Superchilling of rested Atlantic salmon: Different chilling strategies and effects on fish and fillet quality

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ABSTRACT

Rest ed Atlantic salmon was superchilled in seawater slurry (−1.93 ± 0.27 °C). The chilling efficiencies of slurry and crushed ice were compared. The feasibility of using slurry to produce subzero core temperatures before packing was also evaluated. Simulated transport to market, with or without ice after initial superchilling (1 day), was also studied. Fish quality (Quality Index, fillet colour, pH, water content, water-holding capacity, hardness and bacterial loads) was evaluated at arrival to 'market' and after keeping the fish 'in the market' for 1 week. The results were compared with continuous ice (control) or slurry storage. In terms of quality, pre-chilling in slurry and continuous storage in slurry were evidently not advantageous over traditional ice storage, as evaluated after 4 days. After 11 days, both advantages and disadvantages of continuous superchilling were observed. Notably, subsequent ice storage of superchilled fish resulted in increased bacterial load and inferior fillet hardness.

1. Introduction

A major part of the farmed Atlantic salmon (Salmo salar) produced in Norway is traded as bled and gutted whole fish packed in ice. The fish weight is within the extreme limits of about 2–9 kg where the white muscle typically contains 10–20% of fat and 60–70% of water. The seasonal variation in body temperature (seawater temperature) varies from 4 to 20 °C. According to regulations, the core temperature of fish at packing must be less than 4 °C. To achieve this goal, chilling in refrigerated seawater (RSW) tanks (−0.5 to 4 °C) is commonly used in conjunction with live chilling (15–60 min), exsanguination (15–30 min), or storage after gutting (buffer tank). At most processing plants, at least two of these tanks are used in the slaughter line. After packing of bled and gutted salmon, about 20 kg per styrofoam box, typically 25 w/o (or more) of crushed ice is added before the boxes are loaded onto trucks and transported to the market on the same day.

Theoretically, live chilling may be an efficient method of reducing body temperature, particularly where seawater (SW) temperatures are in the range 15–20 °C (summer season). However, in Norway, during most parts of year, the SW temperatures are considerably lower which means that the driving force for heat transfer (temperature difference between harvested fish and refrigerated seawater (RSW)) is rather small for rapid and effective chilling. The alternative, to prolong the holding time in the tank, is not really considered a feasible option, since the holding time would be unrealistically long in the serial processing line, and a bottleneck in the biomass flow would be the result. Even with the additional RSW chilling in bleeding and/or buffer tanks, the resulting core temperatures at packing are typically not lower than 2–6 °C (Erikson, 2008).

The idea of transporting salmon in the styrofoam boxes without ice may be tempting, since this would reduce transport costs dramatically. A prerequisite for such a strategy would of course imply that product safety and quality are not inferior to traditional transport, using crushed ice. Possible advantages of superchilling salmon before transport have occasionally been discussed in the industry. By supplying the fish with an internal ‘cold reservoir’ (e.g. −1 to −3 °C), it might not need additional chilling by addition of ice during transport to market (provided transport times are sufficiently short). Another factor to consider, as the typical packing temperatures are about 4 °C, is that more ice than strictly needed is added to the boxes to chill the fish further to around 0 °C during transport. Pre-chilling to 0 °C (or less), at the plant, might reduce the necessary amount of ice added to the boxes. Theoretically, fish quality may be improved by more rapid chilling. Superchilling (partial freezing) at the plant can be done in a freezing tunnel (blast air or cryogenic gases), where the fish holding time in the tunnel is long enough to facilitate superchilling of the outer layer of the fish or fillet. Alternatively, the fish can be superchilled using dry ice, immersed in RSW, or in brine (slurry). For most fish species, the freezing point of the muscle varies between −0.8 and −1.4 °C (Sikorski, 1990).
Superchilling has been regarded as a means to prolong shelf life. Obviously, the subzero storage temperature must be taken into account. For example, if the shelf life of a certain fish product in ice is 14 days, the predicted shelf life at −1, −2 and −3 °C would be 17, 22 and 29 days, respectively (Huss, 1995). Superchilling of fish is still regarded as a controversial issue; see for example Waterman and Taylor (2001). In short, both positive and negative effects on the quality of different fish species have been reported. Even for the same quality parameter, such as fillet texture, contradictory results are found. It is important to be aware that the potential benefits of superchilling seem to be limited to reducing the rate of spoilage; that is, the method would probably be more effective at long storage times. For example, for maintaining cod quality, superchilling is considered an advantage over ordinary chilled storage only after 12 days post mortem (Waterman & Taylor, 2001). Moreover, a practical challenge, especially with commercial use of superchilling, is the importance of keeping the temperature constant to avoid repeated thawing and freezing (recrystallisation).

For superchilling of salmonids, several studies have been done in different contexts, using different methods to achieve subzero temperatures. As with other fish species, there seem to be positive and negative aspects compared with traditional ice storage. Farmed rainbow trout (Salmo gairdneri irideus) stored at −3 °C reached a k-value of 20% after about 10 days as opposed to more than 20% after 1 day on ice. Furthermore, after 10 days, the TBA values were considerably lower for superchilled salmon (Uchiyama, Ehira, Uchiyama, & Masuzawa, 1978). Duun and Rustad (2008) studied superchilling of vacuum-packed Atlantic salmon fillets at −1.4 and −3.6 °C. Drip loss was not considered a major problem, while fillet hardness was significantly higher for the −3.6 °C chilling regime. Superchilling doubled the storage time compared with ice chilled storage. Furthermore, Sivertsvik, Rosnes, and Kleiberg (2003) studied superchilling, at −2 °C, combined with modified atmosphere packaging (MAP), of fresh Atlantic salmon fillets. Good quality and negligible microbial growth for at least 24 days were documented. By comparison, the shelf lives of the fillets stored in superchilled air, MAP (chilled) or ice were 21, 10, and 7 days, respectively. Atlantic salmon fillet hardness, protein solubility and amount of free amino acids were of comparable magnitudes when salmon were superchilled at −1 °C (no ice) and chilled on ice (4 °C) for 9 and 2 days, respectively (Gallart-Jornet, Rustad, Barat, Fito, & Escriche, 2007). Bahuaud et al. (2008) studied superchilling of prerigor Atlantic salmon fillets for 45 min in a freezing tunnel at −25 °C. When the fillets had reached a core temperature of −1.5 °C, they were stored on ice for up to 4 weeks. Intra- and extracellular ice crystals were formed in the upper layer of the fillets. Myofibre–myofibre detachments were accelerated in superchilled fillets, and increased the amount of myofibre breakages during storage. Nevertheless, fillet texture, as determined instrumentally one week later, was not affected. The initial superchilling also resulted in higher liquid loss. In another study, the average drip loss from salmonids stored in RSW at 1.8, −2.4 or −3.9 °C, after storage for 1 and 2 weeks, was in the range 3.2–4.5%, approximately twice that of fish stored in RSW at 0.0 and −0.8 °C. The weight increase during storage of the latter two groups was somewhat higher. Sodium uptakes (about 0.5% after 2 weeks) were largely similar between treatments (Tomlinson, Geiger, Kay, Utte, & Roach, 1965). Storage of pink salmon (Oncorhynchus gorbuscha) in CSW at −0.5 °C was considered inferior to ice storage for maintaining fish quality (Himelbloom, Crapo, Brown, Babbitt, & Reppond, 1994), whereas Fik, Surówka, and Leszczyńska-Fik (1988) reported that, when superchilling rainbow trout at −2 °C, lower protease activity, lower rancidity and higher sensory scores were achieved when the fish were gutted before superchilling, rather than superchilling the whole fish.

In the present study, we used SW slurry as a means of superchilling. A slurry is a binary system containing water and typically 25–30% of spherical microscopic ice crystals. Compared with flake ice, advantages of using slurries are, for example, higher surface heat exchange rates and less physical damages of fish (Piñeiro, Barros-Velázquez, & Aubourg, 2004). Slurries have been used for a number of different fish species (see Piñeiro et al., 2004).

