example) was added (Angsupanich and Ledward 1998; Ohshima et al. 1993). Consequently, metal-bound protein denaturation during HHP treatment has been reported to facilitate a free metal ion content increase and be responsible for an oxidation stability decrease in stored fish meat after HHP treatment.

Putrid odor assessment provided increasing values with chilling time for all kinds of samples (Table 2). At day 0, no effect could be outlined as a result of any of the previous HHP treatments tested when compared to the control batch. Later on (10-20-

1 day period), fish corresponding to previous T-1 treatment showed lower scores than its  
2 counterpart belonging to T-2 and T-3 conditions; T-1-batch also indicated a lower  
3 putrid odor development for the 15-20-day period when compared to control fish. At the  
4 end of the experiment, the highest putrid odor was detected in the control samples.

5 A marked amine odor development was obtained in all kinds of samples with  
6 chilling time (Table 2). Very low scores could be observed at day 0 in all cases, so that  
7 no direct effect on amine odor development could be accorded to HHP treatment alone.  
8 At day 6, an inhibitory effect could be attributed to all kinds of previous HHP  
9 treatments when compared to untreated fish; however, no differences could be obtained  
10 among the different HHP conditions at that time. At the end of the experiment (15-20-  
11 day period), a lower score was observed in fish submitted to the strongest pressure  
12 condition. This lower value agrees to the above mentioned previous study (Aubourg et  
13 al. 2010) where the greatest inhibitory effect of HHP treatment on microbial  
14 (psychrotrophs and aerobes) parameters was obtained in fish corresponding to the T-3  
15 batch.

16 A shelf life extension as a result of microbial activity inhibition by previous  
17 HHP treatment has been described during the chilled storage of different kinds of fish  
18 foods (Ohshima et al. 1993; Ashie et al. 1996). Thus, Atlantic salmon (*Salmo salar*)  
19 muscle showed a two-day shelf life extension during its refrigerated storage as a result  
20 of a previous HHP (150 MPa for 10 min) treatment (Amanatidou et al. 2000). Related to  
21 non-salmonid species, an HHP treatment (330 MPa for 5 min; 220 MPa for 5 min) led  
22 to a three-day and two-day shelf life enlargement, respectively, in refrigerated red  
23 mullet (*Mullus surmelutus*) (Erkan et al. 2010). Also, refrigerated hake (*Merluccius*  
24 *capensis*) muscle subjected to a previous HHP treatment (400 MPa, three 5-min cycles)  
25 provided an important shelf life increase (Hurtado et al. 2000).

### 1 **3.2.2. Texture changes analysis**

2 Elasticity analysis provided a marked decrease with chilling time in all kinds of  
3 samples (Table 3). At day 0, mean scores indicated a progressive decrease value with  
4 increasing pressure applied; differences were found significant between fish samples  
5 corresponding to T-3 and C conditions. Up to day 15, higher mean scores were  
6 maintained in control samples; however, at the end of the experiment fish samples  
7 corresponding to T-1 condition provided the highest elasticity values.

8 Cohesivity value also showed a decrease throughout the storage time for all  
9 kinds of samples (Table 3). In this parameter, fish corresponding to T-1 batch showed  
10 the highest cohesivity value at day 0. Fish belonging to such condition maintained the  
11 highest mean values throughout the whole storage period; differences with C-fish were  
12 found significant in the 15-20-day period.

13 In agreement to the decrease obtained for the elasticity and cohesiveness values,  
14 an increasing tendency in the gaping score was attained for all kinds of fish samples  
15 throughout the chilling storage period (Table 3). At day 0, a negative effect on fish  
16 quality could be observed as a result of the HHP treatment, greater in the case of the  
17 highest pressure applied (T-3 batch). At the end of the experiment, fish samples  
18 belonging to the two strongest HHP conditions were attributed score 5, while salmon  
19 samples related to T-1 treatment showed the lowest gaping development. Fish  
20 corresponding to T-1 treatment provided a gaping degree lower than 4 throughout the  
21 whole storage period, so that remained below the recommended border line of  
22 acceptability (Andersen et al. 1994). Contrary, control and T-3-fish reached score 4 at  
23 day 15, while fish belonging to T-2 condition reached score 5 at the end of the  
24 experiment.

1           A progressive firmness enlargement with chilling time was obtained in all kinds  
2 of samples, except for those corresponding to the two highest pressure conditions at the  
3 end of the experiment (Table 3). Analysis corresponding to day 0 indicated that a  
4 firmness increase was attained in fish corresponding to C and T-3 batches when  
5 compared with its counterpart belonging to the two other groups. Samples  
6 corresponding to T-1 and T-2 conditions maintained lower mean values throughout the  
7 further chilling time.

8           Deformation assessment did not provide differences among the different kinds  
9 of samples throughout the entire (0-20-day period) chilling period (Table 3), so that no  
10 effect of the different HHP treatments tested could be attributed as such or subsequently  
11 during the chilled storage. Additionally, none of the four conditions tested in the present  
12 research provided a clear tendency with the storage time for the deformation value.

13           Texture is considered to be one of the most important quality attributes of  
14 seafoods, which determines consumer acceptance and hence, the marketability of such  
15 products. One of the biggest problems in the seafood industry, unlike other muscle  
16 foods, is the rapidity with which the flesh softens and it is therefore required to maintain  
17 the initial firmness/tightening texture. Rapid softening of post-harvest fish tissue may be  
18 directly linked to great activity of endogenous proteases such as cathepsins, calcium-  
19 dependent proteases, collagenases, alkaline proteases, digestive enzymes, and so on. As  
20 a result, the connective tissue holding the cells together is reported to be degraded as  
21 muscle damage increases and blocks of cells become readily separated each other, so  
22 that a lower cohesivity score would be observed in muscle (Aitken and Connell 1979).  
23 A common consequence is the development of the phenomenon of gaping, resulting in  
24 tears appearing in the fillet, which further develop with storage time under refrigerated

1 condition and leading to a lower value appearance of the product (Fletcher et al. 2003;  
2 Espe et al. 2004).

