Cataract is one of the most expensive diseases in the farming of Atlantic salmon (Salmo salar L.). In addition to the economic implications, the production of fish with visual disturbance raises ethical questions. Lens changes vary from small opacities, mainly at the anterior pole to complete cataracts. Rapidly developing cataracts frequently lead to increased water uptake, swelling of the lens fibres and occasional rupture of the posterior lens capsule. The cause of cataracts in farmed salmon may be considered multifactorial, with both dietary factors as well as environmental factors involved in cataractogenesis.

In wild migrating postsmolt salmon, osmotic cataracts have been diagnosed in a substantial number of fish during the last years. The changes vary from a hazy opacity in the anterior lens to cataracts causing blindness. Severely affected lenses appear swollen, and large vacuoles can be found in the opaque areas. Defective osmoregulation is the most likely explanation for the lens changes.
parr-smolt transformation (change from freshwater to seawater adaptation) may represent a period when the lens is sensitive to endogenous and exogenous cataractogenic stress. The smolt- and postsmolt periods are generally considered to be critical for growth and health performance, due to osmotic challenges, as well as dramatic hormonal and metabolic changes. These factors may also have impact on lens physiology and lead to pathological changes.

The parr-smolt transformation has also been shown to be a critical period in migrating wild salmon. Studies during the last years have shown that a substantial number of wild salmon from Northern Europe develop transitional lens changes when they enter seawater.

This paper describes cataract changes in salmon, and reviews the factors that so far have been identified to be involved in cataractogenesis in modern salmon farming. The cataract problems encountered in the wild salmon are also discussed.

The salmon lens

The salmon lens is spherical and protrudes through the pupil opening, the anterior part of the lens almost touching the back of the cornea (Fig. 1). In this way the lens creates a wide-angle vision field. Dorsally the lens is attached to the rudimentary ciliary body through a strong ligament. Unlike the mammalian lens, the piscine lens is minimally elastic, and because of its rigidity, accommodation cannot occur by change in lens shape. The position of the lens is adjusted by a muscle, musculus retractor lentis, extending from the ventral floor of the globe to the ventral part of the lens. Thus, accommodation occurs by the lens being moved posteriorly and anteriorly through contraction and relaxation of this muscle. The central part of the lens, the nucleus, is surrounded by the lens cortex. The deep cortex is termed the perinucleus and can usually be easily distinguished in salmon. The lens epithelium consists of a single layer of cells and extends over the whole of the lens, apart from a small area around the posterior pole. As in other species, the lens is nourished by the aqueous humor. Fish only have a rudimentary developed ciliary body, however, studies have shown that there are aqueous producing cells at the iris root. For the lens to maintain its regular protein structure, it is dependent on sufficient supply of certain amino acids. The presence of the amino acids methionine and cysteine is especially important to avoid deficiency-caused aggregation of lens proteins and scattering of light (= cataract).

The lens metabolism of different animal species shows a certain variation. Fish eyes increase considerably in size during juvenile life, with the outer cortical lens fibers showing maximum growth activity. The metabolic activity in the piscine lens is considered high. This may also make the piscine lens susceptible to metabolic changes caused either by malnutrition or by a deficiency in absorption of essential nutrients. Nutritionally induced cataracts cannot be reversed, but can be ceased by correcting the feed insufficiencies. Clinically, this arrest can be demonstrated by apposition of a new zone of clear cortex in the periphery of the lens (Fig. 2).

Clinical examination of the salmon lens

Eye examinations should be performed under reduced light condition after sedation. A mydriatic is not necessary, as most fish have a large, irresponsive pupil. Time and oxygenation of the anesthetic bath affect corneal transparency, thus it is important to keep the time in the anesthetic bath to a minimum. Although examination with a focal light source and retroillumination may provide acceptable results under field conditions, the use of a slit-lamp biomicroscope has proven useful for clinical characterisation and classification of the cataracts, and is applicable under practical conditions. Normal lens findings in salmon vary according to the age of the fish. In parr the different layers are difficult to distinguish, while the nucleus and perinuclear area may be visible in older fish (Fig. 3). Clinically, the anterior lens capsule must be distinguished from the cornea, since these two structures are lying adjacent to each other. A vertical anterior lens suture line is often seen, while it may be more difficult to distinguish the posterior horizontal suture line. Corneal as well as intraocular changes should be noted. Funduscopic examination is possible with indirect ophthalmoscope and a high-diopter lens.