The objectives of the present research were to assess the efficiency of a simple system (slurry made from fresh SW) for the superchilling of whole gutted salmon to (1) reduce core temperature to 0 °C (or lower) before packing, and (2) to compare simulated transport and storage of ‘at plant’ superchilled fish, transported with or without ice in the boxes. The control chilling regime was traditional ice storage. Although hardly a feasible logistics option for the salmon industry, fish were also continuously superchilled in slurry throughout the ‘transport and storage’ phases. In this case, the slurry should merely be regarded as a means to provide subzero temperatures. To obtain the best possible starting point before chilling, and ultimately the best possible market quality, the salmon were subjected to rested harvest just before chilling. Another reason for using rested fish was to make sure there were no initial quality differences (such as different degrees of autolysis) between the experimental groups related to stress or different fish handling practices since such factors are known to produce fish with lower flesh quality (see review by Poli, Parisi, Scappini, & Zampacavallo, 2005). Fish quality was assessed after 4 days post mortem (‘arrival at market’) and after the fish were stored under different conditions for a further 7 days (‘in the market’). Our last goal was to (3) assess whether superchilling was a better method than ice storage for delivering superfresh salmon of optimal quality (rested fish and immediately chilled) directly to the European market (4 days).

2. Materials and methods

2.1. Experimental design

Fig. 1 shows an overview of the experimental design. Our goals were to assess different strategies for using superchilling in a simulated commercial setting to find: (1) whether superchilling in SW-slurry is a more rapid method for chilling fatty salmon compared with in crushed ice, given the limited time available at ‘the plant’ before ‘transport to market’ the same day, (2) reducing transport costs by reducing total weight of the cargo. The fish were ‘transported to the market’ in standard styrofoam boxes, with and without ice, after they had been given an internal ‘cold-storage reservoir’ by superchilling in slurry for one day, (3) evaluating constant superchilling throughout the value chain, from ‘the plant’ through ‘transport and storage at the market’ where the fish typically arrive on day 4. Fish were also superchilled continuously until day 11. This would approximately represent what is normally considered as borderline in terms of freshness (as opposed to degree of spoilage). Traditional ice storage was used as control groups for both days of quality assessment.

2.2. Fish

Sixty-six Atlantic salmon, with individual body weight 3–5 kg, were collected live in April 2007, from the R. Lernes AS fish farm at Kyrrskæterøra in central Norway. The mean SW temperature in the cage for the last few weeks before transport was 7 °C (acclimation temperature) and the fish were fed (Ewos Opal–110 2500 containing 35–39% of protein, 36–40% of fat and 20 mg kg⁻¹ of astaxanthin) until 17 days before transport to our laboratory. Routine analyses, carried out for the fish farmer, showed that fish
Two insulated polyethylene fish chilling tubs (900 l) were used. At the bottom of each tank a tap was inserted for occasional drainage of water. A fish net was firmly attached to a wooden frame (1.04 × 0.85 m) which was inserted into each tub at a height of 0.3 m. After filling the entire tub with slurry, the gutted fish were placed on top of this net in a volume (above the frame) of 0.44 m³. The fish (n = 42) were divided equally between tubs. The resulting gutted fish density in the slurry was 204 kg m⁻³. To be able to store the fish in a relatively uniform slurry consistency (ice:water mixture) throughout the experiment, freshly made slurry was occasionally added in a batchwise manner. Under the stagnant conditions in the tub, the ice and water phases would gradually separate. Before the fish were added to the tub, we had therefore established a routine for maintaining a fairly consistent- looking slurry in the tub. After filling the tub on the first day, we produced fresh slurry when needed, typically once every day or every second day. The slurry was moved to another tub (reservoir) and from there the needed amounts could be pumped to the experimental tubs. The slurry level in the latter tubs was always constant as the slurry input volume was balanced by draining off the water phase from the bottom of the tank. Except from when fish were withdrawn for weighing and measurements of subcutaneous and core temperatures, the system was completely closed (a lid was used).

We wanted to test the most simple system possible, a system that could easily be introduced in processing plants (or on fishing vessels). Hence, we chose to use a fish chilling tub and a slurry made from SW. The quality of the SW was similar to that described above (live fish tanks). The salinity of our SW was 34 corresponding to a freezing point of −1.865 °C at 1 atm air pressure (Fofonoff & Millard, 1983). The texture of the slurry was made rather smooth (pulpable) and it did not have the typical white snowy appearance when a major part of the liquid phase had been drained off. The wanted consistency was achieved by regulating the inlet water flow rate to the 4.5 kW slurry machine (Skoglund Model S-1; Haugesund, Norway).

2.5. Cold storage

Two groups of control fish (styrofoam boxes with ice) were stored in the cold room (4.2–4.5 °C) and for 4 and 11 days before quality of whole fish and fillets were assessed (Fig. 1). Fish in the slurry were sampled and evaluated similarly. In addition, after one day post mortem, some fish from the slurry were transferred to styrofoam boxes with (one group) and without (two groups), ice. These fish were, from then on, stored in the cold room for 3 more days before assessment of quality (‘transport to market’). One of the groups stored without ice was iced in excess on day 4. These fish were stored in the cold room for a further 7 days before quality was assessed (‘in market’). Where crushed ice was added on day 0 length (mean ± SD, n = 58) were then determined as 4339 ± 1046 g and 68 ± 4 cm, respectively. Subsequently, the fish were tagged, gutted, cleaned under running tap water (7 °C), and weighed (t = 0 h) before they were subjected to the different chilling regimes (Fig. 1). Primarily, to record the chilling profiles (first few hours after slaughter), temperature loggers were placed inside the body cavity. At any one time during the experiment, 20 fish had loggers inside the body cavity, n = 12 in slurry and n = 8 in iced fish. The iced fish were placed in crushed ice in styrofoam boxes, and the boxes were stored in a cold room where the air temperature varied from 4.2 to 4.5 °C during the experiment. The fish to be superchilled were submerged in a tub filled with freshly produced slurry (see below).

2.4. The superchilling system

from the same cage as our experimental fish had a mean condition factor of 1.25, a total fat content of 13.5%, 7.5 mg kg⁻¹ of astaxanthin, and Roche colour card and SalmoFan™ readings of 15 and 27, respectively. Fat and colour were determined in the Norwegian Quality Cut.

The fish were netted from the cage and transferred to a 1000 l container containing SW. The container was repeatedly brought ashore with 10–15 fish at the time. The fish were divided into three oxygenated tanks on a truck. The tanks were filled with fresh SW just before loading of fish. The transport time to our laboratory was about 2.5 h at a fish density of about 66 kg m⁻³. At arrival, the stagnant transport waters were heavily oxygen-supersaturated at 150–272% saturation; the SW temperature was 6.8–7.1 °C, and the pH ranged from 6.5 to 6.9. The low pH values were caused by accumulation of carbon dioxide, estimated to be in the range 0.5 to 1.0% of total weight of water. A fish net was firmly attached to a wooden frame (above (live fish tanks). The salinity of our SW was 34 corresponding to a freezing point of −1.865 °C at 1 atm air pressure (Fofonoff & Millard, 1983). The texture of the slurry was made rather smooth (pulpable) and it did not have the typical white snowy appearance when a major part of the liquid phase had been drained off. The wanted consistency was achieved by regulating the inlet water flow rate to the 4.5 kW slurry machine (Skoglund Model S-1; Haugesund, Norway).

2.3. Slaughter and assessment of stress

At day 0, the fish were slaughtered and chilled. One fish at a time was rapidly dip-netted from the holding tank and killed with a sharp blow to the head within 5–10 s. A blood sample was withdrawn from the caudal vein of 16 fish. A syringe coated with heparin was used. The blood was immediately tested for glucose and haematocrit. Initial white muscle pH and the body temperature were then measured directly in the muscle after an incision was made under the dorsal fin by using a scalpel. The weight and fork
and day 1 it constituted 40% of the total fish weight. The high amount of ice added was to ensure proper chilled storage.

