

Does the GH/IGF system mediate the effect of water temperature on fish growth? A review

by

Jean-Charles GABILLARD (1), Claudine WEIL (1), Pierre-Yves RESCAN (1),
Isabel NAVARRO (2), Joaquim GUTIERREZ (2) & Pierre-Yves LE BAIL (1)

ABSTRACT. - In fish, as in all poikilotherms, growth is strongly dependent on water temperature. Given that the GH/IGF system regulates growth, it could mediate the effects of temperature on fish growth. Indeed, before hatching, the higher embryonic growth rate in rainbow trout at high temperatures is associated with higher expression of the IGF2 gene in the whole embryo. Furthermore, post-natal growth fluctuations depend on water temperature and are associated with variations of plasma GH and IGF1. Although seasonal parameters such as photoperiod and nutritional status can also affect GH/IGF system activity, it has been shown that an increased temperature led to a specific increase of plasma GH. Moreover, this increase of plasma GH leads to higher plasma IGF1 levels in correlation with the growth rate. By contrast, plasma IGF2 levels as well as muscular levels of IGF1 and IGF2 mRNA are not specifically modified by temperature. Thus, seasonal fluctuations of water temperature affect growth rate through a direct action on plasma GH and IGF1 levels. The mechanisms of this effect are not yet elucidated, but could arise from modifications of metabolite levels (glucose, amino acids, fatty acids, etc.), which regulate GH secretion directly or indirectly through somatostatin of pancreatic or hypothalamic origin.

RÉSUMÉ. - Le système GH/IGF joue-t-il le rôle de médiateur pour l'effet de la température sur la croissance du poisson ? Une revue.

Les poissons, à l'inverse des mammifères, ne contrôlent pas leur température corporelle (poikilothermes). Cette particularité fait que la température du milieu module le développement embryonnaire et la croissance de l'animal. Étant donné que le système GH/IGF possède un rôle central dans la régulation des processus de croissance, il pourrait être le relais des effets de la température sur la croissance. Au cours du développement embryonnaire, nous avons pu montrer que l'augmentation de la vitesse de développement embryonnaire induite par la température était associée à une augmentation du niveau des ARNm IGF2. Au cours de la croissance post-larvaire, les variations saisonnières de température entraînent des variations de croissance, elles-mêmes associées à des variations du niveau plasmatique de GH et d'IGF1. Bien que des paramètres saisonniers tels que la photopériode et l'état nutritionnel puissent moduler l'activité du système GH/IGF, il a été confirmé que la température entraîne une augmentation spécifique du niveau circulant de la GH. De plus, celle-ci conduit à une augmentation des niveaux circulants de l'IGF1, eux-mêmes associés à la vitesse de croissance. Par contre, le niveau plasmatique d'IGF2 ainsi que l'expression musculaire d'IGF1 et d'IGF2 ne sont pas modifiés par la température. Ainsi, toute élévation de la température augmente directement le niveau circulant de GH et stimule la production endocrine d'IGF1, qui serait alors en grande partie responsable des forts taux de croissance observés. Les mécanismes sous-tendant cet effet ne sont pas encore élucidés, mais pourraient provenir d'une modification des niveaux circulants de certains métabolites (glucose, acides aminés,...) qui réguleraient directement ou indirectement (somatostatine) la sécrétion de GH.

Key words. - Fish growth - Temperature - GH/IGF system - Review.

Fish are extremely sensitive to environmental factors such as oxygen levels, water salinity, temperature, etc. (Brett, 1979). Given that fish are poikilotherms, water temperature is a major determining factor in fish biology. The most obvious effect of high temperatures is an increase of the embryonic development rate without affecting the relative timing of formation of the anatomical structures (Garside, 1966; Vernier, 1969; Peterson *et al.*, 1977). In addition, eggs incubation at low temperature leads, at hatching, to the formation of a higher number of muscle fibres (Stickland *et al.*, 1988; Usher *et al.*, 1994; Nathanailides *et al.*, 1995) and vertebrae (Kwain, 1975). In growing fish, an increased temperature

leads to a faster fish growth rate, in parallel with a higher food intake (Brett and Groves, 1979).

Growth is a complex function mostly regulated by several hormones and growth factors. Among these, thyroid hormones (T3 and T4) are essential for a normal growth rate and injection of T3 can promote fish growth (Higgs *et al.*, 1979). Nevertheless, this growth promoting effect is thought to be dependent on other anabolic hormones belonging to the somatotrophic axis (GH/IGF system) (Donaldson *et al.*, 1979; Mommsen and Moon, 2001). Indeed, the use of GH injections or GH transgenic fish showed the strong potency of GH in stimulating fish growth (McLean and Donaldson, 1993;

(1) Équipe Croissance et Qualité de la Chair des Poissons, Station Commune de Recherches en Ichtyophysiologie, Biodiversité et Environnement SCRIBE-INRA, Campus Beaulieu, 35042 Rennes CEDEX, FRANCE. [gabillard@beaulieu.rennes.inra.fr]

(2) Departament de Fisiologia, Facultat de Biologia, Universitat de Barcelona, Avinguda Diagonal 645, E-08071 Barcelona, SPAIN.

Le Bail *et al.*, 1993). Consistent with these data, the lower growth rate after GH immunodepletion proved the need for endogenous GH in normal growth (Le Bail *et al.*, 1991). In addition, IGF1 injection increases fish growth (McCormick *et al.*, 1992; Chen *et al.*, 2000) and endogenous plasma IGF1 levels are often correlated with growth rate (Beckman and Dickhoff, 1998; Pierce *et al.*, 2001; Mingarro *et al.*, 2002). All these observations raise the possibility that the GH/IGF system can mediate the effects of temperature on growth and development.

After a short description of the GH/IGF system in fish, we will present the current knowledge concerning the effect of temperature on the GH/IGF system during the embryonic and post-larval periods. Hypotheses, explaining the effects of temperature on GH/IGF system activity, will also be discussed.

THE GH/IGF SYSTEM IN FISH

General organisation of the GH/IGF system

The general organisation of the GH/IGF system is similar in both higher vertebrates and fish, and includes growth hormone (GH), GH receptor, IGF1, IGF2, IGF receptors, and IGF binding proteins (Plisetskaya *et al.*, 1994; Duan, 1997; Kelley *et al.*, 2000).