Histological techniques, involving both light microscopy and scanning electron microscopy, are important. In vitro methods for cultivating and studying the salmon lens have been developed, and are at present an important tool in cataract research in salmon. Cataract

Pathologic changes of the fish lens have been described to resemble those seen in mammals, with hydropic swelling of lens fibers, lysis of fibers and attempted fiber regeneration resulting in epithelial hyperplasia especially at the anterior pole, and capsular reduplication. Indeed the epithelial proliferation and anterior subcapsular changes are parts of the majority of slowly developing cataracts, visible as a round or doughnut shaped opacity at the anterior pole (Fig. 4). The changes may progress also to affect the posterior cortex, and subsequently the whole cortical area (Fig. 5, a,b). Initial change in the posterior cortex is present as a saucer-shape opacity. A grading system has been developed for practical use in the salmon farms to monitor severity of cataract changes. A frequent entity, however, is rapid cataract development characterized by signs of increased water uptake with marked swelling of the lens fibres, the lens often filling the pupil opening completely. This results in the loss of the aphacic crescent normally visible in fish (Fig. 6). The swollen lens fibres may also cause increased pressure within
the capsular bag, leading to rupture of the lens capsule with subsequent protrusion and even expulsion of the nucleus into the posterior part of the eye (Fig. 7), as also observed in wolf-fish species, Anarhicas spp.15

In fish, as in other species, cataracts are most often present as irreversible destruction of lens fibres and proliferation of lens epithelium. However, reversible opacity of the lens due to osmotic changes is also a known entity in salmonids.16 Osmotic cataract is reversible if the swelling is not too long lasting or has caused disruption of fibres, though repeated stress may render the lens more susceptible to later cataract development.17 Most salmon species are so-called anadromous, i.e. they are capable of seasonal movement between freshwater and seawater. The transformation from freshwater par to seawater-adapted postsmolts, termed smoltification, implies the change from a hyper-osmotic regulatory mechanism to a hypo-osmotic state within the body. In the freshwater phase a function with ion uptake and water excretion is necessary to maintain correct water and ion balance, while in the seawater phase excretion of ions and maintenance of body hydration is essential.18 Monitoring of cataract after seawater transfer has been used as a means of evaluating the degree of smoltification.19 Parr (freshwater-adapted salmon) exposed to saltwater before smoltification develop osmotic cataract occurring as a swelling of the lens fibres. The changes are clinically visible primarily at the anterior lens pole (Fig. 8). Dietary NaCl supplementation has been shown to improve the hypo-osmoregulatory ability of salmonids by enhancing the pre-adaptive mechanism for coping with the salt load when the smolts enter the sea.19 The cornea of salt water adapted fish is permeable to water, although of a low order, and impermeable to sodium.20,21,22 A study by Bjerkaas and Sveier with measurement of intraocular pressure after a period of fluctuation in water salinity showed higher intraocular pressures in fish that had been exposed to salinity fluctuation than fish that had been kept in water with stable salinity. This could be due either to increased influx through the cornea, or as increased water uptake in the whole body due to poor fluid regulation through periods of osmotic stress.

Osmotic cataracts have been observed in an increasing number of migrating wild postsmolts during the last years. The changes range from small opacities along the anterior suture line to changes affecting the whole lens. Minor changes are considered to be reversible, while more serious osmotic cataract may lead to irreversible changes. Thus, large clear vacuoles as a probable sign of former osmotic stress have been observed in the lenses of adult wild salmon (E. Bjerkaas, pers. obs.). Cataracts in wild salmon are considered to cause reduced survival, however, as visually compromised fish are likely to be caught by predators.

