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Impact of smolt production strategy on vertebral growth and mineralisation during smoltification and the early seawater phase in Atlantic salmon (*Salmo salar*, L.)

Per Gunnar Fjelldal [a,*], Erik-Jan Lock [b], Sindre Grotmol [c], Geir K. Totland [c], Ulla Nordgarden [a], Gert Flik [b], Tom Hansen [a]

[a] *Institute of Marine Research (IMR), Matre Aquaculture Research Station, N-5984 Matredal, Norway*
[b] *Radboud University Nijmegen, Department of Animal Physiology, Toernooiveld 1, 6525 ED Nijmegen, The Netherlands*
[c] *University of Bergen, Department of Biology, Allégt. 41, N-5007 Bergen, Norway*

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Abstract

This study investigates the effect of different smolt production strategies on vertebral morphology (radiology), composition (mineral content) and mechanical strength (load-deformation testing) in Atlantic salmon (*Salmo salar*). Rapid-growing underyearling (0+) smolt were compared with slower-growing yearling (1+) smolt and a reference group of wild smolt (w). The underyearling and yearling smolt were transferred to seawater in October 2002 and May 2003, respectively. The underyearling smolt were reared under continuous light and the yearling smolt under natural light during the first twelve weeks in seawater, at ambient temperatures. Thus, the underyearling smolt hit seawater at 13 °C and were reared at 10–13 °C during the early seawater phase, whereas the yearling smolt hit seawater at 7 °C and were reared at 7–10 °C during the early seawater phase. All groups displayed increased longitudinal growth (up to 9% increase in relative length) of the caudal vertebrae during parr–smolt transformation. However, at transfer to seawater, the underyearling smolt had significantly lower vertebral mineral content (0+ 44%, 1+ 47%, w 50%) and higher incidence of deformed vertebrae (0+ 1.5%, 1+ 0%, w 0%), and at twelve weeks after transfer to seawater significantly lower vertebral mineral content (0+ 36%, 1+ 41%, w 43%), yield-load (0+ 6492 g, 1+ 8797 g, w 9150 g) and stiffness (0+ 7578 g/mm, 1+ 15,161 g/mm, w 20,523 g/mm), and significantly higher incidence of deformed vertebrae (0+ 2.5%, 1+ 0.3%, w 0%). There was a significant correlation between the mineral content and mechanical properties of the vertebrae. The underyearling smolt had significantly elevated plasma concentrations of total Ca, and P and Ca^{2+} during the parr–smolt transformation and in the early seawater phase.

The results show that underyearling smolt may have an increased risk of developing vertebral deformities. It is possible that this risk can be reduced by postponing the start of the short-day treatment. This will reduce the temperature during smoltification, the temperature and daylength during the early seawater phase, and increase the age at smoltification.

Keywords: Atlantic salmon; Smoltification; Vertebrae; Vertebral column; Deformities; Underyearling smolt; Yearling smolt; Mineralisation; Mechanical properties; Plasma minerals

1. Introduction

During the parr–smolt transformation the Atlantic salmon changes from a bottom-dwelling parr to a smolt

* Corresponding author. Tel.: +47 56367521.
E-mail address: pergf@imr.no (P.G. Fjelldal).

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adapted to a pelagic life in the sea (Folmar and Dickhoff, 1980; Hoar, 1988). This transformation involves downstream swimming (Lundqvist and Eriksson, 1985), development of hypo-osmoregulatory ability (Johnston and Saunders, 1981; McCormick et al., 1987), silvering of the body (Johnston and Eales, 1967) and development of a more streamlined body (Farmer et al., 1978). In coho salmon (*Oncorhynchus kisutch*), the change in body shape during parr–smolt transformation is related to differential growth, primarily in the caudal part of the fish (Winans and Nishioka, 1987). The anatomical basis for the change in body shape has, however, not been elucidated. Seasonal changes in photoperiod are the most important environmental cue for parr–smolt transformation (Hoar, 1988; Saunders et al., 1994), which takes place during the spring.