During storage in ice and slurry (days 1–5 and 7–11), core temperatures and temperatures just under the skin were assessed manually. One fish at a time was assessed immediately after being lifted out, from either ice or slurry. The slurry fish were then placed in air (room temperature 15 °C) on a suspended net for 5 min to drain off excess slurry. Excess slurries in oral and body cavities were also removed physically, before weighing (in a partially frozen state). Subsequently, each fish was immediately brought back to chilled storage.

2.6. Fish quality

After cold storage (days 4 and 11), the fish were weighed and quality was assessed (Quality Index Method, QIM) before filleting. Fillet quality was assessed as: ultimate pH, water content, water-holding capacity, texture, colour and bacterial load.

2.7. Analytical methods

2.7.1. Blood glucose

A drop of whole blood from the withdrawn blood sample was placed on a commercial strip which was inserted into an Ascensia Contour meter (Bayer HealthCare LLC, Mishawaka, Indiana, USA). The glucose concentration (mM) was read directly on the display.

2.7.2. Haematocrit

Capillary tubes were immersed in whole blood to collect 5 μl. The tubes were placed and spun in a centrifuge (Compur M1100, Bayer, Leverkusen Germany). Haematocrit (Hct) values, stated as % Hct (red blood cell packed volume), were then determined by direct readings in the centrifuge.

2.7.3. Body and core temperature

The fish body temperature was measured, immediately after killing, in epaxial muscle between the lateral line and the dorsal fin. During cold storage, the core temperature was measured in the thickest part of the gutted fish. To attain some idea of the temperature distribution inside each fish, the subcutaneous temperature was also measured using the same incision made for the initial measurements. A Testo 110 thermometer (Testo AG, Lenzkirch, Germany) was used. During chilling and cold storage, 20 Tinytalk (Gemini Data Loggers, West Sussex, UK) temperature loggers were placed in the body cavity of fish stored in ice and slurry to compare core temperature profiles.

2.7.4. Muscle and fillet pH

Just after killing, the initial pH was measured directly in the white muscle in the same location as the temperature was determined. After filleting on day 4, the pH was measured in the dorsal part of the fillets. A shielded glass electrode (WTW SenTix 41), connected to a portable pH meter (model WTW 315i; WTW, Weilheim, Germany), was used.

2.7.5. Weight changes

The total weight changes during cold storage were evaluated by weighing the gutted fish periodically. Changes in weight were expressed as

\[ \Delta M_t^w = \left( \frac{M_t^w - M_0^w}{M_0^w} \right) \times 100\% \]  

where \( M_0^w \) and \( M_t^w \) were the initial weight and the weight after sampling time \( t \), respectively.

2.7.6. Quality Index Method

On days 4 and 11, the QIM was used to assess external quality attributes of the fish. The QI scheme lists how quality attributes for appearance, that is, skin, texture, eyes, gills and abdomen, change with storage time. For each quality attribute, a score from 0 (very fresh fish) to 3 is given. Finally, the scores for all eleven quality attributes are summarised and presented as a QI score. The maximal possible score is 24 (Sveinsdottir, Martinsdottir, Hylding, Jørgensen, & Kristbergson, 2002).

2.7.7. Water content

The water content of the dorsal muscle was determined by drying a ~2 g sample to constant weight at 105 °C for 24 h. The difference in weight, before and after drying, was taken as the total water content of the sample. The means of three replicates is reported here.

2.7.8. Water-holding capacity

Epaxial muscle was minced and subjected to the low-speed centrifugation method described where a centrifugal force of 230g was used (Hultmann & Rustad, 2002). The water-holding capacity (WHC) is defined as the percentage of water retained in the mince after centrifugation for 5 min. Four parallel samples were run for each fish.

2.7.9. Fillet colour

The colour of whole fillets was objectively assessed by using a computer vision colour measurement system (Erikson & Misimi, 2008). The fillet images were colour calibrated with the Macbeth ColourChecker and the mean \( L^* \), \( a^* \), and \( b^* \) values for the fillets were finally calculated using the Euclidian distance operator (Wyszecki & Stiles, 2000). In addition, the total CIE \( L^*a^*b^* \) colour differences \( \Delta E = \sqrt{(\Delta L^*)^2 + (\Delta a^*)^2 + (\Delta b^*)^2} \) between the various fish groups were calculated to check whether there were any colour differences between treatments.

2.7.10. Fillet texture

Fillet hardness values of fish from all groups were measured by using a TAXT2 Texture Analyser (Stable Micro Systems, Surrey, England). A flat-ended cylindrical plunger (1/2 in diameter) was pressed into the fillets perpendicular to the muscle fibres at a constant speed of 5 mm s \(^{-1}\) until it reached 60% of the fillet height. The measurements were performed at three different locations along the thickest part of the epaxial muscle. The pooled mean value was used as an estimate of fillet hardness for each fish.

2.7.11. Microbial counts

After filleting, about 100 g of epaxial muscle was excised from below the dorsal fin, using sterilised scalpel blades. Each sample was placed in a plastic pouch, sealed, labelled, and transported in ice to the municipal food analysis laboratory (Trondheim kommundirektorat). Ten grammes of the fillet piece (without skin and with previously non-exposed surfaces) was incubated later the same day at 20 °C for determination of total viable counts (TVC) and hydrogen sulphide-producing bacteria (SPB) according to the Nordic Committee on Food Analysis standard, NMKL No. 96, 3rd ed., 2003.

2.8. Statistics

Where in doubt whether the means of two or more experimental groups were significantly different, the groups were compared at the 5% level by using unpaired Student-\( t \) tests. The effect of treatment on fillet colour and hardness was analysed using a one-way ANOVA. Where significance (\( p < 0.05 \)) was indicated, the
Tukey post hoc test (colour) or the multiple range test (hardness) were run.

3. Results and discussion

3.1. Post-harvest condition

One of our goals was to evaluate whether superchilling preserved quality of rested salmon better than did ice storage. To ascertain the actual stress condition of the fish, blood and muscle stress parameters were determined just after killing. At 3.5 mM (Table 1), our blood glucose values were in line with values reported by Waring, Stagg, and Poxton (1992) for unstressed Atlantic salmon. Our mean haematocrit value of 29% Hct, was within the range of 28 ± 2%, typical of rested fish (Iwama, Morgan, & Barton, 1995). Likewise, our mean white muscle pH of 7.5 was typical of rested salmon (Erikson & Misimi, 2008). The initial water content (65.1%) and WHC (94.6%) are discussed below in connection with storage and fillet quality. Since the fish were chilled immediately after killing and gutting, the body temperature of 8.1 °C represented the initial temperature (t = 0 h) of all experimental groups.

3.2. Chilling efficiency and initial temperature profiles

One goal was to compare the chilling efficiency of SW slurry with that of ice to evaluate the feasibility of introducing SW slurry as a method to pre-chill salmon to subzero temperatures before packing (‘chilling at the plant’). For fish placed in styrofoam boxes with ice just after slaughter, the initial body temperature of 8.1 °C was reduced to core temperatures of 2 °C after about 0.5–3 h (data from temperature loggers not shown). Subsequently, the core temperatures during ice storage were never lower than 0.5–1.5 °C (Fig. 2). When the fish were kept immersed in slurry, the core temperatures during ice storage were never lower than 0.5–1.5 °C. After 9 h, the core temperature had stabilised at 1.5 °C. The extra internal ‘cold reservoir’ may then be exploited further, either to reduce the amount of ice in the boxes, or to omit addition of ice altogether. Typical processing times for salmon, from waiting cage or well-boat to packing ready for loading on trucks, varies according to the slaughter method used. However, around 1 h can be considered as a realistic average processing time in the industry. This means that the additional 3 h necessary for pre-chilling to subzero temperatures would imply that the loading of the trucks would be delayed. Moreover, the total costs of chilling the biomass in ice vs slurry would have to be computed. These factors should be weighed against the potentially reduced transport costs, as well as food safety and quality issues (see below).