Factors affecting cataract development in farmed salmon

Nutritional factors

The cause of cataract in farmed salmon may be considered multifactorial. Nutritional-linked cataracts in salmonids have most often been reported in trout species, related to sub-optimal levels of thiamine,23 riboflavin, methionine, cysteine and tryptophan.24,25 Cataracts induced by zinc deficiencies have been described both in trout and salmon species,26,27 caused either directly by low dietary concentrations, or as a secondary consequence of reduced availability due to formation of chelates in the intestine or competitive uptake of other minerals. In general, these nutrients-related cataracts were more often seen when salmonid farming was in its infancy. The more recently occurring cataract outbreaks in farmed Atlantic salmon have been related to rapid growth and smoltification processes,28 suggesting sub-optimal lens nutrition during periods of rapid growth and subsequent increased demand for nutrients. Several studies on nutritional factors considered to be involved in cataractogenesis have been performed during recent years. In brief, no cataract-preventive effect of increasing dietary vitamin A above recommended levels has been shown,29 nor of feeding different concentrations of fat-soluble vitamins (Vitamins E and C).29 As to iron and zinc supplementation, however, results are controversial. Waagbo et al.30 found no effect of increasing dietary zinc and iron above recommended levels,31 in fact a mild cataractogenic effect of increased iron level was demonstrated,29 while Breck et al.32 found a cataract preventative role of added iron and zinc. This variation in results probably show the complex etiology of cataract, and that interaction between nutrients may play a significant role.

In a study by Waagbo et al.30 on the effect of feeding increased concentrations of dietary lipids on cataract development in salmon, fish fed high-energy concentrations showed a higher growth rate than fish fed low dietary lipids. There was also a positive correlation between rapid growth and cataract development in this study. It was hypothesized that besides the potential growth-promoting effect, the dietary lipid may increase the requirement of some micronutrients to support general metabolism and protection against lipid oxidation.

In another study by Bjerkaas & Sveier,33 however, fish that had been fed low dietary fat level showed the highest cataract incidence. In this study growth was not affected by dietary fat level. Decreasing dietary fat leads to a decrease in fat-soluble vitamins, however, as well as to a concurrent increase in dietary carbohydrates. The demonstrated cataractogenic effect of decreased dietary fat level may in fact be an effect of an increase in carbohydrate load. The effect on the general salmon metabolism of high glucose feeding has been described by Hemre and Hansen34; however, no specific research has been carried out on the glucose metabolism in the
In mammals, during hyperglycemia, glucose in the lens is shunted via the pentose pathway to sorbitol. The activity of aldose reductase (AR), which catalyses this conversion, has been shown to be of critical importance in the development of diabetic cataract in mammals. Concentrations of aldose reductase vary between species, and also between breeds within a species. Preliminary studies suggest that the salmon lens level of AR increases during smolification, thus making the salmon lens more susceptible to hyperglycemia-induced cataract (K. Schmidt, pers. communication).

Environmental factors

Large amounts of water are required in the land based smolt production farms, and water from nearby rivers may be a scarce supply in parts of the country. To reduce the amount of water necessary for hatching and the parr stage of development, it is common to improve water quality either by adding small amounts of seawater or by superoxygenation of the water. Little is known about the quality of supply water, and if superoxygenation affects the normal development of the lens. An effect of river water prior to migration into sea is suspected in osmotic cataracts in wild salmon, described later in this paper. However, one cannot exclude that the same fresh water factors may render the lens in the farmed salmon more susceptible to later cataract development.

Infestation with eye flukes (Diplodustomum spp.) occur in salmon, but seem to be of more clinical significance in other species, including trout. The eye flukes use birds and snails as intermediate hosts. In the fish, they penetrate the posterior lens capsule and migrate into the cortex. A small number of flukes causes little reaction in the lens, however, large numbers lead to cataract and blindness.