3 Previous research has shown fish texture to be highly sensitive to pressure and  
4 holding time applied during the HHP treatment, so that it has been postulated that such  
5 a processing may be monitored in order to obtain the desired seafoods texture (Hurtado  
6 et al. 2001; Uresti et al. 2005). HHP treatment often causes proteins to dissociate from  
7 their oligomeric structures, this affecting their subunits by means of partial unfolding  
8 and denaturation as well as protein aggregation and gelation. The observed enlargement  
9 in some texture parameters has been explained on the basis of different chemical  
10 changes such as reinforcement of hydrogen bonds of proteins and enhancement of  
11 disulphide bonds formation (Heremans et al. 1997; Lanier 1998; Pérez-Won et al.  
12 2005). If a refrigerated storage is to be applied after the HHP treatment, it has been  
13 reported that pressure-inactivated enzymes (cathepsin C, collagenase, chymotrypsin-  
14 like, trypsin-like) could be reactivated to various extents depending on the level of the  
15 pressure applied (Ashie et al. 1997).

16 When the HHP treatment effect is analyzed as such (chilling time 0 comparison)  
17 in the present study, it can be depicted that the highest pressure tested (200 MPa) has  
18 led to a lower texture quality, while T-1 condition has provided the most profitable  
19 texture scores (cohesivity and firmness, specially); accordingly, a negative effect of  
20 pressure on texture quality has been detected in the values range tested.

21 At this point, previous related research has provided varying results about the  
22 HHP effect according to the severity (pressure and holding time) of conditions applied.  
23 As a general rule, and according to the present results, stronger conditions have led to  
24 greater texture modifications. This applies to bluefish (*Pomatomus saltatrix*) muscle  
25 (Ashie et al. 1997), cod (*Gadus morhua*) muscle (Angsupanich and Ledward 1998) and



1 Atlantic salmon (*Salmo salar*) fillets (Amanatidou et al. 2000). Contrary to such results,  
2 better texture properties were obtained by Yagiz et al. (2007) in rainbow trout  
3 (*Oncorhynchus mykiss*) and mahi mahi (*Coryphaena hippurus*) fillets.

4         Related to the texture quality loss during the chilled storage, present results have  
5 demonstrated that fish previously treated under T-1 condition have retained a higher  
6 quality level, this according to gaping, elasticity and cohesivity properties. Such a  
7 conclusion agrees to a previous and parallel research, which reported a higher protein  
8 damage during storage in fish corresponding to conditions including the two highest  
9 pressure (T-2 and T-3) values (Ortea et al. 2010); in such study, a marked sarcoplasmic  
10 protein content decrease was observed, in parallel to partial disappearance of a 29-kDa  
11 band in the electrophoretic analysis of such protein fraction.

12         In the case of bluefish (*Pomatomus saltatrix*) muscle (Ashie et al. 1997),  
13 firmness and elasticity showed higher values during refrigerated storage (4-7 °C) in  
14 individuals previously treated at 100 MPa for 30 min when compared to control;  
15 however, fish previously treated under higher (200-300 MPa) pressures provided lower  
16 values in both texture attributes throughout storage. Chéret et al. (2005) found that a  
17 higher hardness was produced in sea bass (*Dicentrarchus labrax*) fillets, previously  
18 treated at 400-500 MPa for 5 min after refrigerated storage (14 days at 4 °C), than in  
19 their counterpart untreated fillets; however, if a 100-200 MPa treatment was applied, no  
20 changes in hardness were obtained up to a 14-day storage. Additionally, a cohesiveness  
21 increase in HHP-treated (100-500 MPa for 5 min) sea bass fillets was obtained at the  
22 end of the storage when compared to control fish.

23

### 1 **3.2.3. Color changes analysis**

2 According to mean values, the Roche scale analysis provided a general decrease  
3 with chilling time in all kinds of samples, specially in control and T-1-treated fish  
4 (Table 4). This decrease can be explained as partial loss of colored carotenoid  
5 compounds (namely, astaxanthin) responsible for the muscle color of salmonid species  
6 (Quevedo et al. 2010). Thus, astaxanthin content has shown to be partially lost during  
7 chilled storage of vacuum-packaged rainbow trout (*Oncorhynchus mykiss*) (Gobantes et  
8 al. 1998) and as a result of the refrigerated storage (up to 5 days at 4 °C) of Atlantic  
9 salmon (*Salmo salar*) (Gordon Bell et al. 1998). In the present research, no differences  
10 could be observed at day 0 among the different kinds of samples, so that a definite  
11 effect of HHP treatment alone on carotenoid content could not be concluded.  
12 Comparison among samples hardly provided significant differences throughout the  
13 chilled storage; at day 15, a higher value was obtained for T-1-treated fish when  
14 compared to its counterpart belonging to the control batch.

15 Regarding the lightness (L\*) mean values (Table 4), an increase with chilling  
16 time for all fish pre-treated under HHP conditions (T-1, T-2 and T-3 batches) could be  
17 observed, this increase being more important in fish corresponding to the two highest  
18 pressure conditions. According to day 0 results, no effect of the HPP treatment could be  
19 concluded; then, higher mean values for fish corresponding to both strongest conditions  
20 (T-2 and T-3 batches) during the 6-20-day period were observed. Differences were  
21 found significant at the end of the experiment when the following increasing score  
22 tendency was attained in fish corresponding to the different conditions: C and T-1 < T-2  
23 < T-3. In all cases, L\* values remained under score 70, which has been depicted as the  
24 permitted border line value for salmonid species (Amanatidou et al. 2000).

1           A marked augmentation of L\* value has already been mentioned as a result of  
2 HHP treatment in different salmonid species such as salmon trout (*Salmo trutta*)  
3 (Matser et al. 2000), Atlantic salmon (*Salmo salar*) (Amanatidou et al. 2000) and  
4 rainbow trout (*Oncorhynchus mykiss*) (Yagiz et al. 2007); in all cases, L\* value  
5 increases were greater by increasing the pressure applied. However, such previous  
6 experiments demonstrated that when considering relatively low pressures (200 MPa or  
7 less), slight L\* value increases, or no increase at all, were obtained according to the  
8 present results.