Growth hormone is synthesized in the *pars distalis* of the pituitary and was purified in fish for the first time in tilapia (*Oreochromis mossambica*) (Farmer *et al.*, 1976). Its expression and secretion depend on several neuropeptides (GHRH, NPY, SRIF, GnRH, dopamine, etc.) and hormones (T3, IGF1, IGF2, etc.) (Holloway and Leatherland, 1998; Peng and Peter, 1997; Peter and Chang, 1999). In contrast to mammals, endogenous basal secretion of GH in fish is very high *in vitro* (Yada *et al.*, 1991; Yada and Hirano, 1992; Blaise *et al.*, 1995a), giving the inhibitors of GH secretion a greater impact (SRIF, IGFs, etc.).

The GH receptor, belonging to the cytokine receptor family, has been mainly characterized by binding studies, in several fish species (Yao and Le Bail, 1999; Hirano, 1991; Gray *et al.*, 1992; Ng *et al.*, 1992; Yao *et al.*, 1991; Zhang and Marchant, 1996). Recently cDNA for the GH receptor in goldfish (*Carassius auratus*) (Lee *et al.*, 2001), turbot (*Psetta maxima*) (Calduch-Giner *et al.*, 2001) and sea bream (*Sparus aurata*) (Calduch-Giner *et al.*, 2003) were cloned and sequenced, revealing the well-conserved motif characteristics of the GH receptor. As observed in mammals, the liver is the main organ expressing the GH receptor (Yao and Le Bail, 1999; Yao *et al.*, 1991; Hirano, 1991; Marti-Palanca and Pérez-Sánchez, 1994; Calduch-Giner *et al.*, 2001).

IGFs (IGF1 and IGF2) are highly conserved between fish and mammals (> 70% similarity), underlying the importance

of these growth factors throughout evolution (Chen *et al.*, 1994). Consistent with the 'Somatomedin' hypothesis, exogenous GH stimulates IGF1 expression in the fish liver (Cao *et al.*, 1989; Shambloft *et al.*, 1995; Moriyama, 1995; Duguay *et al.*, 1996; Guillén *et al.*, 1998), which is the major source of circulating IGF1 (Leroith *et al.*, 2001). In rainbow trout (*Oncorhynchus mykiss*) but not in others species, GH can stimulate hepatic IGF2 expression *in vivo* and *in vitro* (Shambloft *et al.*, 1995; Le Bail *et al.*, 1998). Although IGF1 function appears to be linked to growth regulation (Chen *et al.*, 1994; Beckman and Dickhoff, 1998; Beckman *et al.*, 2001; Mingarro *et al.*, 2002), the specific role of IGF2 is not yet known. Recently, Gabillard *et al.* (2003c) reported that plasma IGF2 levels are associated with the nutritional status rather than with the growth rate.

The IGF type I receptor mediates the biological actions of the IGFs. This receptor is a heterotetramer, with two extracellular α subunits and two intracellular β subunits. The α subunit contains the ligand-binding domain and the β subunit bears the tyrosine kinase domain implicated in the signal transduction. Binding characteristics have been studied in several fish species and the amino-acid sequences indicate a well-conserved structure in teleosts (Navarro *et al.*, 1999; Planas *et al.*, 2000). In mammals, a second IGF receptor binds IGF2: the mannose-6-phosphate/IGF2 receptor (M6P/IGF2 receptor). In amphibian and birds this receptor does not bind IGF2 due to a lack of a specific binding site (Canfield and Kornfeld, 1989; Kiess *et al.*, 1994). The recent report of an IGF2 binding to this receptor in rainbow trout (Mendez *et al.*, 2001) raises questions about its evolution and function.

As in mammals, IGFs circulate in blood bound to specific binding proteins (IGFBP). In several fish species, three forms of IGFBP are present in blood (Kelley *et al.*, 2000; Kelley *et al.*, 2002) with apparent molecular masses of 29 kDa (IGFBP1), 31 kDa (IGFBP2) and 40-43 kDa (IGFBP3). Their nucleotide sequences are now available in zebrafish (*Danio rerio*) (Duan *et al.*, 1999; Maures and Duan, 2002), sea bream (Funkenstein *et al.*, 2002), tilapia (Cheng *et al.*, 2002) and turbot (Duval, 2000) and data concerning the affinity for IGF1 and IGF2 as well as their regulation has begun to be reported (Kajimura *et al.*, 2003; Shimizu *et al.*, 2003).

Regulation of GH/IGF system activity

In fish, biological functions and external factors influence the GH/IGF system activity. For instance, salmon smoltification leads to an increase in plasma levels of GH and IGF1 before transfer to seawater (Bœuf, 1987a; Bœuf, 1987b; Dickhoff *et al.*, 1997). In addition, during sexual maturation of several fish species, plasma levels of GH and IGF1 increase, leading to seasonal variations of hormonal

profiles (Marchant and Peter, 1986; Le Gac *et al.*, 1993; Gomez *et al.*, 1999; Mingarro *et al.*, 2002; Einarsdottir *et al.*, 2002; Bhandari *et al.*, 2003).

External factors such as photoperiod increase the plasma levels of GH, which may be responsible for the stimulation of fish growth (Bœuf and Le Bail, 1999). Nutritional status also modulates GH/IGF system activity. Fasting leads to an increase in plasma GH levels, in several fish species (Sumpter *et al.*, 1991; Duan and Plisetskaya, 1993; Pérez-Sánchez *et al.*, 1995; Marchelidon *et al.*, 1996; Weber and Grau, 1999) and in pituitary GH content (Yao, 1993; Marchelidon *et al.*, 1996; Weber and Grau, 1999), while hepatic GH receptivity decreases (Gray *et al.*, 1992; Yao, 1993; Pérez-Sánchez *et al.*, 1995). This hepatic resistance to GH partly explains the lower plasma levels of IGF1 observed in fasted fish (Duan and Plisetskaya, 1993; Moriyama *et al.*, 1994; Pérez-Sánchez *et al.*, 1995; Gentil *et al.*, 1996; Baños *et al.*, 1999). In addition, a recent study on rainbow trout (Chauvigné *et al.*, 2003) showed an increase of IGF1 gene expression in muscle after refeeding, suggesting an implication of the autocrine and (or) paracrine production of IGF1 in muscle growth recovery. Nevertheless, in cases of moderate food restriction (above maintenance ration), plasma GH levels are unchanged (Pérez-Sánchez *et al.*, 1995; Pierce *et al.*, 2001) while hepatic GH receptivity (Pérez-Sánchez *et al.*, 1995) and plasma IGF1 levels (Pierce *et al.*, 2001) decrease simultaneously.

From these observations, the GH/IGF system activity appears to depend on parameters that fluctuate through the season simultaneously with water temperature. In consequence, to elucidate the specific role of temperature on the GH/IGF activity, these factors have to be taken in account.