In commercial smolt production, artificial photoperiods and elevated temperatures are employed for off-season smolt production. At start-feeding in the spring, salmon fry are exposed to continuous light (Berg et al., 1992) and elevated water temperatures (Siemien and Carline, 1991) in order to stimulate growth. Later, the parr are exposed to one of the two alternative photoperiods, which are used to produce either underyearling or yearling smolt. At a length of 10 cm the underyearling smolt are subjected to a reduction in day length (normally 12 h) for six weeks ('winter'), followed by continuous light for six weeks ('spring'). The fish are then transferred to seawater in the autumn of the same year of hatching. Meanwhile, the yearling smolt are subjected to a natural photoperiod some time between midsummer and late October and transferred to seawater the following spring (Duston and Saunders, 1995; Duncan and Bromage, 1998; Duncan et al., 1998; Hansen et al., 1999). Thus, the underyearling smolt are reared at higher temperatures than yearling smolt both during parr–smolt transformation and the early seawater phase. Furthermore, the underyearling smolt are often reared at continuous light after transfer to seawater to enhance growth (Oppedal et al., 1999), whereas yearling smolt are always reared at natural light at this stage of the production cycle. Thus, underyearling smolt grow more rapidly than yearling smolt both during smoltification and the early seawater phase (Lysfjord et al., 2004). This may affect the mineralisation of vertebral bone, which is a slow process that takes place secondly to the deposition of matrix proteins (Meunier, 2002). Field studies have shown that there is a higher incidence of vertebral deformities among underyearling than yearling smolt at harvest (Djupvik, 2005), and the most common deformity is vertebral compression (Berg et al., 2006; Witten et al., 2005). Whether this may be related to a low mineral content and mechanical strength of the vertebrae remains to be elucidated. Furthermore, the influence of smolt production strategy on plasma concentration of phosphorous and calcium, which are the main constituents of the mineral fraction of the bone (Meunier, 2002), has not been studied. The objectives of the present study were therefore to study the effect of smolt production strategy on the growth, mineralisation and mechanical strength of the vertebrae, and on the plasma concentrations of calcium and phosphorous. Underyearling and yearling smolt reared under ambient temperatures and continuous and natural light during the early seawater phase, respectively, were compared.

2. Materials and methods

2.1. Experimental design

On July 19, 2002, 660 Atlantic salmon (*Salmo salar* L.) parr with a mean weight of 17.7 g, were randomly allocated to six square grey, covered, fibreglass tanks ($1 \times 1 \times 0.25$ m) at the Institute of Marine Research, Matre (60° N, 5° E, Western Norway). Three tanks were subjected to 12 h of light and 12 h of dark for six weeks, followed by continuous light exposure (underyearling smolt), while three tanks received continuous light until October 1, followed by a simulated natural photoperiod (yearling smolt). The fish were from the Aquagen strain and had been reared at continuous light from start feeding (March 15) until the start of the experiment and heated water (12 °C) from start feeding until June. Temperature profiles and photoperiods are shown in Fig. 1A–B.

The underyearling smolt were transferred to seawater tanks on October 23, 2002, while the yearling smolt were transferred on May 8, 2003. Both experimental groups were terminated twelve weeks after transfer to seawater, respectively, i.e. underyearling smolt on Jan. 7 and yearling smolt on July 29, 2003.

For illumination, two 18W fluorescent daylight tubes were employed to produce 960 lx measured under water at the centre of the tank. The light was controlled by automatic timers. The fish were fed using a commercial diet (Bio-optimal® dry feed, BioMar AS, Trondheim, Norway). Water flow was kept above 2.5 l per minute per kilo fish, and during the freshwater phase freshwater was mixed with seawater to approximately 1 ppt. The oxygen saturation of the outlet water was kept above 70%.

A reference group of wild salmon were caught by trawl in mid-May ($n=15$, 59° N, Western Norway, median three years old) and early August 2001 ($n=6$, 68° N, Northern Norway, median two years old). The wild salmon from May were smolt caught outside the