9           As in the present study, previous research also reported L\* value enlargement in  
10 stored fish, which was previously submitted to HHP treatment. Thus, an L\* value  
11 increase with storage time was already observed in HHP-treated (150, 300, 450 and 600  
12 MPa; 15 min) rainbow trout (*Oncorhynchus mykiss*) muscle during a further storage for  
13 6 days at 4 °C (Yagiz et al. 2007).

14           Related to greenness/redness assessment (a\* value) (Table 4), no effect of HHP  
15 treatment can be concluded at time 0. Although some significant differences are  
16 obtained among samples during the chilled storage, a clear tendency can not be  
17 concluded so that no effect of previous HHP treatment can be implied on a\* value in  
18 stored fish. According to mean values, a decreasing tendency for a\* score could be  
19 outlined with chilling time in fish corresponding to T-3 condition. In all cases, a\* value  
20 remained above 13, which has been recognized as the permitted border line score for  
21 salmonid species (Amanatidou et al. 2000).

22           Previous works on fish species have proved a general a\* value decrease as a  
23 result of HHP treatment, this becoming bigger with increasing pressure and holding  
24 time applied (Ohshima et al. 1993; Ashie et al. 1996). However, when relatively low  
25 pressures (200 MPa or less) and short holding times (10 min or less) were encountered,

1 no effect of HHP treatment has been concluded on a\* value, according to the present  
2 research. Such conclusions were obtained on different salmonid species such as Atlantic  
3 salmon (*Salmo salar*) (Amanatidou et al. 2000; Yagiz et al. 2009), rainbow trout  
4 (*Oncorhynchus mykiss*) (Yagiz et al. 2007) and salmon trout (*Salmo trutta*) (Matser et  
5 al. 2000).

6 Concerning the b\* (yellowness/blueness) value assessment (Table 4), a  
7 decreasing effect in all kinds of HHP-treated fish could be concluded at day 0 when  
8 compared to C samples; however, no differences were found as a result of the pressure  
9 (135-200 MPa) applied at that time. Later on (10-20-day storage), fish corresponding to  
10 T-2 and T-3 conditions showed lower values than its counterpart from C and T-1  
11 batches. Additionally, a clear tendency for b\* score during the chilled storage of the  
12 different batches under study could not be concluded.

13 Usually, this color parameter has been related to lipid oxidation development.  
14 Thus, an important relationship between b\* value and the formation of polymerized  
15 Schiff bases and fluorescent compounds (tertiary lipid oxidation compounds) has been  
16 observed (Undeland et al. 2003). Previous studies on the effect of HHP treatment on b\*  
17 value in fish muscle have demonstrated a great dependence on the pressure applied. For  
18 Atlantic salmon (*Salmo salar*) (Yagiz et al. 2009), it could be observed that b\* value  
19 increased when applying a pressure of 300 MPa, but decreased when fish was submitted  
20 to 150 MPa. In the case of carp (*Cyprinus carpio*) fillets (Sequeira-Munoz et al. 2006),  
21 b\* score showed to increase in all tested cases (100-200 MPa for 15-30 min) when  
22 compared to fresh fish. Finally, pressurized turbot (*Scophthalmus maximus*) fillets at  
23 100-200 MPa for 15-30 min provided an increasing b\* value by intensifying both HHP  
24 parameters in comparison with control samples.

1           Regarding the evolution of  $b^*$  value during refrigerated storage in HHP-treated  
2 fish, previous research has also shown no definite tendency as a result of storage time.  
3 Such conclusions are related to sea bass (*Dicentrarchus labrax*) (100 and 200 MPa for 5  
4 min; Chéret et al. 2005) and red mullet (*Mullus surmelutus*) (220 and 330 MPa for 5  
5 min; Erkan et al. 2010) studies.

6

7

#### **4. CONCLUSIONS**

8           A marked effect on sensory and physical attributes of salmon muscle has been  
9 detected as a result of HHP treatment as well as in case of being followed by a chilling  
10 storage. According to several odor (rancid and putrid), texture (elasticity, gaping and  
11 firmness) and color ( $L^*$  value) properties, fish corresponding to T-1 condition has  
12 proved to better maintain such properties throughout the chilled storage than its  
13 counterpart belonging to T-2 and T-3 conditions; additionally, a quality enhancement  
14 was also found when comparison was carried out with control fish (putrid odor,  
15 cohesivity and gaping).

16           Previous research (Aubourg et al. 2010) had demonstrated that T-1, T-2 and T-3  
17 HHP conditions were profitable to partially inhibit microbial activity development  
18 during coho salmon chilled storage. However, marked protein damage was also reported  
19 in fish corresponding to T-2 and T-3 batches after the HHP treatment and during the  
20 further chilled storage (Ortea et al. 2010).

21           Present results have demonstrated that T-1 condition can provide an effective  
22 combination of pressure and holding time in order to better maintain odor, texture and  
23 color properties when this fish species muscle is to be commercialized under the fresh  
24 state. Results obtained in the chilled storage experiment agree to the preliminary  
25 optimization study where T-1 condition was found to be the most convenient HHP

1 treatment to be applied. Present research attest the importance of establishing a  
2 judicious selection of treatment parameters in order to minimize undesirable changes  
3 related to sensory and physical properties.

4

5

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12

1 **FIGURE LEGENDS**

2 **Figure 1**

3 Effect of processing variables (hydrostatic high-pressure, MPa; holding time, min) on  
4 sensory descriptors of salmon muscle: Salmon color uniformity (A), appearance of  
5 white spots (B), elasticity (C) and hardness (D).

6  
7 **Figure 2**

8 Optimization of process variables (hydrostatic high-pressure, MPa; holding time, min)  
9 and evaluation of the desirability function: Estimated multiple response surface (A) and  
10 contour of estimated response surface (B).