REGULATION OF THE GH/IGF SYSTEM BY TEMPERATURE

During embryonic development

Somatotroph cells appear very early during the embryonic development of salmonids (Mal *et al.*, 1989; Saga *et al.*, 1993; Naito *et al.*, 1993; Yang *et al.*, 1999; Jones *et al.*, 2001; Gabillard *et al.*, 2003b) and IGF system messengers have been detected early in embryos of rainbow trout (Greene and Chen, 1997; Greene and Chen, 1999; Gabillard *et al.*, 2003b), gilthead seabream (Funkenstein *et al.*, 1996), and zebrafish (Ayaso *et al.*, 2002; Maures *et al.*, 2002; Maures and Duan, 2002). Since the GH/IGF system is involved in growth in mammals (Leroith *et al.*, 2001), it is tempting to speculate that it could mediate the effect of temperature on embryonic growth rate.

We have recently investigated this point since no data were available (Gabillard *et al.*, 2003c). We showed in rainbow trout embryos, that the somatotroph cells appear at stage

Table I. - Duration (days) of rainbow trout embryo incubation at 4, 8 and 12°C to reach different stages of development according to Vernier (1969). Stage 22: pigment on the choroid periphery, appearance of the cardinal vein. Stage 24: 6 aortic arches, appearance of the caudal vein. Stage 25: anal fin bud, caudal artery and vein reach the tail extremity. [Temps (jours) d'incubation à 4, 8 et 12 °C des embryons de truite arc-en-ciel pour atteindre les différents stades de développement selon Vernier (1969). Stade 22 : Pigmentation périphérique de la choroïde, apparition de la veine cardinale. Stade 24 : 6 arcs aortiques, apparition de la veine cardinale. Stade 25 : bourgeon de la nageoire anale, artère et veine caudales atteignant l'extrémité de la queue.]

	4°C	8°C	12°C
Stage 22	42	21	14
Stage 24	48	24	16
Stage 25	52	26	17
Hatching	81	46	28

24 (according to Vernier, 1969), whatever the rearing temperature (4, 8 or 12°C), and that temperature does not change the levels of GH protein and transcript in hatched embryos. Therefore, at least in this species, GH is unlikely to mediate the effect of temperature on embryonic growth rate (Tab. I).

Concerning the IGF system, IGF1 mRNA levels, in the whole embryo of rainbow trout, were similar at 4, 8 or 12°C (Gabillard *et al.*, 2003c) and this probably results from the absence of variations in GH expression. By contrast, an increase in the amount of IGF2 mRNA was observed with increasing temperatures (Fig. 1), and is related to the enhancement of embryonic growth rate. Given that, in rainbow trout and zebrafish there is a higher expression of IGF2 than IGF1 gene in the whole embryo (Greene and Chen,

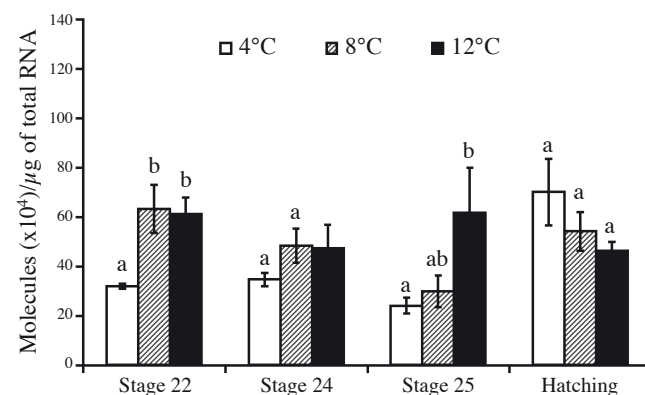
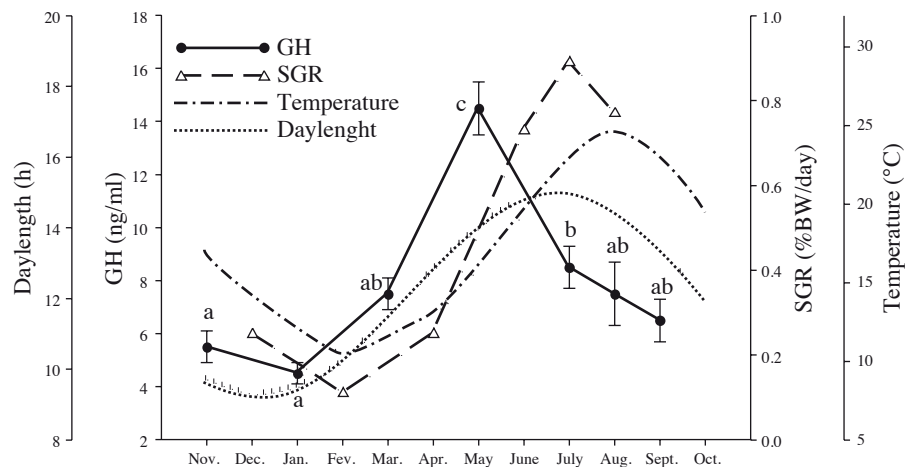


Figure 1. - Quantity of IGF2 mRNA determined by real time PCR, in rainbow trout embryos at stage 22, 24, 25 and at hatching. Differences were determined by the non-parametric Mann-Whitney U-Test. Differences between letters indicate a significant ($p < 0.05$) difference between means within the same stage. Data from Gabillard *et al.* (2003b). [Quantité d'ARNm IGF2 déterminée par PCR en temps réel, chez des embryons de truite arc en ciel aux stades 22, 24, 25 et à l'éclosion. Les différences significatives sont déterminées par le test non-paramétrique de Mann-Whitney. Deux lettres différentes indiquent que les moyennes sont différentes pour un même stade ($p < 0,05$). Les données proviennent de Gabillard *et al.* (2003b).]

Figure 2. - Seasonal variations in daylength, water temperature, plasma GH and specific growth rate (SGR) in sea bream (*Sparus aurata*). Multiple comparisons among means were made with the Duncan Multiple Range test. Values with the same letter are not significantly different ($p < 0.05$). Data from Pérez-Sánchez (1994). [Variations saisonnières de la photopériode, de la température de l'eau, de la GH plasmatique et du taux de croissance spécifique chez la daurade (*Sparus aurata*). Les comparaisons multiples entre les moyennes ont été faites avec le test de Duncan. Les moyennes avec les mêmes lettres ne sont pas significativement différentes ($p < 0,05$). Les données proviennent de Pérez-Sánchez (1994).]