3.3. Cold storage

Occasional manual temperature measurements in the slurry tubs showed that the temperature gradient in the volume containing fish never exceeded 0.1–0.3 °C at any one point in time. Over the whole storage period (11 days), the mean (±SD; n = 14) slurry temperature was −1.93 ± 0.27 °C. This was less cold than the recommended superchilling temperature of cod at −2.2 °C to avoid damage of tissues due to formation of large ice crystals (Waterman & Taylor, 2001). Duun and Rustad (2008) used calorimetry to determine the ice content of superchilled salmon. At −1.4 and −3.6 °C, the ice fractions were 32 ± 2% and 49 ± 5%, respectively. If we use a simple linear approximation of their data, the ice fraction in our salmon would be around 36%.

Fig. 2 shows subcutaneous and core temperatures of fish subjected to the different chilling regimes. On day 1, two different chilling regimes were established, namely, ice storage at 1–2 °C, present day core temperatures at packing of salmon (Erikson, 2008). The extra internal ‘cold reservoir’ may then be exploited further, either to reduce the amount of ice in the boxes, or to omit addition of ice altogether. Typical processing times for salmon, from waiting cage or well-boat to packing ready for loading on trucks, varies according to the slaughter method used. However, around 1 h can be considered as a realistic average processing time in the industry. This means that the additional 3 h necessary for pre-chilling to subzero temperatures would imply that the loading of the trucks would be delayed. Moreover, the total costs of chilling the biomass in ice vs slurry would have to be computed. These factors should be weighed against the potentially reduced transport costs, as well as food safety and quality issues (see below).

| Table 1 |

<table>
<thead>
<tr>
<th>Blood glucose (mM)</th>
<th>Haematocrit (%)</th>
<th>Muscle pH</th>
<th>Muscle water (%)</th>
<th>WHC (%)</th>
<th>Body temperature (°C)</th>
</tr>
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<tbody>
<tr>
<td>3.5 ± 0.5</td>
<td>29 ± 1</td>
<td>7.52 ± 0.01</td>
<td>65.1 ± 0.9</td>
<td>94.6 ± 1.2</td>
<td>8.1 ± 0.0</td>
</tr>
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Means ± SEM (glucose: n = 16; haematocrit: n = 15; muscle pH: n = 27; muscle water: n = 17; water-holding capacity: n = 13; body temperature: n = 58).

4 The fish were acclimatised to SW temperatures of 7–8 °C during the last weeks before harvest.
and superchilling at −1.5 to −2 °C. These levels persisted throughout storage. During ice storage, there was approximately a 1 °C difference between core and subcutaneous temperatures. By contrast, the temperature distribution in superchilled fish was more even, as no such gradients were observed. Also, fish-to-fish variations in temperature were smaller than those with ice storage.

The temperature of superchilled fish transferred to boxes without ice on day 1 started to increase slowly at first and a temperature gradient was, as expected, established due to heat transfer between fish and the new environment (air). Two days later (day 3), the core and subcutaneous temperatures were about 0.5 °C on either side of 0 °C. As the internal cold reservoir within the fish was being depleted, the temperature started to increase at a greater rate. On day 4, the temperatures in the fish were 3−4 °C and the core and subcutaneous temperatures were about 1 °C higher than those in their iced counterparts. Thus, the transport concept of superchilling salmon at the plant without ice in the boxes seemed just about feasible under the present conditions (pre-chilling to −1.5 to −2 °C, storage in closed styrofoam boxes at a surrounding temperature of 4.5 °C). However, under less ideal conditions, the concept would, at this stage (days 3−4), be vulnerable to relatively rapid temperature rises that might reduce the quality of the product considerably (no ‘buffer ice’ in boxes). When such fish were iced on day 4 (‘fish in market’), the temperature from then on basically resembled the fish in the ice storage group (control).

The other fish group, which was kept in slurry for 1 day, before being stored in boxes with ice until day 4, had (by this time) temperatures similar (1−2 °C, data not shown) to those of the iced fish (control). The ice was still present in the boxes of control fish, which can be regarded as a safety precaution compared with the concept of using no ice.

3.4. Weight changes

The weight changes during storage of whole, gutted salmon are shown in Fig. 3. The ice-stored fish initially lost weight but, after 2 days post mortem, the weight loss from then on stabilised at about 2%. In contrast, the fish stored in the SW slurry increased their weight gradually, ending up at a weight gain of 2.5 and 6% at days 4 and 11, respectively.

At day 1, two of the groups of slurry chilled fish were transferred either to ice or no-ice storage. By contrast with the slurry group, these groups of fish had actually lost weight. One of the groups was different form the slurry group (p < 0.05). This might have been due to possible individual differences at an early stage of storage where the differences in weight were small and more difficult to assess accurately. During further storage, with or without ice, the weight losses of these groups basically resembled traditional ice storage. The mean values of the fish that had been pre-chilled in slurry for 1 day were slightly lower, although not significantly so. This means that, in terms of weight loss, the concept of transporting salmon without ice was acceptable. On the other hand, the weight increase of the fish kept continuously in slurry is not acceptable from a commercial point of view, since Norwegian fish quality regulations (Kvalitetsoverforsskrift for fisk og fiskevær Kap 3, Sections 3−6.5) prohibit storage of fish for more than 3 days in water. The salt and water uptakes from the skin side of large salmon are insignificant, due to the subcutaneous layer of fat (Gallart-Jornet et al., 2007a). Since the fish were gutted, the major part of weight increase can therefore be explained by uptake of salt and water from the belly cavity region. Comparatively, when salmon fillets were immersed in 4% brine at 4 °C, the weight increases after 4 and 11 days were 15 and about 23%, respectively (Gallart-Jornet et al., 2007b). The weight gain of our slurry fish on day 11 was 6% when measured just after the experiment was terminated. Interestingly, when the fish were re-weighed after 3 h in air, the mean weight gain was reduced to 2.4%. This indicated that excess weight, possibly in the form of loosely bound water, was rapidly lost when the fish were taken out of the slurry.

By comparison, storage of ungutted sockeye salmon (Oncorhynchus nerka) showed a weight loss of <1% at −0.8 °C whereas there was a weight increase of <1% at −1.8 °C. After 1 and 2 weeks at 0 and −0.8 °C, the mean weight gains were 2 and 3.5%, respectively. At −1.8, −2.4 and −3.9 °C, the mean weight gains were 1% (1 week) and 2.5% (2 weeks) (Tomlinson et al., 1965). Bronstein et al. (1985) compared weight changes of gutted chinook salmon (Oncorhynchus tschawytscha) in RSW at 0 °C with ice storage. After 4 and 7 days, the weight increases of fish in RSW were 2.0% and 3.8%, respectively, whereas the weight of the iced stored fish varied around ±0.3% over the same period. Notably, when the RSW chilled fish were transferred to ice after 7 days, the fish gradually lost all the water gained.

3.5. Rigor mortis and cold stiffness

We did not assess rigor mortis during ice storage since this has already been repeatedly reported. Rested Atlantic salmon with an initial pH of 7.5 (Table 1) can be expected to have a prerigor period of 25−30 h, and peak rigor after 48 h, and the fish will be in a postrigor state after 60−72 h (Misimi, Erikson, Digre, Skavhaug, & Mathiassen, 2008). In slurry, on the other hand, the nature of the rigor development is not known. The obvious problem one would to encounter, is related to the difficulty of separating true rigor from cold stiffness. Nevertheless, in the fish kept in slurry for 1 day and then stored, with or without ice (in air), the stiffness decreased from 48 h (day 2) to 72 h post mortem. This indicated that storage in slurry for 24 h (equal to the expected prerigor period) did not seem to have an effect on rigor duration for the rested fish.