## REFERENCES

- 1
- 2
- 3 Aitken, A., & Connell, J. (1979). Fish. In: Priestley, R. (ed.) *Effects of heating on food*  
4 *stuffs*, pp. 219-254. Applied Science Publishers Ltd., London, UK.
- 5 Amanatidou, A., Schlüter, O., Lemkau, K., Gorris, L., Smid, E., & Knorr, D. (2000).  
6 Effect of combined application of high pressure treatment and modified  
7 atmospheres on the shelf life of fresh Atlantic salmon. *Innovative Food Science*  
8 *and Emerging Technologies*, 1, 87-98.
- 9 Andersen, U., Stromsnes, A., Steinsholt, K., & Thomassen, M. (1994). Fillet gaping in  
10 farmed Atlantic salmon (*Salmo salar*). *Norwegian Journal of Agricultural*  
11 *Science*, 8, 165-179.
- 12 Angsupanich, K., & Ledward, D. (1998). High pressure treatment effects on cod (*Gadus*  
13 *morhua*) muscle. *Food Chemistry*, 63, 39-50.
- 14 Ashie, I., & Simpson, B. (1996). Application of high hydrostatic pressure to control  
15 enzyme related fresh seafood texture deterioration. *Food Research International*,  
16 29, 569-575.
- 17 Ashie, I., Simpson, B., & Ramaswamy, H. (1997). Changes in texture and  
18 microstructure of pressure-treated fish muscle tissue during chilled storage.  
19 *Journal of Muscle Foods*, 8, 13-32.
- 20 Ashie, I., Smith, J., & Simpson, B. (1996). Spoilage and shelf-life extension of fresh  
21 fish and shellfish. *Critical Reviews in Food Science and Nutrition*, 36, 87-121.
- 22 Aubourg, S., Tabilo-Munizaga, G., Reyes, J., Rodríguez, A., & Pérez-Won, M. (2010).  
23 Effect of high-pressure treatment on microbial activity and lipid oxidation in  
24 chilled coho salmon. *European Journal of Lipid Science and Technology*, 112,  
25 362-372.



- 1 Chéret, R., Chapleau, N., Delbarre-Ladrat, C., Vérrez-Bagnis, V., & De Lamballerie, M.  
2 (2005). Effects of high pressure on texture and microstructure of sea bass  
3 (*Dicentrarchus labrax* L.) fillets. *Journal of Food Science*, 70, E477-E483.
- 4 Chevalier, D., Le Bail, A., & Ghoul, M. (2001). Effects of high pressure treatment (100-  
5 200 MPa) at low temperature on turbot (*Scophthalmus maximus*) muscle. *Food*  
6 *Research International*, 34, 425-429.
- 7 Codex Alimentarius (1999). *Directrices para la Evaluación Sensorial del Pescado y*  
8 *los Mariscos en Laboratorio*. Norma Técnica CAC/GL 31-1999.  
9 <http://www.pes.fvet.edu.uy/cursos/mail2.pdf>.
- 10 Derringer, G., & Suich, R. (1980). Simultaneous optimization of several response  
11 variables. *Journal of Food Quality and Technology*, 12, 214-219.
- 12 Erkan, N., Üretener, G., & Alpas, H. (2010). Effect of high pressure (HP) on the quality  
13 and shelf life of red mullet (*Mullus surmelutus*). *Innovative Food Science and*  
14 *Emerging Technologies*, 11, 259-264.
- 15 Erkan, N., Üretener, G., Alpas, H., Selçuk, A., Özden, Ö., & Buzrul, S. (2011). Effect of  
16 high hydrostatic pressure (HHP) treatment on physicochemical  
17 properties of horse mackerel (*Trachurus trachurus*). *Food and Bioprocess*  
18 *Technology*, 4, 1322-1329.
- 19 Espe, M., Ruohonen, K., Bjørnevik, M., Frøyland, L., Nortvedt, R., & Kiessling, A.  
20 (2004). Interactions between ice storage time, collagen composition, gaping and  
21 textural properties in farmed salmon muscle harvested at different times of the  
22 year. *Aquaculture*, 240, 489-504.
- 23 FAO (2007a) Fishery statistics. *Aquaculture Production. Yearbook 2005*, 100/2, p. 73.  
24 Food and Agriculture Organization of the United Nations, Rome, Italy.

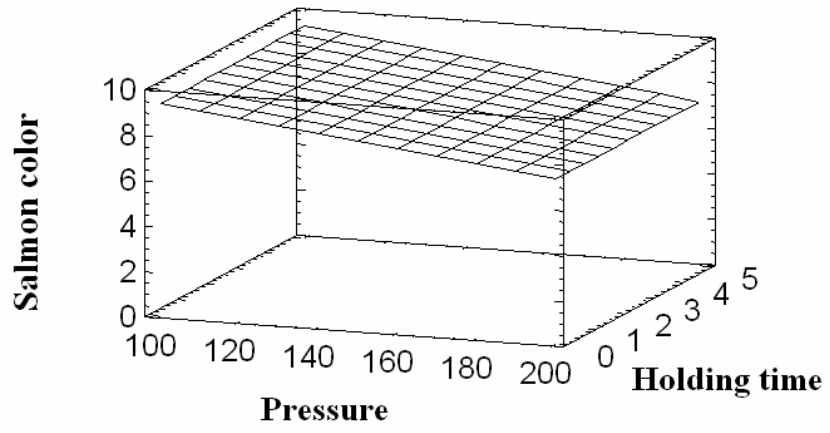
- 1 FAO (2007b) Fishery statistics. *Capture Production. Yearbook 2005*, 100/1, p. 79. Food  
2 and Agriculture Organization of the United Nations, Rome, Italy.
- 3 Fletcher, G., Corrigan, V., Summers, G., Leonard, M., Jerrett, A., & Black, S. (2003).  
4 Spoilage of rested harvested king salmon (*Oncorhynchus tshawytscha*). *Journal*  
5 *of Food Science*, 68, 2810-2816.
- 6 Gobantes, I., Choubert, G., & Gómez, R. (1998). Quality of pigmented (astaxanthin and  
7 canthaxanthin) rainbow trout (*Oncorhynchus mykiss*) fillets stored under  
8 vacuum packaging during chilled storage. *Journal of Agricultural and Food*  
9 *Chemistry*, 46, 4358-4362.
- 10 Gordon Bell, J., McEvoy, J., Webster, J., McGhee, F., Millar, R., & Sargent, J. (1998).  
11 Flesh lipid and carotenoid composition of Scottish farmed Atlantic salmon  
12 (*Salmo salar*). *Journal of Agricultural and Food Chemistry*, 46, 119-127.
- 13 Heremans, K., Van Camp, J., & Huyghabaert, A. (1997). High pressure effects on  
14 proteins. In: Damodaran, S., & Paraf, M. (eds.) *Fundamentals of Food Proteins*  
15 *and Their Applications*, pp. 473-502. Marcel Dekker, New York, USA.
- 16 Howgate, P. (1992). *Codex review on inspection procedures for the sensory evaluation*  
17 *of fish and shellfish, CX/FFP, 92/14*.
- 18 Hurtado, J., Montero, P., & Borderías, A. J. (2001). Chilled storage of pressurized  
19 octopus (*Octopus vulgaris*) muscle. *Journal of Food Science*, 66, 400-406.
- 20 ISO (1993) Sensory analysis: Methodology. *General guidance for the selection,*  
21 *training and monitoring of assessors*. Part 1: Selected assessors. In: *ISO-*  
22 *standard 8586-1*, The International Organization for Standardization, Geneva,  
23 Switzerland.