1999; Ayson *et al.*, 2002; Maures *et al.*, 2002; Gabillard *et al.*, 2003b), IGF2 could be a predominant growth factor during development and would partly explain the effects of temperature on the embryonic growth rate.

During post-larval growth

Seasonal variations of GH/IGF system activity

Seasonal fluctuations of post-larval growth (from first feeding to mature fish) are associated with water temperature changes. As in brown trout (*Salmo trutta*), GH injection enhanced growth rate compared to control fish in March but not in July (Swift, 1954), the authors hypothesized that endogenous GH level could be higher in July than in March. Consistent with this hypothesis, Swift and Pickford (1965), using a bioassay, observed higher pituitary GH content in perch (*Perca fluviatilis* L.) during summer. Moreover, a histological study showed that somatotroph cells of the brown bullhead (*Ictalurus nebulosus* Lesueur) tend to be larger (Farbridge *et al.*, 1985) in summer. Finally, using radioimmunological assay, it was confirmed in chinook salmon (*Oncorhynchus tshawytscha*) (Silverstein *et al.*, 1998), coho salmon (*Oncorhynchus kisutch*) (Duan *et al.*, 1995), goldfish (Marchant and Peter, 1986; Marchant *et al.*, 1986) and sea-bream (Pérez-Sánchez *et al.*, 1994b; Mingarro *et al.*, 2002) that plasma GH (Fig. 2) and also IGF1 (or IGF-like) levels increase by the end of spring and during summer. In the light of these results, the seasonal hormonal variation of GH and IGF1 seems to parallel the annual fluctuations of temperature. It is thus tempting to speculate that temperature regulates plasma levels of GH and IGF1. Nevertheless, in these studies, others parameters such as photoperiod, food intake, reproductive stages or the smoltification process, may influence GH/IGF system activity and account partly for the seasonal variations of plasma GH and IGF1 levels.

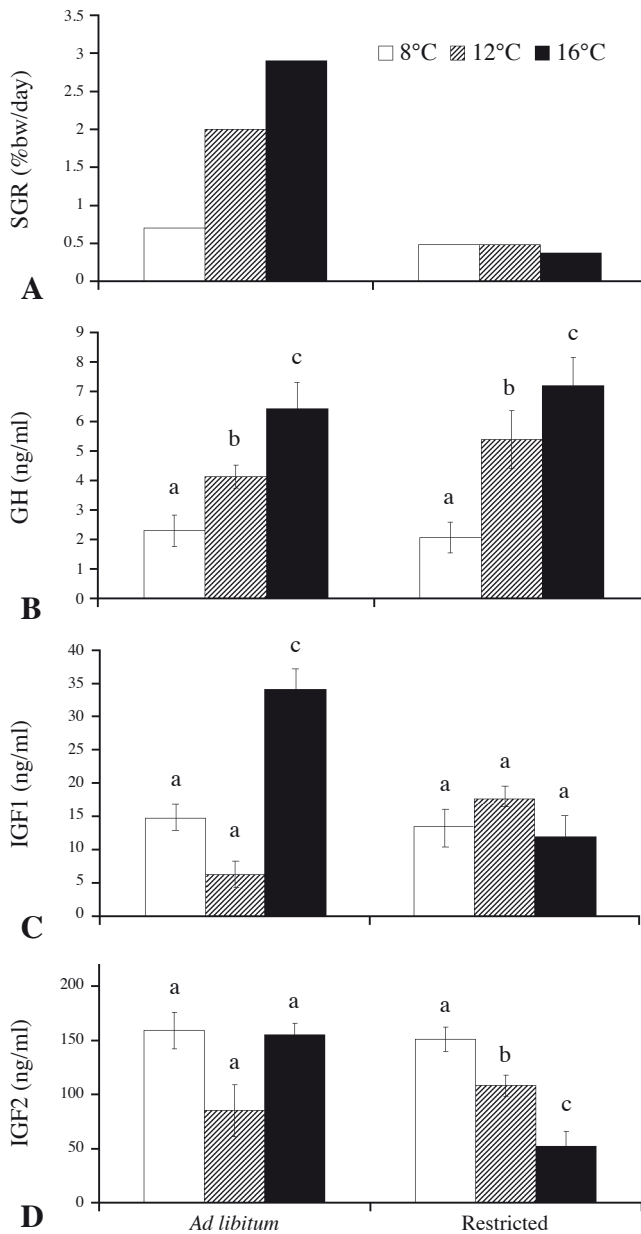
Several authors have attempted to clarify the influence of water temperature on GH/IGF system activity. Under natural photoperiod, a higher temperature increases the levels of

plasma GH in rainbow trout (Barrett and McKeown, 1989), as well as the levels of plasma IGF1 in salmon species (Beckman *et al.*, 1998; McCormick *et al.*, 2000; Larsen *et al.*, 2001; McCormick *et al.*, 2002) and in catfish (Silverstein *et al.*, 2000). Given that photoperiod influences the GH/IGF system activity, it is not possible to distinguish the specific effect of temperature. On the other hand, under constant photoperiod, an increased temperature always raises plasma GH levels in tilapia (Ricordel *et al.*, 1995), turbot (Bœuf *et al.*, 1999), rainbow trout (Yao, 1993) and Atlantic salmon (*Salmo salar*) (Bjornsson *et al.*, 1989). Therefore, seasonal variations of GH/IGF system activity would not result solely from changes in photoperiod, reinforcing the idea that temperature is involved in GH/IGF system regulation. Nevertheless, given that temperature influences food intake (Brett, 1979), it cannot be excluded that variations in GH/IGF system activity result from differences of nutritional status.

Specific effects of temperature on GH/IGF system activity

Recently, to assess the putative involvement of nutritional status in the effect of temperature on GH/IGF system activity, we performed two types of experiments in rainbow trout (Gabillard *et al.*, 2003a; Gabillard *et al.*, 2003d). In the first, fish were reared at 8, 12 or 16°C and were fed *ad libitum* to obtain fish with different growth rates (Fig. 3A) and similar nutritional status (100% of the *ad libitum* ration at each temperature studied). In the second, fish were fed with the same ration to have similar growth (Fig. 3A) despite distinct nutritional status (90%, 70%, 50% of the *ad libitum* ration at 8, 12 16°C respectively). By comparing the results from both experiments, it was possible to highlight the variations of GH/IGF system activity that may be specifically due to temperature.

