Spawning coloration and sperm quality in a large lake population of Arctic charr (Salmonidae: Salvelinus alpinus L.)

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The modern theories of sexual selection predict that male sexual ornaments may have evolved as reliable signals of male fertilization efficiency. However, among the studies of fishes with external fertilization, the results have yielded ambiguous evidence. In the present study, we present data on the phenotypic relationships between red spawning coloration and ejaculate quality (spermatocrit, sperm motility) from Arctic charr, Salvelinus alpinus. We studied two generations (F1 and F2) of males from a large lake population, reared in a standardized hatchery environment, to determine whether differential hatchery history, or duration of hatchery selection, affected the variation in ejaculate characteristics or abdominal coloration. After controlling for body length, there was no difference between the hatchery generations in these traits. However, the degree of redness increased with fish size. We found a positive correlation between sperm velocity and sperm longevity, indicating a functional integration between these sperm features across generations. Sperm velocity was also positively correlated with male redness. Therefore, the finding obtained in the present study suggests that the carotenoid-based ornamentation in Arctic charr may provide information about differences between males in their fertilization potential. © 2009 The Linnean Society of London, Biological Journal of the Linnean Society, 2009, 98, 794–802.


INTRODUCTION

Conspicuous male ornaments during reproduction are commonly found in various animal species. Especially in species where males offer females gametes but neither resources, nor parental care, indirect genetic benefits to the offspring (i.e. good genes or compatible genes; Mayrs & Hill, 2004; Neff & Pitcher, 2005) can form a major selective force in the evolution of female mate choice (Andersson, 1994; Møller & Alatalo, 1999; Kokko et al., 2003). However, females could also directly benefit from choosing more elaborately ornamented males if they thereby improve the changes of mating with more fertile males. This assumption is the background for the phenotype-linked fertility hypothesis, which states that the male display of sexual ornaments reliably advertises male fertility via condition dependency of the ornaments and the sperm (Sheldon, 1994).

Increasing attention has been recently devoted to the idea of a phenotypic relationship between sexually selected characters and ejaculate quality (Pizzari,
Jensen & Cornwallis, 2004; Malo et al., 2005; Parker et al., 2006; Rogers et al., 2008), although such studies have yielded contradictory results. Among fishes, there is ambiguous evidence for a linkage between the expression of sexual ornaments and various sperm quality indices. Positive correlations have been found in some of the studies (Kortet et al., 2004; Másvær, Liljedal & Folstad, 2004; Locatello et al., 2006; Pitcher, Rodd & Rowe, 2007), whereas others have found no or even negative associations (Liljedal, Folstad & Skarstein, 1999; Skinner & Watt, 2007; Liljedal, Rudolfson & Folstad, 2008). Moreover, there can be a significant intra-specific variation with respect to which components of the male’s phenotype potentially predict insemination success (Pitcher & Evans, 2001). These findings may partly result from the fact that such phenotypic relationships are often tested in populations where varying environmental effects may obscure the underlying genetic associations between male ornaments and fertilization efficiency.

The prevalence of carotenoid-based ornaments, particularly in the versatile signalling of fishes and birds, has made them an ideal study subject in the context of sexual selection. Carotenoids usually appear as red–yellows, and these integumentary colours in feathers and skin are generally assumed to serve as reliable signals of the bearer’s health, vigour, and genetic quality (Olson & Owens, 1998; Möller et al., 2000). Because primary and secondary sex traits are promoted by the same sex hormones, namely androgens (Folstad & Skarstein, 1997; Hillgarth, Ramenofsky & Wingfield, 1997), the expression of carotenoid-derived colour signals may be directly associated with the males’ capacity for sperm production. Furthermore, the allocation of carotenoids for ornamental purposes might reflect low immune activity within the body as well as the reduced exposure of ‘nonself’ sperm cells to an autoimmune attack (Folstad & Skarstein, 1997; Liljedal et al., 1999). Another explanation rests on the role of carotenoids as antioxidants (i.e. functioning to inactivate free radicals), which have a deleterious effect on both sperm quality and the substrates responsible for male ornamentation (von Schantz et al., 1999; Blount, Möller & Houston, 2001). However, it has been recently suggested that carotenoid-based sexual traits may rather signal the availability of nonpigmentary antioxidants (Bertrand, Faivre & Sorci, 2006; Pike et al., 2007; Pérez, Lores & Velando, 2008). Either way, intense carotenoid-dependent ornamental traits may imply high body supplies of antioxidants, which have a potential to reduce the susceptibility of sperm to oxidative stress and thus increase fertility (Greco et al., 2005).