Toxic factors may also affect the lens through presentation in the aqueous. Antiparasitic treatment with dichlorvos was suspected to cause cataract in Atlantic salmon, however, this agent is no longer in use for routine treatment against ectoparasites. Ocular examination of fish eyes for cataract has been suggested as a means of monitoring water pollution, as several pollutants have been shown to lead to cataract development in different fish species. Oxidative stress is considered to be an important factor in cataractogenesis, and earlier immunohistochemic studies on cataractous lenses from farmed Atlantic salmon have shown that oxidation of both lipids and nucleic acid is involved. Histidine and histidine-related compounds are known to act as antioxidants in the lens, stabilizing biological membranes. Another effect of histidine in the lens may be that of osmoregulation. Cataracts caused by histidine deficiency have been described in kittens, and Hall et al. have shown that omission of feed histidine is cataractogenic in rats. It was suggested that this was a result from a reduction in protein synthesis at a time of rapid growth of the lens. In a study in rats, however, lens transparency seemed to be preserved even when total dietary protein was maintained at a level that severely retarded body growth. Recent studies have shown a cataract mitigating effect of adding dietary histidine to the salmon feed. However, even if there is a marked positive effect of increasing histidine level, the fish still develop cataract during periods of increased growth, even when fed high histidine.

Rapid growth has already been mentioned as being involved in cataractogenesis. Typically, the salmon undergo parr-smolt transformation and are transferred to sea in the spring; however, in modern farming it has been increasingly common to provoke parr-smolt transformation already in the preceding fall (S-0 fish). With increasing water temperature the fish metabolism and appetite increase, and cataracts are usually observed in the late summer. The S-0 fish have usually been most severely affected. This may be because of a steep growth curve after a winter period of little feed uptake.
Increasing water temperature is a means of provoking cataract under experimental conditions; however, fluctuating temperature has also been shown to cause cataract. In a study by Bjerkaas et al.,55, parr were exposed to steady low or high temperature, or high temperature with cold-water fluctuations. Temperature fluctuations caused fastest growth rate and most severe cataracts, while low temperature resulted in slow growth and minor cataracts. Subsequently, the fish were individually marked and maintained together in seawater over the summer season. Cataract progressed in all groups, fish from the low temperature group showing the fastest growth and developing cataract to the same degree as fish from the other groups. This shows that fluctuation in water temperature may cause both increased growth rate and cataract and that cataract development started in the freshwater phase continues after transferral to seawater. Fluctuation in water temperature caused by both water currents and weather conditions can be expected in natural farming conditions, and is an unpredictable factor contributing to cataract development.

Another unpredictable factor under natural farming conditions is change in water salinity. A common entity is to observe osmotic lens changes shortly after the fish have been transferred from freshwater to seawater. Through blood samples and measurement of the enzyme ATPase the farmers try to find the optimal time of transfer for the majority of the fish, but not all the fish will undergo parr-smolt transformation at exactly the same time. Salinity fluctuation is also inevitable under natural conditions, due to water currents, rainfall and snow melting, and will affect the osmotic balance in the salmon. In a study with fluctuating water salinity, cataract scores were higher in the exposed fish compared to fish maintained at stable water salinity.53

Wild salmon

The effect of water salinity has been demonstrated in studies of wild salmon during the last years. A high incidence of migrating wild postsmolts with “white eyes” caught in research trawls has been of increasing concern. Based on the observed fish size and knowledge on the general migration paths of European postsmolts,56 the fish are considered to consist of a combination of both British and Norwegian stocks. Thus, the phenomenon seems not to be geographically restricted. Wild salmon with ocular opacities could be expected to face problems in finding food and may also be easy prey. Cataract in wild salmon is therefore expected to cause both reduced growth and reduced survival, and could potentially have serious negative effects on the population.

The ocular changes have been shown to represent osmotic cataracts, with opacities varying from a small haziness around the anterior vertical suture line to changes affecting the whole lens, with swelling of lens fibres and occasional formation of large vacuoles (Figures 9 a,b). Histologically, widened sutures, vacuolation of lens epithelium and cortex, and proteinaceous lakes subjacent to the epithelium have been the most frequent changes, while extensive cortical necroses and epithelial proliferation have been seen in a few cases.