In both experiments, temperature did not lastingly affect IGF1 and IGF2 mRNA levels in muscle, suggesting that differences in muscular growth, due to temperature, do not involve variations in muscular production of IGF peptides. At



the endocrine level, plasma IGF2 levels were similar in fish fed *ad libitum* whatever the temperature, while in restricted fish, high temperature decreased them (Fig. 3D). Thus, temperature does not seem to directly regulate plasma IGF2 levels, which instead tend to reflect the nutritional status of fish. For IGF1, an inverse situation was observed, since temperature increased plasma IGF1 levels only in *ad libitum* fed fish but not in restricted fish (Fig. 3C). In this case, the endocrine production of IGF1 was clearly associated with the growth rate, as has been observed in several fish species (Pérez-Sánchez *et al.*, 1994a; Matthews *et al.*, 1997; Duan, 1998; Pierce *et al.*, 2001; Beckman *et al.*, 2001). Temperature increased plasma GH levels in fish fed *ad libitum* as well as in restricted

Figure 3. - Specific growth rate (A), plasma GH (B), plasma IGF1 (C) and plasma IGF2 (D) of rainbow trout (50-60 g) reared at three different temperatures (8, 12 and 16°C). Fish were fed *ad libitum* or restricted (1.2%/bw), and maintained under these conditions until they reached the weight of 50-60 g. For the *ad libitum* fish, the time to reach this weight was 6, 7 and 10 weeks at 16, 12 and 8°C respectively. The restricted fish weighted 50-60 g after 12 weeks. Differences were determined by the non-parametric Mann-Whitney U-Test. Different letters indicate differences ($p < 0.05$) between means. Data Gabillard *et al.*, 2003c, 2003d. [Taux de croissance spécifique (A), niveaux de GH plasmatique (B), d'IGF1 plasmatique (C) et d'IGF2 plasmatique (D) chez la truite arc-en-ciel (50-60 g) élevée à trois températures différentes (8, 12, 16°C). Les poissons ont été nourris à volonté ou restreints (1.2%/poids corporel), et maintenus dans ces conditions jusqu'à ce qu'ils atteignent le poids de 50-60 g. Pour les poissons nourris *ad libitum*, le temps nécessaire pour atteindre ce poids a été de 6, 7 et 10 semaines à 16, 12 et 8°C respectivement. Les poissons restreints ont atteint 50-60 g après 12 semaines. Les différences significatives ont été déterminées par le test U de Mann-Whitney. Des lettres différentes indiquent que les moyennes sont significativement différentes. Données d'après Gabillard *et al.*, 2003c, 2003d.]

fish (Fig. 3B). These results demonstrate that the effects of temperature on plasma GH levels are independent of the nutritional status. In trout fed *ad libitum*, rearing temperature increased growth rate proportionally to plasma GH levels. Thus at 8°C, plasma GH levels could be a limiting factor of growth rate. The positive correlation between plasma GH and IGF1 (Pearson's correlation coefficient $R^2 = 0.10$; $p < 0.01$ calculated by linear regression of Pearson) in *ad libitum* fed fish suggests that high temperatures increase endocrine production of GH, which in turn enhances IGF1 expression in the liver and plasma IGF1 levels (Gabillard *et al.*, 2003a). The absence of correlation between plasma GH and IGF1, in restricted fish, suggests that the GH receptor expression is lowered, which remains to be shown.

Overall these data strongly suggest that seasonal variations of water temperature affect growth rate through an increase of plasma GH and IGF1 levels. Nevertheless, the mechanism by which temperature regulates GH secretion is not yet elucidated.

Effect of temperature on plasma GH levels: Explanatory hypotheses

Recently, several works have reported that low temperatures increase plasma insulin levels in various salmonids (Larsen *et al.*, 2001; Capilla *et al.*, 2003; Gabillard *et al.*, 2003d). Interestingly, in our experiments (Gabillard *et al.*, 2003d), a negative correlation was found between insulin and GH plasma levels (Pearson's correlation coefficient $R^2 = 0.22$; $p < 0.001$). It is unlikely that endogenous insulin inhibits GH secretion, since *in vitro*, insulin acts at a pharmacological dose (100-fold higher than the physiological levels) (Blaise *et al.*, 1995b; Rousseau *et al.*, 1998; Duval *et al.*, 2002). Nevertheless, insulin secretagogues and insulin-regulated metabolites, such as glucose, amino acids, fatty acids, could be involved in the effect of temperature on plasma GH