The Arctic charr (Salvelinus alpinus L.) is a highly suitable model species for studying the associations between secondary sexual ornaments and sperm traits (Másvær et al., 2004). Charr males fertilize the eggs externally, and neither males, nor females provide parental care to offspring after spawning (Sigurjónsdóttir & Gunnarson, 1989). Before and during the breeding season, mature males form hierarchical groups and develop a red abdominal ornamentation that is correlated with parasite intensities and immune activity (Skarstein & Folstad, 1996; Liljedal et al., 1999; Skarstein, Folstad & Liljedal, 2001). Previous studies from wild-caught charr have revealed that the degree of carotenoid coloration also may be related to male fertility traits. Másvær et al. (2004) found that redder males had higher sperm production (i.e. testes mass, milt mass and sperm cell numbers produced) than paler males; but see also Liljedal et al. (1999). Yet a recent insemination experiment demonstrated that more colourful male charr have lower parentage success than their less conspicuous rivals when ejaculates with equal sperm numbers compete (Liljedal et al., 2008). This suggests that the lower competitive ability of the ejaculates from more intensively coloured males was a result of sperm traits other than sperm numbers.

In the present study, we examined whether the two important phenotypic traits, red spawning coloration and body size, are correlated with appropriate measures of male reproductive quality (or primary sexual traits) in a large lake Arctic charr (Lake Inari, Finland) population, reared in a standard environment (fish hatchery). Both the first and the second hatchery generations of wild-collected fish were used to examine the alternative hypothesis that differential hatchery history had an effect on these traits.

MATERIAL AND METHODS

STUDY FISH AND THEIR SAMPLING

The experiment was carried out in mid-October 2007 at the facilities of Sarmijärvi Aquaculture station (Finnish Game and Fisheries Research Institute), in north-eastern Finland. The charr were descended from the nearby Lake Inari population and represented the first (F1) and second (F2) hatchery generations (year classes 2002 and 2001, respectively), both of which had been produced by pairwise fertilizations (F1; N = 300 pairs; F2; N = 76 pairs). Furthermore, the F2 group had been produced by specifically avoiding matings between close relatives. The fish were reared similarly in oblong outdoor tanks (area 200 m², water volume 200 m³) and fed continuously (ad libitum) with carotenoid-rich salmonid food (Rehuraisio Emovital; astaxanthin content 80 mg kg⁻¹). The temperature of the inflow water and the lightning conditions both followed the natural rhythm.
Prior to measurements, the fish were fasted for more than 3 weeks. Twenty randomly chosen mature males from both generations were stripped for all available milt and placed into discrete group-specific tanks for 5 days to prohibit spawning activity during the replenishment of their sperm reserves. The anaesthetized fish (MS-222) were measured for total length ($L_T$) to the nearest millimetre and photographed on a grey background under standardized light conditions for subsequent analysis. Thereafter, each fish was carefully dried around the genital pore to avoid sample contamination and the produced milt was collected in individual Petri dishes by pressing the abdomen towards the vent.

**Sperm quality measurements**

Sperm quality parameters were quantified immediately after the stripping of males. Spermatocrit, which is defined as the percentage of a given volume of semen that is occupied by cells, was measured by centrifuging a homogenized proportion of the milt in a capillary tube for 3 min at 11,500 r.p.m. (5396 g) with a mini-centrifuge (Compur-electronic Gmbh). Computer-assisted sperm analysis was employed to estimate variation in sperm velocity; for a more detailed description of the method, see Rudolfsen et al. (2006). Briefly, sperm activity was initially video-recorded for 40 s after activation, specifically, the precise moment that the subsample of pure milt was exposed to 4.5 mL of water on a cooled (approximately 5 °C) microscope slide (Leja Products BV). Recordings were made using a CCD B/W video camera (Sony XC-ST50CE PAL) attached to a negative phase-contrast microscope (Olympus CH30) with a ×10 magnification objective. Video recordings were later analysed using the HTM-CEROS sperm tracker software (CEROS, version 12, Hamilton Thorne Research). The parameters measured were: average path velocity ($V_{AP}$), straight line velocity ($V_{SL}$), and curvilinear velocity ($V_{CL}$) (Rurangwa et al., 2004). The velocity estimates were based on the mean velocity of all motile cells (i.e. those exceeding the predetermined threshold values $V_{AP} > 10 \text{µm s}^{-1}$ and $V_{SL} > 20 \text{µm s}^{-1}$) recorded at 10, 20, 30, and 40 s after activation. The percentage of motile cells 40 s after activation was used as an estimate of sperm longevity. For statistical analysis, the average over two replicates within each male was used for each motility measure. For four individuals, sperm swimming speed could not be reliably quantified and, consequently, they were excluded from final analyses.