- 1 Lanier, T. (1998). High pressure processing effects of fish proteins. In: Shahidi, F. (ed.)  
2 *Process-induced Chemical Changes in Food*, pp. 45-55. Plenum Press, New  
3 York, USA.
- 4 Matser, A., Stegeman, D., Kals, J., & Bartels, P. (2000). Effects of high pressure on  
5 colour and texture of fish. *High Pressure Research*, 19, 109-115.
- 6 Montero, P., Pérez-Mateos, M., & Borderías, A. J. (1998). Chilled storage of high  
7 pressure and heat-induced gels of blue whiting (*Micromesistius poutassou*)  
8 muscle. *Zeitschrift für Lebensmittel Untersuchung und Forschung*, 207, 146-  
9 153.
- 10 Myers, R. H., & Montgomery, D. C. (1995). *Response surface methodology: Process*  
11 *and product optimization using designed experiments*. John Wiley & Sons, Inc,  
12 New York, USA.
- 13 Norton, T., & Sun D.-W. (2008). Recent advances in the use of high pressure as an  
14 effective processing technique in the food industry. *Food and Bioprocess*  
15 *Technology*, 1, 2-34.
- 16 Ohshima, T., Ushio, H., & Koizumi, C. (1993). High-pressure processing of fish and  
17 fish products. *Trends in Food Science and Technology*, 4, 370-375.
- 18 Oms-Oliu, G., Martín-Belloso, O., & Soliva-Fortuny, R. (2010). Pulsed light treatments  
19 for food preservation. A review. *Food and Bioprocess Technology*, 3, 13-23.
- 20 Ortea, I., Rodríguez, A., Tabilo-Munizaga, G., Pérez-Won, M., & Aubourg, S. (2010).  
21 Effect of hydrostatic high-pressure treatment on proteins, lipids and nucleotides  
22 in chilled farmed salmon (*Oncorhynchus kisutch*) muscle. *European Food*  
23 *Research and Technology*, 230, 925-934.
- 24 Ozen, B., & Floros, J. (2001). Effects of emerging food processing techniques on the  
25 packaging materials. *Trends in Food Science and Technology*, 12, 60-67.

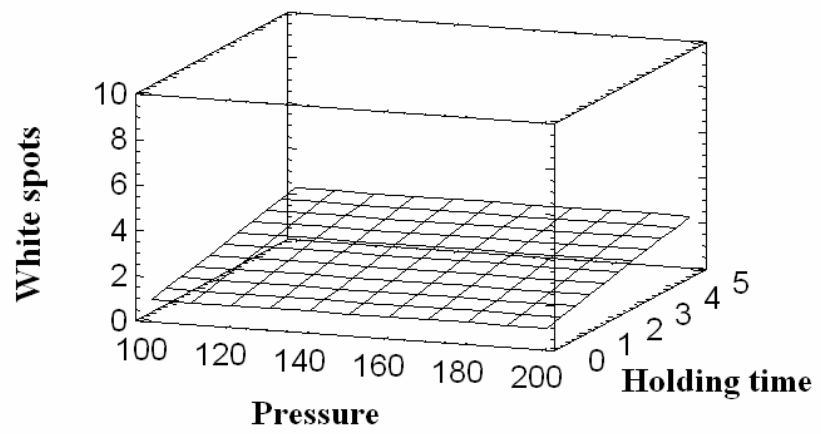
- 1 Pérez-Won, M., Tabilo-Munizaga, G., & Barbosa-Cánovas, G. (2005). Effects of ultra  
2 high pressure on bay scallop (*Aequipecten irradians*) adductor muscles. *Food*  
3 *Science and Technology International*, 11, 477-484.
- 4 Quevedo, R., Aguilera, J. M., & Pedreschi, F. (2010). Color of salmon fillets by  
5 computer vision and sensory panel. *Food and Bioprocess Technology*, 3, 637-  
6 643.
- 7 Ramírez, R., Saraiva, J., Pérez Lamela, C., & Torres, J. A. (2009). Reaction kinetics  
8 analysis of chemical changes in pressure-assisted thermal processing. *Food*  
9 *Engineering Reviews*, 1, 16-30.
- 10 Rodríguez, A., Cruz, J. M., Paseiro-Losada, P., & Aubourg, S. (2011). Effect of a  
11 polyphenol-vacuum packaging on lipid deterioration during an 18-month frozen  
12 storage of coho salmon (*Oncorhynchus kisutch*). *Food and Bioprocess*  
13 *Technology*, DOI: 10.1007/s11947-011-0588-5, *in press*.
- 14 Rouillé, J., Le Bail, A., Ramaswamy, H., & Leclerc, L. (2002). High pressure thawing  
15 of fish and shellfish. *Journal of Food Engineering*, 53, 83-88.
- 16 Sequeira-Muñoz, A., Chevalier, D., Le Bail, A., Ramaswamy, H., & Simpson, J. (2006).  
17 Physicochemical changes induced in carp (*Cyprinus carpio*) fillets by high  
18 pressure processing at low temperature. *Innovative Food Science and Emerging*  
19 *Technologies*, 7, 13-18.
- 20 Sigurgisladóttir, S., Hafsteinsson, H., Jonsson, A., Nortvedt, R., Thomasses, M., &  
21 Torrisen, O. (1999). Textural properties of raw salmon fillets as related to  
22 sampling method. *Journal of Food Science*, 64, 99-104.
- 23 Undeland, I., Hultin, H., & Richards, M. (2003). Aqueous extracts from some muscles  
24 inhibit hemoglobin-mediated oxidation of cod muscle membrane lipids. *Journal*  
25 *of Agricultural and Food Chemistry*, 51, 3111-3119.