For the fish stored continuously in slurry, our subjective impression was that the fish were somewhat stiffer during the period of 24−72 h post mortem. Notably, the fish were never judged as extremely stiff at any one point during storage. In contrast, Johansen et al. (1997) observed that, when Atlantic salmon were immersed in CSW at −1.5 °C, the fish became extremely stiff before rigor onset of other groups stored at 0 °C and −0.5 °C. This cold stiffness phenomenon did not change during the period of the experiment (50 h). Even though our fish were stored at a lower
temperature (−1.9 °C), the same kind of stiffness was not observed by us. Johansen et al. (1997) speculated that the muscle fatty acid composition (lipid unsaturation level affected by feed composition) might play a role in the degree of cold stiffness.

Although the fish were not very stiff when they were removed from the slurry to be filleted, we still had to wait until the next day before the fish became supple enough for filleting and quality assessment. In a commercial situation, this aspect must also be taken into account for fish processors. In the market place, such fish might be incorrectly perceived by the consumers as being a thawing frozen product, that is, if the fish are presented too early to the consumers after superchilled storage.

3.6. Fish appearance – Quality Index scores

At mean QI scores of 6.8 and 6.4 (Table 2), the ice-stored and superchilled fish were similar at day 4 (p > 0.05). For fish stored in slurry for 1 day and then stored, either with or without ice, the mean QI scores were higher, although not significantly different, at 7.9 and 8.2, respectively. Comparing the latter two groups, our data suggest that addition of ice was not necessary to maintain (external) quality as well as with the iced counterparts. Generally, it can be concluded that the more rapid initial chilling and the maintenance of fish quality during superchilling was inferior to ice storage. Our data on external quality generally indicated that the potential assets of superchilling became evident only after prolonged storage times.

To get further insight into the actual changes occurring in the fish, eye and gill scores are also shown in Table 2. The other QI parameters, related to skin and abdomen, were similar for all chilling regimes. The skin score varied between 0 (pearl-shiny overall) and 1 (less pearl-shiny) on both days 4 and 11. No blood was present in abdomen (the body cavity was washed after gutting), and generally the abdomen score increased from 0 (neutral) on day 4 to 1 (cucumber, melon) one week later.

At day 4, neither pupils nor eye form had been affected differently by the different chilling regimes (p > 0.05). The gill colour of the iced fish had a more fresh-looking appearance than had that of fish immersed in slurry (p < 0.05). On the other hand, the fish stored continuously in slurry for 4 days had the lowest gill mucus score. There was a tendency for higher mucus scores in fish transferred from slurry to boxes, with or without ice. Moreover, there was a tendency that gill odour was becoming less prominent in fish stored continuously in slurry.

After 11 days post mortem, the QI scores of the fish stored continuously in slurry were clearly lower than those of the two other groups (p < 0.05). In other words, external quality was better maintained with superchilling than with ice storage. Pupils, eye form, gill mucus and gill odour all scored lowest for the superchilled fish (p < 0.05). Notably, the gills of the superchilled fish had a ‘clean-washed’ appearance. In our appraisal, we chose to put this fact as a ‘0’ score (‘transparent’). The fish stored in ice were invariably given a gill mucus score of ‘2’ (brown, clotted). For the gill colour, however, superchilling was inferior to ice storage. Our data on external quality generally indicated that the potential assets of superchilling became evident only after prolonged storage times.

When comparing ice storage (control) with ‘superchilling at plant’ followed by ‘transport to market’ without ice, and subsequent storage in ice ‘in market’, there were no differences in external quality (p > 0.05) except for a slightly lower eye form score for fish in the latter group (p < 0.05). This finding alone suggests that the concept of transporting such fish to the market could be beneficial in terms of saving transport costs although quality was not improved by superchilling fish ‘at the plant’.

Sveinsdottir et al. (2002) reported average QI scores of Atlantic salmon stored on ice for 4 and 11 days as about 5 and 10, respectively, somewhat lower than our corresponding ice-stored values at around 7 and 13 (Table 2). They suggested a rejection point at a QI score of 16, corresponding to 20 days of ice storage. As with superchilled turbot (Piñeiro et al., 2005), we also observed less mucus and gill odour with our superchilled salmon. In contrast, we did not observe cloudy eyes as a result of superchilling, a phenomenon

---

Table 2

<table>
<thead>
<tr>
<th>Quality parameter (range)</th>
<th>Day 4</th>
<th>Slurry</th>
<th>Slurry (1 day) – ice (3 days)</th>
<th>Slurry (1 day) – no ice (3 days)</th>
<th>Slurry (1 day) – no ice (3 days) – ice (7 days)</th>
</tr>
</thead>
<tbody>
<tr>
<td>QI (0–24)</td>
<td>6.8 ± 0.7</td>
<td>6.4 ± 0.9</td>
<td>8.2 ± 0.7</td>
<td>7.9 ± 0.8</td>
<td>NA</td>
</tr>
<tr>
<td>Pupils (0–2)</td>
<td>0.8 ± 0.2</td>
<td>0.9 ± 0.1</td>
<td>1.3 ± 0.2</td>
<td>0.9 ± 0.2</td>
<td>NA</td>
</tr>
<tr>
<td>Eye form (0–2)</td>
<td>1.0 ± 0.0</td>
<td>1.0 ± 0.0</td>
<td>1.0 ± 0.0</td>
<td>1.0 ± 0.0</td>
<td>NA</td>
</tr>
<tr>
<td>Gill colour (0–2)</td>
<td>0.4 ± 0.3</td>
<td>1.4 ± 0.2</td>
<td>0.9 ± 0.3</td>
<td>1.1 ± 0.3</td>
<td>NA</td>
</tr>
<tr>
<td>Gill mucus (0–2)</td>
<td>1.5 ± 0.2</td>
<td>1.1 ± 0.2</td>
<td>1.9 ± 0.1</td>
<td>1.9 ± 0.1</td>
<td>NA</td>
</tr>
<tr>
<td>Gill odour (0–3)</td>
<td>0.5 ± 0.2</td>
<td>0.1 ± 0.1</td>
<td>0.7 ± 0.2</td>
<td>0.6 ± 0.2</td>
<td>NA</td>
</tr>
<tr>
<td>Water (%)</td>
<td>60.1 ± 0.8</td>
<td>61.5 ± 0.6</td>
<td>64.9 ± 0.8</td>
<td>63.8 ± 2.0</td>
<td>69.2 ± 4.0</td>
</tr>
<tr>
<td>WHC (%)</td>
<td>92.2 ± 1.0</td>
<td>93.7 ± 0.7</td>
<td>95.0 ± 0.6</td>
<td>93.7 ± 1.3</td>
<td>93.7 ± 1.3</td>
</tr>
<tr>
<td>pH</td>
<td>6.3 ± 0.03</td>
<td>6.0 ± 0.08</td>
<td>6.4 ± 0.05</td>
<td>6.9 ± 0.04</td>
<td>NA</td>
</tr>
<tr>
<td>Hardness (N)</td>
<td>17.7 ± 0.6</td>
<td>16.7 ± 0.7</td>
<td>13.4 ± 0.6</td>
<td>14.7 ± 0.6</td>
<td>NA</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Day 11</th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>QI (0–24)</td>
<td>13.0 ± 0.4</td>
<td>9.6 ± 0.4</td>
<td>NA</td>
<td>NA</td>
<td>13.0 ± 0.5</td>
</tr>
<tr>
<td>Pupils (0–2)</td>
<td>1.9 ± 0.1</td>
<td>1.3 ± 0.2</td>
<td>NA</td>
<td>NA</td>
<td>1.8 ± 0.2</td>
</tr>
<tr>
<td>Eye form (0–2)</td>
<td>2.0 ± 0.0</td>
<td>1.0 ± 0.0</td>
<td>NA</td>
<td>NA</td>
<td>1.5 ± 0.2</td>
</tr>
<tr>
<td>Gill colour (0–2)</td>
<td>1.1 ± 0.1</td>
<td>2.0 ± 0.0</td>
<td>NA</td>
<td>NA</td>
<td>1.3 ± 0.2</td>
</tr>
<tr>
<td>Gill mucus (0–2)</td>
<td>2.0 ± 0.0</td>
<td>0.5 ± 0.3</td>
<td>NA</td>
<td>NA</td>
<td>2.0 ± 0.0</td>
</tr>
<tr>
<td>Gill odour (0–3)</td>
<td>1.9 ± 0.1</td>
<td>1.4 ± 0.2</td>
<td>NA</td>
<td>NA</td>
<td>1.8 ± 0.2</td>
</tr>
<tr>
<td>Water (%)</td>
<td>63.5 ± 1.4</td>
<td>59.2 ± 1.0</td>
<td>NA</td>
<td>62.2 ± 1.1</td>
<td>62.2 ± 1.1</td>
</tr>
<tr>
<td>WHC (%)</td>
<td>93.6 ± 1.0</td>
<td>89.1 ± 1.5</td>
<td>NA</td>
<td>90.1 ± 1.5</td>
<td>90.1 ± 1.5</td>
</tr>
<tr>
<td>Hardness (N)</td>
<td>14.3 ± 0.7</td>
<td>15.7 ± 0.6</td>
<td>NA</td>
<td>NA</td>
<td>12.9 ± 0.7</td>
</tr>
</tbody>
</table>