**Colour assessment**

To estimate the red spawning coloration on the abdominal region, digital images were measured using a graphical user interface designed for the MATLAB environment (InFotonics Center, University of Joensuu, Finland) to produce numerical estimates for the red, green, and blue intensities in the RGB mode (Stevens et al., 2007). The means of these colour parameters were calculated for each fish within two specified areas (Fig. 1), and the values were further averaged. Red intensity was calculated according to the formula: $I_R = \text{red}/(\text{red} + \text{green} + \text{blue})$ (Liljedal et al., 2008), and this measure was highly correlated with two alternative colour measurements (i.e. hue and saturation), defined in the converted HSV colour model ($r = -0.682$, $N = 40$, $P < 0.001$ and $r = 0.973$, $N = 40$, $P < 0.001$, respectively). Unlike saturation, $I_R$ showed normal sample frequencies and was therefore selected along with hue for a colour variable. Hue is expressed as an angle on a continuous circular scale (0–360°), so that the hue scores closer to zero represent a higher degree of red coloration (Skarstein & Folstad, 1996). It can be thus said to be a more qualitative measure of redness.

**Statistical analysis**

We used SPSS, version 15.0, for Windows (SPSS Inc.) for the statistical analysis. Variable distributions were checked for normality and variance homogeneity.
to verify the assumptions of parametric statistics. The arc-sine square-root transformation was applied to sperm longevity and $I_R$ variables to fulfill their normality assumption. Because there were no ovarian fluid gradients that could have directed the course of sperm cells (Urbach, Folstad & Rudolfsen, 2005), cell trajectories were not expected to be linear and thus the measures of the actual point-to-point track followed by the cells (VCL) was expected to be the most relevant indicator of sperm swimming speed. In addition, the two other velocity parameters were highly correlated with VCL (both $r > 0.98$, both $P < 0.001$, $N = 36$) and so we omitted them in the analyses as redundant variables.

To test whether hatchery generations differed in their sperm or colour properties, we first used multivariate analysis of covariance in which the three sperm measures or two colour measures were the dependent variable(s), fish length was a covariate, and generation was a fixed factor. To examine whether the decrease in VCL differed between generations, we used a repeated measurements analysis of variance (ANOVA), using measurements of sperm velocity from 10–40 s after activation as the within-subject variable. Otherwise, only the VCL 10 s post-activation was included in the analyses because this measurement is the one that is most likely to be under selection (Levitan, 2000). Controlling for the effect of male length ($L_T$), partial correlation coefficients between sperm and colour variables were formed. Sensu Nakagawa (2004), we did not use Bonferroni or similar corrections for the multiple comparisons ($N = 10$ pairwise tests), but present all test probabilities as two-tailed. Because we did not obtain the measures of sperm velocity parameters from all males, sample sizes varied.

**RESULTS**

There was a significant difference in body size between the hatchery generations as a result of their different ages (mean length ± SE = 48.7 ± 0.74 cm and 55.2 ± 1.19 cm for $F_1$ and $F_2$ generations, respectively; $t$-test, $t_{33} = -4.551, P < 0.001$). The sperm traits (spermatocrit, VCL, longevity) did not differ between the hatchery generations [multivariate analysis of covariance (MANCOVA), $F_{3,31} = 1.153, P = 0.343$], nor were they related to male length (covariate: $F_{3,31} = 1.185, P = 0.332$). However, the spermatocrit showed a negative relationship with fish length among the males from the first hatchery generation ($r = -0.540, P = 0.014, N = 20$), but not the second ($r = 0.189, P = 0.426, N = 20$). Sperm swimming speed declined significantly from 10–40 s after sperm activation (repeated measures ANOVA, time: $F_{3,32} = 165.01, P < 0.001$), although there was no generation-specific effect of the rate of decline (generation: $F_{1,34} = 0.008$, $P = 0.931$; time × generation: $F_{3,32} = 1.275, P = 0.300$) (Fig. 2).

There was no difference in the variation of red coloration ($I_R$, hue) between generations (MANCOVA, $F_{2,36} = 1.056, P = 0.220$), when the effect of $L_T$ was taken into account ($F_{2,36} = 6.114, P = 0.005$). Redness increased with male body length (Fig. 3A).