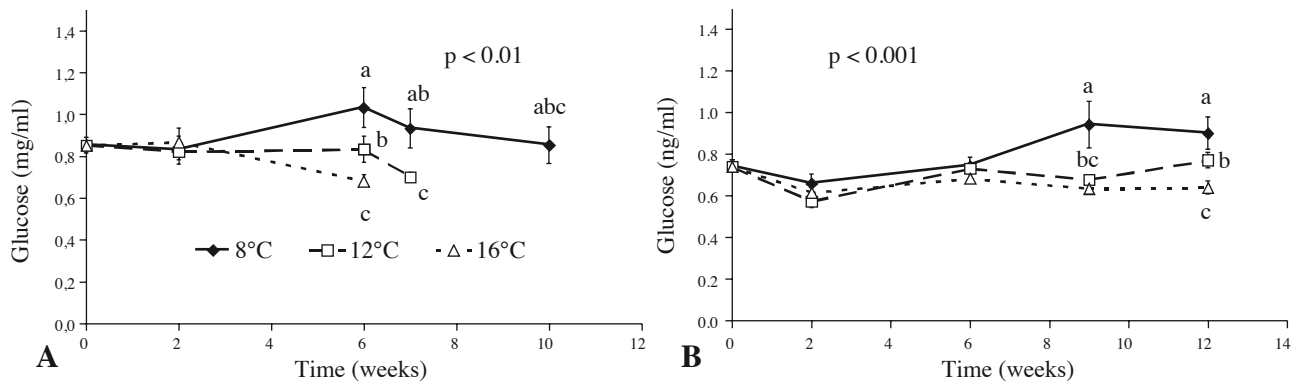


Figure 4. - Plasma glucose levels of rainbow trout reared at 8, 12 and 16°C. Fish were fed *ad libitum* (A) or restricted (1.2%/bw) (B), and maintained under these conditions until they reached the weight of 50-60 g. For the *ad libitum* fish, the time to reach this weight was 6, 7 and 10 weeks at 16, 12 and 8°C respectively. The restricted fish weighed 50-60 g after 12 weeks. Plasma glucose levels were measured with 10 μ l of plasma using the Glucose RTU kit (Biomérieux, Ref. 61 269). Each mean (\pm SEM) corresponds to the measurement of at least 10 fish. A non-parametric ANOVA (Kruskal-Wallis rank test) was used to determine whether temperature have a significant (p value) effect over the time. Non-parametric analysis was used because not all parameters were normally distributed. Where there is a significant temperature effect, different letters indicate difference (p < 0.05; non-parametric Mann-Whitney U-test) between means at week 6 and end of experiment. [Niveaux plasmatiques du glucose chez des truites arc-en-ciel élevées à 8, 12 et 16°C. Les poissons ont été nourris à volonté (A) ou restreints (B) (1.2%/poids corporel), et maintenus dans ces conditions jusqu'à ce qu'ils atteignent le poids de 50-60 g. Pour les poissons nourris ad libitum, le temps nécessaire pour atteindre ce poids a été de 6, 7 et 10 semaines à 16, 12 et 8°C, respectivement. Les poissons restreints ont atteint 50-60 g après 12 semaines. Le niveau de glucose a été mesuré à partir de 10 μ l de plasma en utilisant le kit Glucose RTU (Biomérieux, Réf. 61 269). Chaque moyenne (\pm SEM) correspond à la mesure d'au moins 10 poissons. Une ANOVA non-paramétrique (Kruskal-Wallis) a été utilisée pour déterminer si la température avait un effet significatif (valeur p) au cours de l'expérimentation. Une analyse non-paramétrique a été utilisée car tous les paramètres n'avaient pas une distribution normale. Quand il existait un effet significatif de la température, les moyennes significativement différentes ont été représentées par des lettres différentes (p < 0,05 ; test U de Mann-Whitney).]

levels. For instance, an *in vitro* study performed in tilapia showed an inhibition of GH secretion by glucose (Rodgers *et al.*, 1992). In addition, low temperatures seem to increase plasma glucose levels as revealed by several studies (Connors *et al.*, 1978; Brett, 1979; Capilla *et al.*, 2003). To determine whether glucose might be involved in the effect of temperature on GH secretion, we measured its levels in our previous experiments (Gabillard *et al.*, 2003a; Gabillard *et al.*, 2003d). Our results indicated that low temperatures increased plasma glucose levels in fish fed *ad libitum* (Fig. 4A) as well as in fish fed with an equivalent ration (Fig. 4B). These higher glucose levels could be due to a delay in gastric emptying and intestinal absorption of nutrients (Brett, 1979; Larsen *et al.*, 2001; Capilla *et al.*, 2003) and could partly explain the higher levels of insulin. Moreover, we found a negative correlation between glucose and GH levels (Pearson's correlation coefficient $R^2 = 0.10$; $p < 0.001$), which tends to confirm the hypothesis of a partial inhibition of GH secretion by glucose. Nevertheless, the weakness of this correlation means that other regulating factors might be implicated.

The central nervous system, through neuropeptides (GHRH, SRIF, NPY, dopamine, GnRH, TRH, etc.) modifies GH mRNA levels, GH synthesis and secretion (Peng and Peter, 1997; Holloway and Leatherland, 1998; Peter and Chang, 1999). In rainbow trout, endogenous GH secretion is predominantly under a negative control (Yada *et al.*, 1991; Yada and Hirano, 1992; Blaise *et al.*, 1995a), in which somatostatin (SRIF) acts as the major inhibitor (Pérez-Sánchez *et al.*, 1992; Blaise *et al.*, 1995a). In goldfish, hypothalamic somatostatin mRNA levels are lower in summer when plasma GH levels are highest (Marchant *et al.*, 1989), and the individual levels of plasma GH were found to be negatively correlated with the levels of plasma somatostatin (Holloway *et al.*, 1999). Somatostatin is expressed in other tissues than hypothalamus such as the endocrine pancreas (Lin *et al.*, 2000; Lin and Peter, 2001), where its expression is upregulated by glucose (Ehrman *et al.*, 2000; Melroe *et al.*, 2000). Thus, in addition to a direct effect on GH secretion, high glucose levels at low temperature may lead to an elevation of somatostatin plasma levels, which in turn would inhibit GH secretion. Thus, it is plausible that somatostatin mediates part of the temperature effect on plasma GH levels.

As an alternative to these 'metabolic' hypotheses, it is conceivable that thermoreceptors are present in fish, which would transmit the signal to the somatotrophs. In homeotherms, variations of body temperature are detected through sensorial receptors belonging to the TRP family (Transient Receptor Potential) (Montell *et al.*, 2002; Story *et al.*, 2003). These thermoreceptors are non-selective cation channels and are expressed in specialized neurones of the peripheral nervous system. In fish, electrophysiological studies suggest the presence of such receptors (Murray, 1971). The characterisation of such receptors in fish will be of great interest to better understand the mechanisms underlying physiological adaptation to temperature and to elucidate the link with endocrine control of growth.

CONCLUSION

In conclusion, the data available in the literature and our results show that the effect of temperature on GH/IGF system is different according to the period of fish life. Before hatching, IGF2 but not GH and IGF1, would partly mediate the stimulatory effect of temperature on the embryonic growth rate. Later, during post-larval period, growth-promoting effect of temperature is mediated neither by autocrine/paracrine expression of IGF1 and IGF2 nor by plasma IGF2 levels, which rather reflect the nutritional status of the fish. By contrast, it appears clearly that environmental temperature promotes growth through a direct effect on GH secretion that leads to an elevation of plasma IGF1. If temperature effect on GH is constantly observed, the associated elevation of plasma IGF1 takes place only when fish are under optimal conditions of nutrition. The mechanism by which temperature stimulate GH secretion remains to be clearly elucidated.

Acknowledgements. - The authors are grateful to B. Britton for English improvement of this article.