Means ± SEM (n = 7–9).

Different letters (a, b, or c) between treatments (rows) on each day mean significant difference (p < 0.05).

| A | Pupils: 0 – clear and black, metal shiny; 1 – dark grey; 2 – matt grey. |
| B | Eye form: 0 – convex; 1 – flat; 2 – sunken. |
| C | Gill colour/appearance: 0 – red/dark brown; 1 – pale red, pink/light brown; 2 – grey-brown, brown, grey, green. |
| D | Gill mucus: 0 – transparent; 1 – milky, clotted; 2 – brown, clotted. |
| E | Gill odour: 0 – fresh, seaweed; 1 – metal, cucumber; 2 – sour, mouldy; 3 – rotten. |
| F | No significant differences (p > 0.05). |
which has been observed when chilling gilthead seabream (*Sparus aurata*) in a slurry at –2.2 °C (Huidobro, Mendes, & Nunes, 2001).

### 3.7. Fillet quality

#### 3.7.1. Water content

The mean white muscle water content of the rested salmon was 65.1% at day 0 (Table 1). This indicated a white muscle fat content of approximately 15% (since the sum of fat and water equals about 80%, Katikou, Hughes, & Robb, 2001). By comparison, the values of fish stored in ice (60.1%) and slurry (61.5%) were significantly different at day 4 (Table 2). After 11 days, only fish in slurry seemed to exhibit a different water content (59.2%, *p* < 0.05). On day 4, the fish stored in slurry for 1 day, followed by ice storage for a further 3 days, had significantly higher water content (64.9%) than had fish stored in ice and slurry. A week later, the slurry fish had lower water (59.2%) than had the two other groups (*p* < 0.05), a rather peculiar result when the weight increase of slurry fish is taken into account (Fig. 3). We strongly suspect that the results were not a valid estimate for the water content of the whole fillet. In a fatty species, such as farmed salmon, the potential effect of the different chilling regimes on water content is difficult to assess, due to the non-uniform fat distribution in this species. The lipid content in Atlantic salmon fillets has been found to vary from 2% to 19% (Katikou et al., 2001). Since there is a strong correlation between lipid and moisture contents, we think our varying water content probably reflected the non-uniform fat distribution more than the potential effects of the chilling regimes. Grossly speaking, a water content of ~60–65% is nevertheless quite normal for large farmed Atlantic salmon. In line with our salmon, Ofstad, Kidman, Myklebust, Olsen, and Hermansson (1995) reported fillet water contents of ~66% at a fat content of about 15%.

#### 3.7.2. Water-holding capacity

Compared with the mean WHC of 94.6% just after slaughter (Table 1), the WHC of all groups at day 4 (range 92.2–95.0%), had not changed significantly (Table 2). Among the groups, only the fish kept in slurry for 1 day and before ice storage for 3 days, were different (higher WHC, *p* < 0.05). After 11 days, the iced group was still not different (*p* > 0.05) from the initial value, whereas the other two groups exhibited significantly lower WHC values at 89.1% and 90.1%. Among the groups, the fish kept in slurry throughout storage had a slightly lower WHC (*p* < 0.05). This is in line with a previous study, showing that superchilling gradually reduces WHC with increased storage time (Fik et al., 1988). During line with a previous study, showing that superchilling gradually reduces WHC with increased storage time (Fik et al., 1988). During further storage in air, this seemed to have a detrimental effect on the water content of the whole fillet. In a fatty species, such as farmed salmon, the potential effect of the different chilling regimes on water content is difficult to assess, due to the non-uniform fat distribution in this species. The lipid content in Atlantic salmon fillets has been found to vary from 2% to 19% (Katikou et al., 2001). Since there is a strong correlation between lipid and moisture contents, we think our varying water content probably reflected the non-uniform fat distribution more than the potential effects of the chilling regimes. Grossly speaking, a water content of ~60–65% is nevertheless quite normal for large farmed Atlantic salmon. In line with our salmon, Ofstad, Kidman, Myklebust, Olsen, and Hermansson (1995) reported fillet water contents of ~66% at a fat content of about 15%.

#### 3.7.3. pH

On day 4, the fillet pH of the different groups ranged from 6.67 to 6.42 (Table 2), that is, a drop of 0.8–1.1 units from the initial values of the rested fish (Table 1). The fish stored without ice after 1 day in slurry exhibited significantly lower pH values than did the fish in the ice and slurry groups, possibly due to a higher rate of *post mortem* glycolysis. The temperatures of these fish at day 4 were somewhat higher than those of the other fish (Fig. 2). Compared with this pH level (about pH 6.4), the other fish groups had probably not yet attained the typical ultimate pH values of farmed salmon. Under normal fasting periods (1–2 weeks), as our fish were subjected to, the ultimate pH is typically about 6.3 ± 0.1 (Hultmann & Rustad, 2002).

#### 3.7.4. Hardness

Fillet hardness, as affected by the various chilling treatments, is shown in Table 2. The highest value recorded was for the control group, stored 4 days in ice, whereas the lowest values were obtained for the treatments with slurry for 1 day, no ice for 3 days and on ice for 7 days. Considering both traditional ice storage and continuous storage in slurry, the hardness decreased with storage time (days 4–11), a well-established fact when fish are subjected to chilled storage (Hultmann & Rustad, 2002). Moreover, considering the changes in hardness from all treatments, our data indicated that storage time had at least as big an effect as the chilling regime, suggesting that softening and tenderisation, rather than tissue damage due to partial freezing, were the major causes of the lowered hardness.

At day 4, there was no difference in hardness between ice and continuous slurry storage (*p* > 0.05). However, where fish were taken from slurry after 1 day and subsequently stored, with or without ice, these treatments produced significantly softer fillets.

After a further week of storage (day 11), there was still no significant difference in hardness between traditional ice storage and continuous superchilling. However, the fish that were superchilled initially, then ‘transported’ without ice and finally kept on ice for another week, had significantly lower hardness than had the fish subjected to continuous superchilling.

Overall, our data suggest that continuous superchilling *per se* did not change fillet hardness compared with ice storage. However, when changing the chilling medium, from liquid phase (slurry) to further storage in air, this seemed to have a detrimental effect on fillet texture.

Regarding superchilling *per se*, our results are in accordance with those of Gallart-Jornet et al. (2007c) who concluded that salmon fillet hardness did not change during 9 days of superchilled storage at –1 °C, and that the hardness values were comparable to those of fish stored in ice. Similarly, texture analysis of salmon pre-chilled at –1.5 °C revealed that fillet texture was not affected when determined after 7 days (Bahuaud et al., 2008). On the other hand, in the case of mullet (*Mugil spp.*) stored up to 10 days on ice or at –2 °C, the superchilled fish were consistently softer during the entire storage period (Lee & Toledo, 1984).