Because the two hatchery generations did not differ from each other with respect to coloration or sperm features, we combined the data for further partial correlation analyses (for the respective correlation coefficients, see Table 1). After controlling for male body length, we found a strong positive correlation between sperm longevity and VCL ($P < 0.001, N = 36$). There were also moderate, although nonsignificant, inter-relationships between spermatocrit and both sperm motility traits (Table 1). VCL showed a significant correlation with both red intensity ($P = 0.004, N = 36$; Fig. 3B) and red hue ($P = 0.007, N = 36$). The significant influence of redness on VCL was also revealed by the univariate analyses of covariance ($I_R =$ covariate: $F_{1,32} = 7.667, P = 0.009$; $I_R ×$ generation: $F_{1,32} = 2.670, P = 0.112$, or, alternatively, hue = covariate: $F_{1,32} = 5.688$, $P = 0.023$; hue × generation: $F_{1,32} = 1.409, P = 0.244$).

**DISCUSSION**

The present study provides some evidence for the phenotype-linked fertility hypothesis that sperm velocity was positively associated with the degree of male red spawning coloration among a large lake population of Arctic charr, reared in a controlled envi-
Sperm motility has been found to predict male fertilization success (Froman et al., 1999; Rurangwa et al., 2004), and, under sperm competition, sperm velocity is probably the prime determinant of paternity (Birkhead et al., 1999; Levitan, 2000; Gage et al., 2004; Liljedal et al., 2008; Rudolfsen et al., 2008; Fitzpatrick et al., 2009). Our observations are thus consistent with the phenotype-linked fertility hypothesis (Sheldon, 1994): the expression of a sexual ornament may signal a male reproductive trait that potentially determines male fertility.

There are alternative mechanistic causes for the general association between male fertility and ornamental traits. In wild Arctic charr populations, both the males’ carotenoid-based coloration and fertilizing potential can be mediated by the individual differences in resistance to parasitic infections (Skarstein & Folstad, 1996; Liljedal et al., 1999; Måsvær et al., 2004). Increased immune activity may canalize resources away from ornamentation and sperm production, as well as interfere with developing sperm cells, which are regarded as nonself to the male (Folstad & Skarstein, 1997; Hillgarth et al., 1997). Hence, the males that are resistant or capable of maintaining a low immunological defence against pathogens and parasites before and during reproduction will have more intense carotenoid-based coloration and higher sperm quality (Skarstein & Folstad, 1996; Liljedal et al., 1999). Because the fish in the present study had been housed in a controlled environment and fed with commercial food (i.e. there was no parasite transmission through the diet), the differences of intrinsic resistance may have been less important for generating the between-individual variability in ornamental coloration and sperm quality. Alternatively, males exhibiting carotenoid-rich coloration may also be those with high body supplies of sperm-protective antioxidants (von Schantz et al., 1999; Blount et al., 2001). Carotenoids themselves may not play an active role in mitigating oxidative stress (Isaksson & Andersson, 2008), but, instead, carotenoid-based ornaments could signal an individual’s availability of a more general antioxidant defence.

**Table 1.** Partial phenotypic correlations between red intensity ($I_R$), red hue, spermatocrit, sperm velocity (10 s after activation) and sperm longevity in sexually mature male Arctic charr when controlling for the effect of fish body length

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Hue</th>
<th>Spermatocrit</th>
<th>VCL</th>
<th>Sperm longevity</th>
</tr>
</thead>
<tbody>
<tr>
<td>$I_R$</td>
<td>-0.682***</td>
<td>0.168</td>
<td>0.475**</td>
<td>0.213</td>
</tr>
<tr>
<td>Hue</td>
<td>-0.108</td>
<td>-0.449**</td>
<td>-0.186</td>
<td></td>
</tr>
<tr>
<td>Spermatocrit</td>
<td>0.302</td>
<td></td>
<td></td>
<td>0.275</td>
</tr>
<tr>
<td>VCL</td>
<td></td>
<td></td>
<td></td>
<td>0.838***</td>
</tr>
</tbody>
</table>

Sample sizes are in the range 36–40. VCL, curvilinear velocity.

**P < 0.01; ***P < 0.001.**

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(e.g. the dietary intake of vitamins A, C, and E) (Hartley & Kennedy, 2004; Bertrand et al., 2006; Pike et al., 2007; Pérez et al., 2008).