- 1 Uresti, R., Velázquez, G., Vázquez, M., Ramírez, R., & Torres, J. A. (2005). Effects of  
2 sugars and polyols on the functional and mechanical properties of pressure-  
3 treated arrowtooth flounder (*Atheresthes stomias*) proteins. *Food Hydrocolloids*,  
4 *19*, 964-973.
- 5 Vinagre, J., Rodríguez, A., Larraín, M<sup>a</sup>. A., & Aubourg, S. (2011). Chemical  
6 composition and quality loss during technological treatment in coho salmon  
7 (*Oncorhynchus kisutch*). *Food Research International*, *44*, 1-13.
- 8 Whittle, K., Hardy, R., & Hobbs, G. (1990). Chilled fish and fishery products. In:  
9 Gormley, T. (ed.) *Chilled foods. The state of the art*, pp. 87-116. Elsevier  
10 Applied Science, New York, USA.
- 11 Yagiz, Y., Kristinsson, H., Balaban, M., & Marshall, M. (2007). Effect of high pressure  
12 treatment on the quality of rainbow trout (*Oncorhynchus mykiss*) and mahi mahi  
13 (*Coryphaena hippurus*). *Journal of Food Science*, *72*, C509-C515.
- 14 Yagiz, Y., Kristinsson, H., Balaban, M., Welt, B., Ralat, M., & Marshall, M. (2009).  
15 Effect of high pressure processing and cooking treatment on the quality of  
16 Atlantic salmon. *Food Chemistry*, *116*, 828-835.
- 17  
18  
19  
20

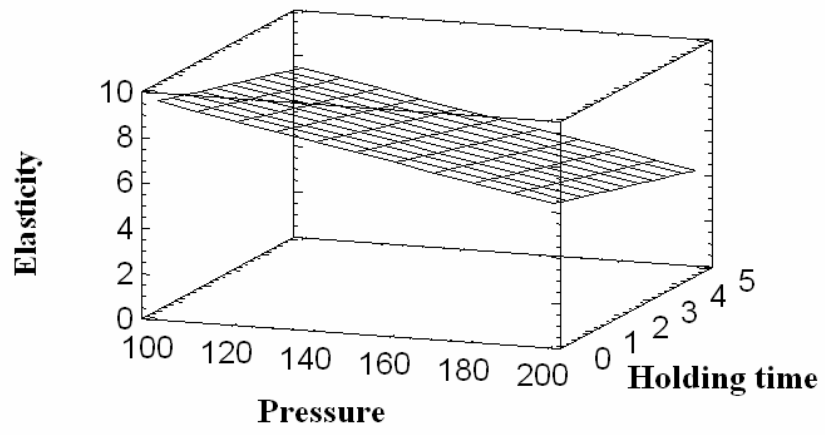
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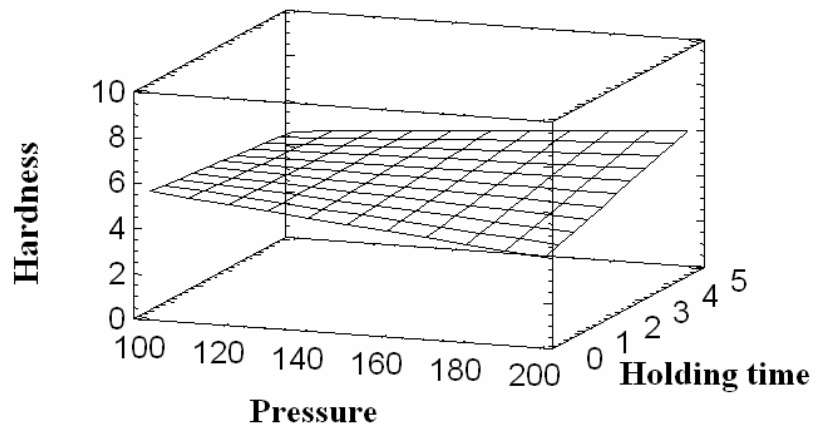
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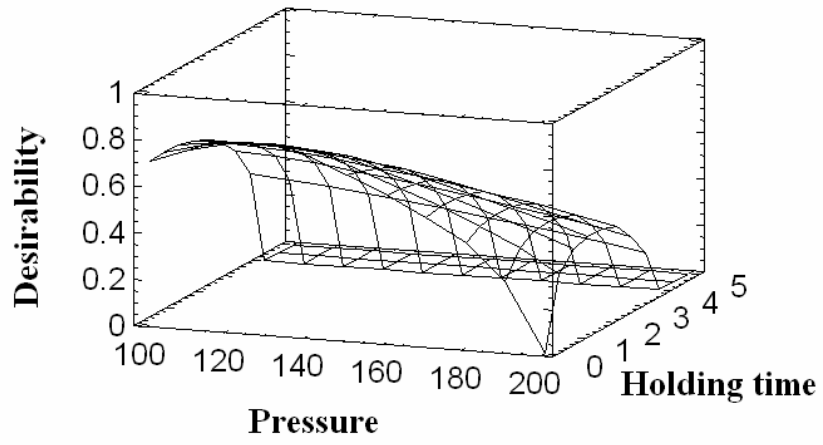
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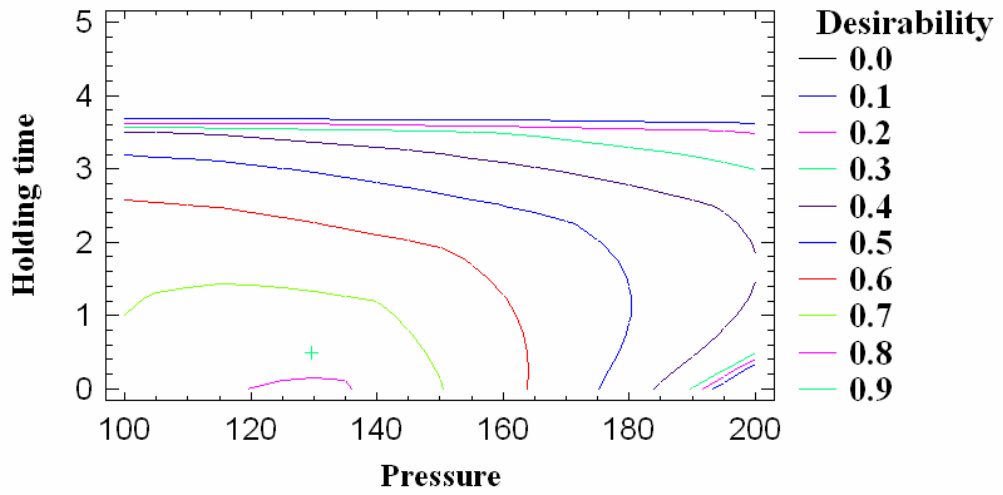
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**E**