#### 3.7.5. Colour

Fillet colour, as affected by the various chilling regimes, is shown in Table 3. The data represent averages of the entire fillet as determined by computer vision. Using this method, the *a*’ and *b*’ values are considerably higher than those normally reported when the Minolta Chroma Meter is used (Eriksen & Misimi, 2008). This is probably due to the fact that the latter type of instrument measures colour in direct contact with the flesh, whereas the image acquisition of the computer vision method is done at a distance from the object in a light box under controlled illumination, a situation more akin to the perception of colour by the human eye.

When comparing the effect of treatments on fillet colour at day 4 (Table 3), the lightness (*L*’ values) of ice stored fillets was lower than those exposed to the other chilling regimes (*p* < 0.05). In terms of redness (*a*’ values), yellowness (*b*’ values) and chroma (*C*’*a*’), the fillets from fish stored continuously in slurry, and in slurry for 1 day, followed by ice storage for 3 days, were slightly more red and yellow and they had higher colour saturation than had their iced-stored counterparts (*p* < 0.05). The hue angles were, however, not different between treatments (*p* > 0.05). As we can see from the total colour differences (*ΔE* values), fillet colour was not much affected by the different chilling regimes relative to
the control group (ice storage). Furthermore, the specific colour changes were of similar magnitude.

At day 11, there were a few significant differences between treatments (\(L^*\) and \(H_\alpha\) values). Otherwise, the \(a^*\), \(b^*\) and \(C_\alpha\) values were similar (\(p > 0.05\)). The total colour changes, relative to the control group at day 11, were minor. Thus, summing up colour data on days 4 and 11, it was clear that the different chilling regimes did not produce dramatic differences in fillet colour and, in practice, choice of chilling regime would probably not be an issue in this respect.

When considering the effect of storage time (from days 4 to 11), the iced-stored fillets were slightly lighter (higher \(L^*\) values) and redder (higher \(a^*\) values), but had slightly less yellow (lower \(b^*\) values) and lower hue angles (\(p < 0.05\)). Previous ice storage of similarly treated rested salmon from days 0 to 7 also revealed significant, but modest, changes in colour where storage resulted in lighter, less red and yellow fillets, with lower hue angles and chroma (Erikson & Misimi, 2008). Continuous storage (days 4–11) of our rested salmon in slurry did not result in lighter fillets (\(p > 0.05\)). However, yellowness, hue and chroma all decreased somewhat (\(p < 0.05\)). Storage, either with ice or in slurry, had merely a minor effect on the total colour difference and was of magnitude similar to the differences between treatments.

Scientific reports of changes in fillet colour as affected by superchilling are scarce. Limited data from superchilling of vacuum-packed Atlantic salmon fillets indicated higher lightness at \(-3.6^\circ C\) than at \(-1.6^\circ C\) or under ice-stored conditions. No differences in redness and yellowness were found (Duun & Rustad, 2008). On the other hand, frozen storage of Atlantic salmon fillets at \(-20^\circ C\) results in increased \(L^*\), \(a^*\) and \(b^*\) values (Regost, Jakobsen, & Rørå, 2004).

### 3.7.6. Bacterial loads

At days 4 and 11, our ice-stored salmon exhibited total viable counts of about \(2 \times 10^5\) and \(4.3 \times 10^6\) cfu g\(^{-1}\), respectively (Fig. 4). The value at day 11 exceeded the proposed limit of acceptance for human consumption which is \(10^5\) cfu g\(^{-1}\) (ICMSF, 1986). That said, elevated TVC values do not necessarily mean a high spoilage potential. For a closer assessment of the spoilage potential, further characterisation of the bacterial flora would be needed (Hansen, Markøre, Rudi, Langsrud, & Eie, 2009). Although large numbers of bacteria are usually found on spoiling fish, only a part of the flora can be classified as active spoilers. In particular, \(H_2S\)-producing bacteria are associated with fish spoilage. The predominant spoilage of seafood from cold and temperate waters is Shewanella putrefaciens (Gram, Tolle, & Huss, 1987).

At day 4, the TVC values for the various chilling regimes were comparatively low and varied between 545 (slurry group) and

### Table 3

Colour of fillets cut from rested Atlantic salmon subjected to different chilling regimes for 4 and 11 days post mortem.

<table>
<thead>
<tr>
<th>Colour feature</th>
<th>Ice (control)</th>
<th>Continuous slurry (1 day) – ice</th>
<th>Slurry (1 day) – no ice</th>
<th>Ice (control)</th>
<th>Continuous slurry</th>
<th>Slurry (1 day) – no ice</th>
</tr>
</thead>
<tbody>
<tr>
<td>(L^*)</td>
<td>43.4 ± 0.1a</td>
<td>46.3 ± 0.2b</td>
<td>48.3 ± 0.4b</td>
<td>47.6 ± 0.3b</td>
<td>46.7 ± 0.2c</td>
<td>45.9 ± 0.2a</td>
</tr>
<tr>
<td>(a^*)</td>
<td>56.1 ± 0.1a</td>
<td>58.2 ± 0.3b</td>
<td>57.9 ± 0.2c</td>
<td>56.9 ± 0.2c</td>
<td>57.5 ± 0.1c</td>
<td>57.6 ± 0.1a</td>
</tr>
<tr>
<td>(b^*)</td>
<td>47.4 ± 0.1a</td>
<td>49.1 ± 0.2b</td>
<td>49.9 ± 0.1c</td>
<td>47.9 ± 0.1c</td>
<td>46.1 ± 0.1c</td>
<td>45.5 ± 0.1a</td>
</tr>
<tr>
<td>(H_\alpha)</td>
<td>40.2 ± 0.0b</td>
<td>40.1 ± 0.1b</td>
<td>40.2 ± 0.0b</td>
<td>40.1 ± 0.1b</td>
<td>38.7 ± 0.0c</td>
<td>38.2 ± 0.0b</td>
</tr>
<tr>
<td>(C_\alpha)</td>
<td>73.4 ± 0.1b</td>
<td>76.2 ± 0.3b</td>
<td>75.8 ± 0.2b</td>
<td>74.5 ± 0.2b</td>
<td>74.3 ± 0.1c</td>
<td>74.1 ± 0.1c</td>
</tr>
<tr>
<td>(\Delta L^*)</td>
<td>40.2 ± 0.0a</td>
<td>40.1 ± 0.1b</td>
<td>40.2 ± 0.0a</td>
<td>38.7 ± 0.0a</td>
<td>38.2 ± 0.0b</td>
<td>38.6 ± 0.0ab</td>
</tr>
<tr>
<td>(\Delta L_\alpha)</td>
<td>-</td>
<td>5.4 ± 0.3b</td>
<td>4.3 ± 0.2b</td>
<td>3.8 ± 0.1b</td>
<td>3.7 ± 0.3c</td>
<td>3.7 ± 0.3c</td>
</tr>
</tbody>
</table>

Means ± SEM (\(n = 13–16\) fillets); Dissimilar letters indicate significant differences between treatments at the 5% level, either at day 4 (a or b) or at day 11 (x or y); * denotes significant differences between ice storage for 4 and 11 days, whereas § denotes significant differences between continuous storage in slurry for 4 and 11 days.

- **A** Chilling regime.
- **B** Total colour difference (\(\Delta L^* = \sqrt{(\Delta L^*)^2 + (\Delta a^*)^2 + (\Delta b^*)^2}\)) relative to the control group at day 4.
- **C** Total colour difference relative to the control group at day 11.
- **D** Storage time.
- **E** Total colour difference between ice storage for 4 and 11 days.
- **F** Total colour difference between continuous storage in slurry for 4 and 11 days.