Previous studies of guppies (Poecilia reticulata Peters) suggest that, independent of body size, carotenoid pigmentation can be positively linked with sperm movement (Locatello et al., 2006; Pitcher et al., 2007), as well as with the number of sperm deposited (Pilastro et al., 2002; Pitcher et al., 2007; but see also Pitcher & Evans, 2001; Skinner & Watt, 2007). Interestingly, our results revealed that male body length (Lc) was not a significant predictor of ejaculate characteristics, whereas it did have a positive correlation with male redness. Although there did not appear to be a general trade-off between the attained body size (or age) and ejaculate quality, we found a negative correlation between spermatocrit and male length in the first hatchery generation. This is likely to be related to the differential social status of individuals (Rudolfesen et al., 2006), which is determined by the relative body size within the group of males present, with larger males being more dominant (Gross, 1996; in charr, see Sigurjónsdóttir & Gunnarson, 1989; Blanchfield & Ridgway, 1999). Subordinate charr males are known to rapidly invest more both in sperm quantity and quality, presumably to compensate for their disadvantaged breeding position in relation to the dominant males (Liljedal & Folstad, 2003; Rudolfesen et al., 2006; Haugland et al., 2009). Additionally, Liljedal et al. (2008) found that colourful males gain lower parentage than their less ornamented counterparts when equal numbers of sperm from rival males compete for fertilization. In their study, the authors suspected that the more efficient sperm of the paler males could result, at least in part, from their lower social status. Also in the present study, the formation of size-related social hierarchies during the few days before the measurements is a potential confounding factor affecting the observed within-group relationships between coloration and sperm traits. The smaller individuals, especially among the F1 fish, may have increased their ejaculate quality relatively (i.e. both sperm density and motility) compared to the larger, more colourful fish.

Consistent with the observations in roach (Rutilus rutilus L.) (Kortet et al., 2004) and African cichlid fishes (Cichlidae) (Fitzpatrick et al., 2009), we found a positive correlation between spermatocrit velocity and sperm longevity. A functional inter-dependence between these features is a good reflection of the metabolic performance of the sperm cells, and suggests that sperm energetics have been the target of particularly intense selection as a result of sperm competition (Fitzpatrick et al., 2009). In a typical spawning situation of Arctic charr where several males simultaneously release their milt in close proximity to eggs (Sigurjónsdóttir & Gunnarson, 1989), initial sperm velocity may have precedence over endurance in terms of fertilization success (Levitan, 2000; Liljedal et al., 2008; Fitzpatrick et al., 2009). In addition, spermatocrit showed signs of covariance with both sperm motility variables, implying that these traits are phenotypically integrated to some extent rather than representing totally independent components of fertilizing efficiency. Unlike sperm number and milt volume, sperm motility may be less dependent on the intra-testicular steroid content, but is mostly determined by the intra-cellular ATP stores (Christen, Gatti & Billard, 1987; Cummins, 1998; Froman et al., 1999, 2002). Because sperm motility is susceptible to the activity of maternally-derived mitochondrial genes (Cummins, 1998; Pizzari & Birkhead, 2002), directional selection on sperm density and sperm motility may not occur contemporaneously (Froman et al., 2002; Pizzari & Birkhead, 2002); but see also Fitzpatrick et al. (2009). It is also possible that the mitochondrial genes themselves, or their interaction with nuclear genes, mediate a relationship between some male ornaments and sperm quality (Pizzari et al., 2004).

Predicting the phenotypic linkage of primary and secondary sex traits from captive-bred brood stocks involves both advantages and drawbacks in comparison with wild fish. Most importantly, the culture environment essentially reduces, although not totally removes, the among-individual variation arising from confounding environmental effects. Nevertheless, captive conditions are radically different from natural habitats, which can easily alter and/or relax the selective pressures operating on various phenotypic traits and thus ultimately reduce the frequency of genotypes adapted to reproduce in the wild (Lynch & O’Hely, 2001; Wedekind, 2002; Frankham, 2008). Hatchery selection and inbreeding have been noted as being among the major causes of the rapid genetic divergence of hatchery fish from their wild ancestors (Verspoor, 1988; Wang & Ryman, 2001; Wedekind et al., 2007). Both hatchery generations in the present study had been produced by a large number of pairwise fertilizations, which is presumably an effective means to prevent the loss of genetic diversity, as well as to prevent the selection for efficient sperm owing to sperm competition. Furthermore, the possibility of inbreeding among the F1 fish had been minimized with controlled matings, and thus inbreeding depression (genetic load) for sexual coloration (van Oosterhout et al., 2003) or fertility traits (Gomendio, Cassinello & Roldan, 2000; Margulis & Walsh, 2002; Gage et al., 2006) is unlikely in our sample. It remains to be investigated, however, whether an exposure to artificial selection over multiple generations would result in less clear phenotypic correla-
tions between sperm traits and sexually selected ornaments.

In conclusion, the results obtained in the present study provide some support for the idea that male ornamental traits reveal information about primary sexual traits. After controlling for environmental conditions and body size, male abdominal redness was positively correlated with sperm motility. Thus, the spawning coloration of Arctic char males may provide information about differences in fertilization potential between males.

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