During parr-smolt transformation, there is normally a marked increase in the activity of the ion pump Na'-K'-ATPase in gills. This enzyme is considered to be involved in both ion uptake and excretion. An increase in enzyme activity normally occurs when the fish adapt to seawater and is part of the development of hypoosmotic osmoregulation.18 In a study of migrating postsmolts in 2002, samples were taken from six normal-eyed fish and 18 fish with cataract. Mean gill Na-K ATPase activity in the normal fish was 25.9g/g protein. In comparison, the gill Na-K ATPase in fish with osmotic cataract was 13.7g/g protein (Figure 10). Cataract severity varied from small opacities at the anterior pole to changes affecting major parts of the lenses. The lens fibre cells are normally held in a relative dehydrated state by the action of the Na/K pump. Changes in the Na, K or CI permeability of the lens, or in its Na pump rate will eventually alter the ability of the lens to control its swelling.57 Osmotic cataract in salmonids has been extensively studied by Iwata et al.,16 coho salmon parr exposed to salt-water developing osmotic lens changes after 1-3 hours. In our study, osmolality of the aqueous was measured in two pooled samples from the same fish as previously described. A higher aqueous osmolality was found in the fish with cataract than in normal fish (Table 1). These results indicate that the affected postsmolt migrate to sea even if they are not metabolically prepared to do so, when they still express a hyperosmotic osmoregulation.

UV-radiation has been described as a cause of cataract earlier in this paper. At the membrane level, UV radiation may inhibit Na'-K'-ATPase activity.58 UV-related cataracts are of an irreversible nature and does not primarily present as extended osmotic swelling. An effect of reduced or fluctuating water pH cannot be excluded as cause of osmotic cataract in the migrating wild salmon. Acid water has been recognized as a problem for freshwater fish in certain regions of Norway since the 1920ies and has caused losses in fish populations in many Norwegian rivers.59 The Atlantic salmon is more sensitive to acid water than other naturally occurring salmonids. Exposure of smolting Atlantic salmon to acid water has been shown to inhibit the increase in gill Na'-K'-ATPase activity normally occurring during parr-smolt transformation, hence reducing seawater tolerance.60 In parr, exposure to acid water alone does not affect gill Na'-K'-ATPase activities, whereas exposure to aluminium (Al) containing acid water causes reduced enzyme activity. In soft water low in organic matter, which is typical for acidified areas in Norway, high levels of Al together with low levels of calcium (Ca) are considered to be important to the toxicity of water.59 Liming of rivers to neutral pH has been standard procedure for many years,60 however,
it has been demonstrated that mixing zones of Al-rich acid water and limed or neutral water may be even more toxic to fish than the Al-rich acid water itself, and with osmoregulatory failure as a major sign. It cannot be excluded that sub lethal environmental factors, mainly a moderate reduction or fluctuation in water pH, may have been involved in the development of osmotic cataracts in the wild migrating postsmolts, with lens changes as the only visible sign of defective osmoregulation.

In this paper the major causes of Atlantic salmon cataract identified so far have been reviewed. As cataract represents a major problem in modern salmon farming, further research is necessary to identify and modify additional factors involved in cataractogenesis. The recent increase in cataract incidence in wild salmon represents a new and serious problem. Although the living conditions of these two groups of salmon are different, and feed deficiencies are unlikely in wild salmon, one cannot exclude that common environmental factors may be suspected as cause of cataract in both groups of salmon.

References


553-557.


Fig. 2. Growth of a clear peripheral cortical zone indicating a normalization of cataractogenous factors.
Fig. 3. The nucleus and perinuclear area may be visible in normal lenses of older fish.

Fig. 4. Epithelial proliferation and anterior sub capsular changes are parts of the majority of slowly developing cataracts.

Fig. 5. Cataracts may progress also to affect the posterior cortex, and subsequently the whole cortical area.
Fig. 6. Rapidly developing cataracts are characterized by swelling of the lens, the lens often filling the pupil opening completely. This results in the loss of the aphacic crescent normally visible in fish.

Fig. 7. Swelling of lens tissue may lead to rupture of the lens capsule with subsequent protrusion of the nucleus into the posterior part of the eye.

Fig. 8. Parr (freshwater-adapted salmon) exposed to saltwater before smoltification develop osmotic cataract occurring as a swelling of the lens fibres, clinically visible primarily at the anterior lens pole.
Table 1

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Osmolality (mol/kg) of aqueous humor in wild Atlantic salmon with and without osmotic cataract. The table shows the results of three consecutive measurements in two pooled samples from fish with and without cataract, respectively. Method: Vapor pressure osmometer (Vapro®, Wescor, Inc. Utah, USA).