Fig. 4. Total viable counts (TVC) and sulphide-producing bacteria (SPB) in rested Atlantic salmon fillets. The fish were filleted after 4 and 11 days post mortem. Just after killing, gutted fish were subjected to different chilling regimes: ice storage (control), superchilling at \(-1.5\)–\(-2.7\)\(^\circ C\) in a seawater slurry, superchilling in slurry for 1 day, before storage with, or without ice for a further 3 days. One group of the fish ‘transported’ without ice was subsequently stored in ice for a further 7 days. Means ± SEM (\(n = 8\)). Different letter over each bar, A, B or C, and, a, b or c, means that the bacterial counts were different (\(p < 0.05\)) for the TVC and SPB, respectively.
8088 cfu g⁻¹ (1 day in slurry before 3 days without ice group). Thus, storage in slurry did not yet show significantly lower growth of bacteria than with the iced fish (control). However, when fish stored in slurry were transferred to boxes, with or without ice (air storage), this led to increased bacterial growth (p < 0.05). Storage for 3 days without ice tended to result in higher bacterial counts than when crushed ice was added to the boxes. Day 11, superchilled fish exhibited considerably lower TVC (2.4 × 10⁷ cfu g⁻¹) than did the two other groups. The bacterial growth in fish that had been superchilled for 1 day, before being ‘transported’ without ice for 3 days and then kept for a further 7 days ‘in the market’, was approximately similar (2.1 × 10⁸ cfu g⁻¹) to that of fish that had been stored in ice continuously (4.4 × 10⁸ cfu g⁻¹; p < 0.05).

Regarding sulphite-reducing bacteria, the bacterial numbers were very low, less than approximately 100 cfu g⁻¹, for all chilling regimes on day 4 (Fig. 4). Again, superchilling, followed by air storage without ice, tended to produce higher bacterial numbers. A week later, the SPB numbers were still comparatively low as they ranged from 11 × 10² (slurry group) to 239 × 10² (1 day in slurry, 3 days without ice group, 7 days in ice) cfu g⁻¹. With these types of bacteria, the storage in slurry was not particularly advantageous compared with traditional ice storage. Once again it was observed that, when fish were transferred from slurry to chilled storage in air, this tended to stimulate bacterial growth. This effect has also been observed by Piñeiro et al. (2005), who found that, when turbot were stored in slurry (−1.5 °C) for 10 and 17 days, and were subsequently transferred to ice for a further 1–3 days (‘in market’), their bacterial numbers also increased rapidly. However, their bacterial numbers were still lower than those in fish that had been stored continuously in ice. The reason for the more rapid bacterial growth rate after storage in slurry might be related to the fact that our slurry probably contained various low molecular weight compounds (easily accessible to microorganisms) originating from the gutted fish. These compounds would have gradually accumulated in the liquid phase. After storage in slurry, our fish were placed directly in ice without being washed. When given access to the higher levels of oxygen during ice storage (in air), this might in turn have resulted in more rapid growth of aerobic bacteria.

Thus, except for the groups of fish stored in ice, and superchilled for 1 day, kept without ice for 3 days and then iced for a further 7 days, all other groups of fish exhibited bacterial numbers (TVC and SSB) well below the proposed limit for human consumption.

By comparison, Sveinsdottir et al. (2002) reported TVC values of about 10⁷ and 10⁶ cfu g⁻¹ for salmon stored on ice for 4 and 12 days, respectively. Regarding the H₂S-producing bacteria, our values for the two storage times were <10 and 5 × 10⁴ cfu g⁻¹, whereas corresponding values of Sveinsdottir et al. (2002) were <5 and 10⁶ cfu g⁻¹, respectively. Since all our chilling regimes produced fish with low levels of SPB, the levels of volatile sulphur-containing compounds in our salmon were probably also rather low.

Taken together, it appears that superchilling of gutted fish was not better than traditional ice storage in terms of microbiology on day 4. Superchilling of fish just after slaughter generally produced somewhat higher bacterial numbers compared with iced and continuous slurry storage. There was also a tendency that omitting ice in the boxes during ‘transport’ resulted in inferior results compared with the iced counterparts. Superchilling was not particularly effective for reducing the number of spoilage bacteria (SPB) after 11 days of subzero storage. In contrast, superchilling was a very effective chilling method for inhibiting growth of bacteria contributing to the TVC. When considering the use of slurries in the cold chain, it is important to be aware of the changes in bacterial growth rates that can occur when the fish are transferred from one chilling medium to another.

4. Summary and conclusions

Chilling salmon in slurry was somewhat more rapid than in ice. However, for both pre-chilling (1 day) and continuous storage in slurry, superchilling was not considered advantageous over traditional ice storage when salmon quality was assessed after 4 days post mortem. In other words, superchilling did not preserve the high quality of rested fish better than did ice-stored fish. After 11 days post mortem, the potential advantages of superchilling became more prominent as the lower QI score revealed less gill mucous and gill odour, clearer pupils and better maintenance of eye form. The disadvantages of using a slurry for superchilling were inferior gill colour and weight increase. Moreover, superchilling resulted in a lower water-holding capacity, indicating changes in protein structure. However, lower fillet hardness was only observed in cases where fish were transferred to subsequent ice storage after superchilling. Fillet colour was only modestly affected by chilling regime.

Pre-chilling of salmon in slurry to subzero temperatures to establish an internal ‘cold-reservoir’ before subsequent air storage (‘transport’) with, or without ice, resulted in lower quality 4 days post mortem compared with both continuous ice and slurry storage. Chilled storage without ice tended to be the poorest method in this respect. Nevertheless, if such fish were subsequently stored in ice for a further week (‘in market’), the quality was comparative to fish that had been stored in ice continuously for 11 days.

Our results indicate that superchilling of Atlantic salmon could, to some extent, represent an advantage over traditional chilled storage only after about 11 days. This is largely in line with data presented by both Waterman and Taylor (2001) and Merritt (1965), who concluded that superchilling of cod at −3 °C and −2 °C was inferior to traditional ice storage for up to 9 days and 10–12 days, respectively. Furthermore, our data suggest that it is necessary to evaluate flesh quality, not just immediately after storage in slurry, but also after the fish are subsequently stored on ice (e.g. refrigerated display).

We conclude that superchilling of salmon did not contribute to better maintenance of freshness, but rather, can only be regarded as a means to slow down the rate of spoilage.

Superchilling of fatty, gutted salmon in slurry was more efficient than was chilling in crushed ice, and the time necessary to reach subzero temperatures would probably not be unrealistically long for a processing plant. Nevertheless, even though lower body temperatures were achieved ‘at the plant’, the method did not prove particularly beneficial, as used under the present conditions. Furthermore, the concept of using a slurry just after slaughter to produce fish with an internal ‘cold reservoir’ to reduce transport costs indicated that ‘transport to market’ without ice (3 days) was a borderline case under the present storage conditions as judged by the ability to keep temperatures low. Possible inferior product quality might be the trade-off. In practice, a less ideal cold chain than that used here, would likely increase risks related to food safety and incidences of economic losses due to claims. On the other hand, the concept would probably be more viable if the surrounding temperatures could be lowered to, for example, 0 °C during transport. Since superchilled fish would be quite stiff after transport to market, a possible disadvantage could be that one would have to wait for an extra day before processing would be possible. If presented to customers too soon after transport, there could be a chance that the product could be regarded as a frozen product.

Some of the disadvantages of using a slurry for the superchilling of gutted salmon (water uptake and increased bacterial growth rate after changing to ice storage) can probably be avoided by using a freezing tunnel for initial subzero chilling, or alternatively,
in combination with continuous subzero storage in air. For example, air-based superchilling of cod results in a weight loss of 3%, somewhat lower than that of melting ice at 1–2% (Merritt, 1965).

With the current focus, in the salmon industry, to process and deliver high-quality salmon rapidly to the market, the present results suggest it would be rather difficult to imagine that the concept of superchilling of gutted fish in slurry fits with such a marketing strategy. A more realistic concept for using superchilling may be in connection with prerigor filleting to produce ready-made consumer packages. Such end-products can be superchilled and distributed directly to consumers, perhaps in combination with other technologies such as MAP (Hansen et al., 2009; Sivertsvik et al., 2003) or vacuum-packaging (Duun & Rustad, 2008).

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References