REFERENCES

- AYASO E., NOLAN C.M. & L. BYRNES, 2002. - Zebrafish insulin-like growth factor-I receptor: Molecular cloning and developmental expression. *Mol. Cell Endocrinol.*, 191: 137-148.
- AYSON F.G., DE JESUS E.G., MORIYAMA S., HYODO S., FUNKENSTEIN B., GERTLER A. & H. KAWAUCHI, 2002. - Differential expression of insulin-like growth factor I and II mRNAs during embryogenesis and early larval development in rabbitfish, *Signanus guttatus*. *Gen. Comp. Endocrinol.*, 126: 165-174.
- BAÑOS N., PLANAS J.V., GUTIERREZ J. & I. NAVARRO, 1999. - Regulation of plasma insulin-like growth factor-I levels in brown trout (*Salmo trutta*). *Comp. Biochem. Physiol. C, Pharmacol. Toxicol. Endocrinol.*, 124: 33-40.
- BARRETT B.A. & B.A. MCKEOWN, 1989. - Plasma growth hormone levels in *Salmo gairdneri*: Studies on temperature and the exercise intensity/duration relationship. *Comp. Biochem. Physiol.*, 94A: 791-794.
- BECKMAN B.R. & W.W. DICKHOFF, 1998. - Plasticity of smolting in spring chinook salmon: Relation to growth and insulin-like growth factor-I. *J. Fish. Biol.*, 53: 808-826.
- BECKMAN B.R., LARSEN D.A., MORIYAMA S., LEE-PAWLAK B. & W.W. DICKHOFF, 1998. - Insulin-like growth factor-I and environmental modulation of growth during smoltification of spring chinook salmon (*Oncorhynchus tshawytscha*). *Gen. Comp. Endocrinol.*, 109: 325-335.
- BECKMAN B.R., SHEARER K.D., COOPER K.A. & W.W. DICKHOFF, 2001. - Relationship of insulin-like growth factor-I and insulin to size and adiposity of under-yearling chinook salmon. *Comp. Biochem. Physiol. A, Mol. Int. Physiol.*, 129: 585-593.
- BHANDARI R.K., TANIYAMA S., KITAHASHI T., ANDO H., YAMAUCHI K., ZOHAR Y., UEDA H. & A. URANO, 2003. - Seasonal changes of responses to gonadotropin-releasing hormone analog in expression of growth hormone/prolactin/somatolactin genes in the pituitary of masu salmon. *Gen. Comp. Endocrinol.*, 130: 55-63.
- BJORNSSON B.T., THORARENSEN H., HIRANO T., OGASAWARA T. & J.B. KRISTINSSON, 1989. - Photoperiod and temperature affect plasma growth hormone levels, growth, condition factor and hypothyroidism ability of juvenile Atlantic Salmon (*Salmo salar*) during parr-smolt transformation. *Aquaculture*, 82: 77-91.
- BLAISE O., LE BAIL P.-Y. & C. WEIL, 1995a. - Lack of gonadotropin releasing-hormone action on *in vivo* and *in vitro* growth hormone release, in rainbow trout (*Oncorhynchus mykiss*). *Comp. Biochem. Physiol.*, 110C: 133-141.
- BLAISE O., WEIL C. & P.-Y. LE BAIL, 1995b. - Role of IGF-I in the control of GH secretion in rainbow trout (*Oncorhynchus mykiss*). *Growth Regul.*, 5: 142-150.
- BŒUF G., 1987a. - Bases physiologiques de la salmoniculture : le phénomène de la smoltification. *Pisc. Fr.*, 88: 5-18.
- BŒUF G., 1987b. - Bases physiologiques de la salmoniculture : osmorégulation et adaptation à l'eau de mer. *Pisc. Fr.*, 87: 28-40.
- BŒUF G. & P.-Y. LE BAIL, 1999. - Does light have an influence on fish growth? *Aquaculture*, 177: 129-152.
- BŒUF G., MARTIN P., SÈVÈRE A., PERSON-LE RUYET J., PICHAVANT K., BUREL C., LE ROUX A., CAUTY C., MARCHELIDON J., LE BAIL P.-Y. & J. SMAL, 1999. - Somatotropin, thyroid hormones and growth in turbot (*Psetta maxima*): Effects of temperature, hypoxia and ammonia. *In: Comparative Endocrinology and Neurology* (Roubos E.W., WendelaarBonga S.E., Vaudry H. & A. De Loof, eds), pp. 163-165. Maastricht: Shaker Publishers.
- BRETT J.R., 1979. - Environmental factors and growth. *In: Bioenergetics and Growth* (Hoar W.S., Randall D.J. & J.R. Brett, eds), pp. 599-675. New York: Academic Press.
- BRETT J.R. & T.D. GROVES, 1979. - Physiological energetics. *In: Bioenergetics and growth* (Hoar W.S., Randall D.J. & J.R. Brett, eds), pp. 280-344. New York: Academic Press.
- CALDUCH-GINER J.A., DUVAL H., CHESNEL F., BŒUF G., PÉREZ-SÁNCHEZ J. & D. BOUJARD, 2001. - Fish growth hormone receptor: Molecular characterization of two membrane anchored forms. *Endocrinology*, 142: 3269-3273.
- CALDUCH-GINER J.A., MINGARRO M., DE CELIS S.V.R., BOUJARD D. & J. PEREZ-SANCHEZ, 2003. - Molecular cloning and characterization of gilthead sea bream (*Sparus aurata*) growth hormone receptor (GHR). Assessment of alternative splicing. *Comp. Biochem. Physiol. B, Biochem. Mol. Biol.*, 136: 1-13.
- CANFIELD W.M. & S. KORNFELD, 1989. - The chicken liver cation-independent mannose 6-phosphate receptor lacks the high affinity binding site for insulin-like growth factor II. *J. Biol. Chem.*, 264: 7100-7103.
- CAO Q.P., DUGUAY S.J., PLISSETSKAYA E., STEINER D.F. & S.J. CHAN, 1989. - Nucleotide sequence and growth hormone-regulated expression of salmon insulin-like growth factor I mRNA. *Mol. Endocrinol.*, 3: 2005-2010.