**F**





**TABLE 1**

**Regression models of hydrostatic high-pressure process on sensory descriptors of salmon muscle\***

<b>Sensory descriptor</b>	<b>Regression coefficients</b>				<b>Determination coefficient (R<sup>2</sup> value)</b>
	<b>Constant</b>	<b>hydrostatic high-pressure</b>	<b>Holding time</b>	<b>hydrostatic high-pressure × holding time</b>	
Salmon color uniformity	11.454	- 0.021	-	-	71.450
White spots appearance	0.875	-	0.302	-	77.204
Elasticity	12.815	- 0.033	- 0.393	-	97.477
Hardness	7.262	- 0.017	- 0.753	0.006	99.973

\* Only significant ( $p < 0.05$ ) regression coefficients are expressed.

**TABLE 2**

**Odor assessment\* in chilled salmon muscle that was previously treated under different hydrostatic high-pressure (HHP) conditions\*\***

Attribute	Chilling time (days)	Previous HHP treatment			
		C	T-1	T-2	T-3
Rancid odor	0	a 0.2±0.1 z	a 0.6±0.1 y	a 0.6±0.1 y	a 0.5±0.1 y
	6	b 0.9±0.1 x	a 0.6±0.1 z	a 0.7±0.1 y	b 0.7±0.1 y
	10	c 1.9±0.2 z	b 1.8±0.2 z	b 2.5±0.3 y	c 2.4±0.3 y
	15	d 3.5±0.2 y	c 3.0±0.2 z	c 4.2±0.3 x	d 3.7±0.2 yx
	20	d 3.9±0.3 z	d 3.8±0.2 z	d 5.0±0.3 y	e 4.7±0.3 y
Putrid odor	0	a 0.2±0.1	a 0.2±0.1	a 0.3±0.1	a 0.4±0.1
	6	b 0.5±0.1	b 0.5±0.1	b 0.5±0.1	a 0.4±0.1
	10	c 1.3±0.2 z	c 1.3±0.2 z	c 1.5±0.2 y	b 1.6±0.2 y
	15	d 2.6±0.2 y	d 1.9±0.2 z	d 3.1±0.2 x	c 2.6±0.2 y
	20	e 4.3±0.2 x	e 3.3±0.3 z	e 3.8±0.2 y	d 3.7±0.3 y
Amine odor	0	a 0.2±0.1	a 0.2±0.1	a 0.2±0.1	a 0.3±0.1
	6	b 0.8±0.1 y	b 0.4±0.1 z	b 0.4±0.1 z	a 0.4±0.1 z
	10	c 1.1±0.2 z	c 1.1±0.1 z	c 1.6±0.2 y	b 1.3±0.2 z
	15	d 3.2±0.2 x	d 2.9±0.2 y	d 2.7±0.3 y	c 1.9±0.2 z
	20	e 5.5±0.5 y	e 5.5±0.4 y	e 5.4±0.3 y	d 4.2±0.3 z

\* Mean values of three replicates ± standard deviation are given (n=3). For each attribute and for each chilling time, values followed by different letters (z, y, x) denote significant (p<0.05) differences among treatments. For each attribute and for each treatment, values preceded by different letters (a-e) denote significant (p<0.05) differences as a result of chilling time. No letters are included in cases where no significant differences (p>0.05) were obtained.

\*\* Treatment abbreviations: Control (C), 135 MPa for 30 s (T-1), 170 MPa for 30 s (T-2), 200 MPa for 30 s (T-3).

**TABLE 3**

**Sensory (elasticity, cohesiveness and gaping) and physical (firmness and deformation) assessment of texture\* in chilled salmon muscle that was previously treated under different hydrostatic high-pressure (HHP) conditions\*\***

Attribute	Chilling time (days)	Previous HHP treatment			
		C	T-1	T-2	T-3
Elasticity	0	d 7.6±0.3 y	d 7.3±0.3 zy	d 7.1±0.4 zy	d 6.9±0.2 z
	6	c 7.0±0.3	d 6.9±0.3	d 6.9±0.4	cd 6.6±0.4
	10	b 6.4±0.3 y	c 6.1±0.2 zy	c 5.9±0.2 z	c 6.1±0.3 zy
	15	b 6.0±0.2 y	b 5.7±0.2 zy	b 5.4±0.2 z	b 5.5±0.2 z
	20	a 4.7±0.3 y	a 5.2±0.2 x	a 3.9±0.3 z	a 4.8±0.3 y
Cohesiveness	0	d 7.2±0.3 z	d 7.9±0.4 y	d 7.2±0.4 z	d 7.4±0.3 z
	6	cd 6.8±0.2	c 7.1±0.3	d 6.8±0.3	cd 7.0±0.3
	10	c 6.4±0.3 zy	c 6.6±0.3 y	c 5.9±0.3 z	c 6.5±0.3 y
	15	b 5.8±0.2 y	b 6.1±0.1 x	b 5.1±0.2 z	b 6.0±0.2 yx
	20	a 4.6±0.3 z	a 5.3±0.2 y	a 4.6±0.3 z	a 5.2±0.4 y
Gaping***	0	a 1 z	a 2 y	a 2 y	a 3 x
	6	a 1 z	a 2 y	b 3 x	a 3 x
	10	b 2 z	a 2 z	b 3 y	a 3 y
	15	c 4 y	b 3 z	b 3 z	b 4 y
	20	c 4 y	b 3 z	c 5 x	c 5 x
Firmness (N)	0	a 10.6±0.7 y	a 6.7±2.0 z	a 7.4±2.7 z	a 10.3±2.2 y
	6	a 11.7±1.0 y	a 9.3±1.0 z	a 10.6±2.6 zy	a 10.8±1.7 zy
	10	b 18.2±1.4 y	b 14.9±1.3 z	b 17.6±1.0 y	c 18.8±1.5 y
	15	c 22.8±1.4 y	b 14.6±2.4 z	b 20.6±1.5 y	d 24.2±1.6 y
	20	d 27.6±1.3 x	a 15.7±1.1 y	a 11.6±2.6 z	b 16.2±1.1 y
Deformation (mm)	0	ab 18.9±1.7	19.0±1.3	18.0±3.4	19.3±1.3
	6	ab 19.2±1.5	18.5±3.5	19.9±0.1	18.8±2.7
	10	ab 18.8±2.8	19.7±0.4	19.6±0.4	19.7±0.3
	15	a 17.1±1.3	19.1±1.8	18.4±1.7	18.1±1.1
	20	b 20.0±0.1	19.5±0.7	19.7±0.5	19.6±0.3

\* Mean values of three replicates ± standard deviation are given (n=3). For each attribute and for each chilling time, values followed by different letters (z, y, x) denote significant (p<0.05) differences among treatments. For each attribute and for each treatment, values preceded by different letters (a-d) denote significant (p<0.05) differences as a result of chilling time. No letters are included in cases where no significant differences (p>0.05) were obtained.

\*\* Treatment abbreviations as expressed in Table 2.

\*\*\* Statistical analysis was achieved on the corresponding slit numbers.

**TABLE 4**

**Sensory (Roche scale) and physical (CIE L\*, a\*, b\*) color analysis<sup>§</sup> in chilled salmon muscle that was previously treated under different hydrostatic high-pressure (HHP) conditions<sup>§§</sup>**

Descriptor	Chilling time (days)	Previous HHP treatment			
		C	T-1	T-2	T-3
Roche scale	0	b 25.8±1.0	b 27.0±1.7	25.5±1.4	24.9±1.4
	6	ab 24.1±1.3	ab 24.6±1.2	25.1±1.5	24.1±1.3
	10	ab 24.5±1.0	b 25.9±1.4	25.5±1.0	24.5±1.1
	15	a 23.0±0.8 z	ab 24.8±0.8 y	24.4±1.0 zy	24.3±1.1 zy
	20	a 23.0±0.8	a 23.6±0.9	24.2±1.0	23.8±1.2
L* (lightness)	0	ab 49.0±1.0	a 47.2±0.9	a 48.6±0.8	a 48.5±1.6
	6	a 48.0±1.1 z	abc49.9±1.8zy	ab 50.5±1.3 y	ab 50.4±0.9 y
	10	bc 51.0±1.3 y	ab 48.5±0.7 z	c 53.7±1.0 x	b 51.5±1.1 y
	15	c 51.2±0.5 z	c 50.9±0.6 z	c 52.7±0.5 y	b 52.0±1.7 zy
	20	bc 50.9±1.3 z	c 51.1±0.8 z	c 52.9±0.6 y	c 54.2±0.5 x
a* (redness/greenness)	0	b 34.9±0.2	ab 35.1±1.4	34.6±1.3	b 34.6±1.5
	6	abc 34.6±1.7	a 33.4±0.7	34.0±0.6	b 34.5±1.5
	10	a 32.2±1.0 z	b 36.0±0.7 y	32.6±2.3 z	ab 33.2±0.1 z
	15	a 33.4±1.0 z	ab34.5±1.2 zy	35.3±0.8 y	ab 33.4±1.3 z
	20	c 36.0±0.6 y	a 33.1±1.4 z	33.3±1.9 z	a 31.5±1.1 z
b* (yellowness/blueness)	0	b 35.9±0.2 y	ab 33.9±1.4 z	33.2±1.3 z	33.5±1.5 z
	6	ab 34.2±2.1	a 32.0±1.0	31.8±1.1	33.3±1.1
	10	a 34.5±0.5 y	c 36.5±1.3 x	32.6±1.2 z	33.3±0.6 z
	15	a 34.8±0.7 y	bc 34.7±0.9 y	32.3±1.0 z	32.4±1.2 z
	20	b 36.3±0.5 x	b 34.1±0.7 y	32.5±0.7 z	32.7±1.3 z

<sup>§</sup> Mean values of three replicates ± standard deviation are given (n=3). For each attribute and for each chilling time, values followed by different letters (z, y, x) denote significant (p<0.05) differences among treatments. For each attribute and for each treatment, values preceded by different letters (a-c) denote significant (p<0.05) differences as a result of chilling time. No letters are included in cases where no significant differences (p>0.05) were obtained.

<sup>§§</sup> Treatment abbreviations as expressed in Table 2.