- CAPILLA E., MÉDALE F., NAVARRO I., PANSEERAT S., VACHOT C., KAUSHIK S.J. & J. GUTIERREZ, 2003. - Muscle insulin binding and plasma levels in relation to liver glucokinase activity, glucose metabolism and dietary carbohydrates in rainbow trout. *Regul. Pept.*, 110: 123-132.
- CHAUVIGNÉ F., GABILLARD J.-C., WEIL C. & P.Y. RESCAN, 2003. - Effect of refeeding on IGF1, IGF2, IGF receptors, FGF2, FGF6 and myostatin mRNA expression in rainbow trout (*Oncorhynchus mykiss*) myotomal muscle. *Gen. Comp. Endocrinol.*, 132: 209-215.
- CHEN J.Y., CHEN J.C., CHANG C.Y., SHEN S.C., CHEN M.S. & J.L. WU, 2000. - Expression of recombinant tilapia insulin-like growth factor-I and stimulation of juvenile tilapia growth by injection of recombinant IGFs polypeptides. *Aquaculture*, 181: 347-360.
- CHEN T.T., MARSH A., SHAMBLOTT M., CHAN K.M., TANG Y.L., CHENG C.M. & B.Y. YANG, 1994. - Structure and evolution of fish growth hormone and insulin-like growth factor genes. In: *Molecular Endocrinology of Fish* (Farrell A.P. & D.J. Randall, eds), pp. 180-209. San Diego, New York, Boston, London, Sydney, Tokyo, Toronto: Academic Press.
- CHENG R.S., CHANG K.M. & J.L. WU, 2002. - Different temporal expressions of tilapia (*Oreochromis mossambicus*) insulin-like growth factor-I and IGF binding protein-3 after growth hormone induction. *Mar. Biotechnol.*, 4: 218-225.
- CONNORS T.J., SCHNEIDER M.J., GENOWAY R.G. & S.A. BARRACLOUGH, 1978. - Effect of acclimation temperature on plasma levels of glucose and lactate in rainbow trout, *Salmo gairdneri*. *J. Exp. Zool.*, 206: 443-449.
- DICKHOFF W.W., BECKMAN B.R., LARSEN D.A., DUAN C. & S. MORIYAMA, 1997. - The role of growth in endocrine regulation of salmon smoltification. *Fish. Physiol. Biochem.*, 17: 231-236.
- DONALDSON E.M., FAGERLUND U.H.M., HIGGS D.A. & J.R. MCBRIDE, 1979. - Hormonal enhancement of growth. In: *Bioenergetic and Growth* (Hoar W.S., Randall D.J. & J.R. Brett, eds), pp. 455-597. New York: Academic press.
- DUAN C., 1998. - Nutritional and developmental regulation of insulin-like growth factors in fish. *J. Nutr.*, 128: 306S-314S.
- DUAN C. & E.M. PLISETSKAYA, 1993. - Nutritional regulation of insulin-like growth factor-I mRNA expression in salmon tissues. *J. Endocrinol.*, 139: 243-252.
- DUAN C., PLISETSKAYA E.M. & W.W. DICKHOFF, 1995. - Expression of insulin-like growth factor I in normally and abnormally developing coho salmon (*Oncorhynchus kisutch*). *Endocrinology*, 136: 446-452.
- DUAN C.M., 1997. - The insulin-like growth factor system and its biological actions in fish. *Am. Zool.*, 37: 491-503.
- DUAN C.M., DING J., LI Q., TSAI W. & K. POZIOS, 1999. - Insulin-like growth factor binding protein 2 is a growth inhibitory protein conserved in zebrafish. *Proc. Natl. Acad. Sci. U.S.A.*, 96: 15274-15279.
- DUGUAY S.J., LAI-ZHANG J., STEINER D.F., FUNKENSTEIN B. & S.J. CHAN, 1996. - Developmental and tissue-regulated expression of IGF-I and IGF- II mRNAs in *Sparus aurata*. *J. Mol. Endocrinol.*, 16: 123-132.
- DUVAL H., 2000. - Caractérisation des différentes composantes du système IGF chez un poisson évolué, le turbot *Psetta maxima*. Thèse de Doctorat, 137 p. Univ. Rennes.
- DUVAL H., ROUSSEAU K., ELIES G., LE BAIL P.-Y., DUFOUR S., BÉUF G. & D. BOUJARD, 2002. - Cloning, characterization, and comparative activity of turbot IGF-I and IGF-II. *Gen. Comp. Endocrinol.*, 126: 269-278.
- EHRMAN M.M., MELROE G.T., KITTILSON J.D. & M.A. SHERIDAN, 2000. - The expression of preprosomatostatin II mRNAs in the Brockmann bodies of rainbow trout, *Oncorhynchus mykiss*, is regulated by glucose. *Gen. Comp. Endocrinol.*, 118: 150-160.
- EINARSDOTTIR I.E., SAKATA S. & B.T. BJORNSSON, 2002. - Atlantic halibut growth hormone: Structure and plasma levels of sexually mature males and females during photoperiod-regulated annual cycles. *Gen. Comp. Endocrinol.*, 127: 94-104.
- FARBRIDGE K.J., BURKE M.G. & J.F. LEATHERLAND, 1985. - Seasonal changes in the structure of the adenohypophysis of the brown bullhead (*Ictalurus nebulosus* Lesueur). *Cytobios*, 44: 49-66.
- FARMER S.W., PAPKOFF H., HAYASHIDA Y., BEWLEY T.A., BERN H.A. & C.H. LI, 1976. - Purification and properties of teleost growth hormone. *Gen. Comp. Endocrinol.*, 30: 91-100.
- FUNKENSTEIN B., SHEMER R., AMULY R., COHEN I. & S.J. CHAN, 1996. - Nucleotide sequence of the promoter region of *Sparus aurata* insulin-like growth factor I gene and expression of IGF-I in eggs and embryos. *Mol. Mar. Biol. Biotechnol.*, 5: 43-51.
- FUNKENSTEIN B., TSAI W., MAURES T. & C. DUAN, 2002. - Ontogeny, tissue distribution, and hormonal regulation of insulin-like growth factor binding protein-2 (IGFBP-2) in a marine fish *Sparus aurata*. *Gen. Comp. Endocrinol.*, 128: 112-122.
- GABILLARD J.C., WEIL C., RESCAN P.-Y., NAVARRO I., GUTIERREZ J. & P.-Y. LE BAIL, 2003a. - Effects of environmental temperature on IGF1, IGF2 and IGF type I receptor expression in rainbow trout (*Oncorhynchus mykiss*). *Gen. Comp. Endocrinol.*, 133: 233-242.
- GABILLARD J.-C., DUVAL H., CAUTY C., RESCAN P.Y., WEIL C. & P.-Y. LE BAIL, 2003b. - Differential expression of the two GH genes during embryonic development of rainbow trout (*Oncorhynchus mykiss*) in relation with the IGFs system. *Mol. Reprod. Dev.*, 64: 32-40.
- GABILLARD J.-C., RESCAN P.Y., WEIL C., FAUCONNEAU B. & P.-Y. LE BAIL, 2003c. - Effects of temperature on GH/IGF system gene expression during embryonic development of rainbow trout (*Oncorhynchus mykiss*). *J. Exp. Zool.*, 298A: 134-142.
- GABILLARD J.-C., WEIL C., RESCAN P.Y., NAVARRO I., GUTIERREZ J. & P.-Y. LE BAIL, 2003d. - Environmental temperature increases plasma GH levels independently of the nutritional status in rainbow trout (*Oncorhynchus mykiss*). *Gen. Comp. Endocrinol.*, 133: 17-26.
- GARSIDE E.T., 1966. - Developmental rate and vertebral number in salmonids. *J. Fish. Res. Bd Canada*, 23: 1537-1551.
- GENTIL V., MARTIN P., SMAL J. & P.-Y. LE BAIL, 1996. - Production of recombinant insulin-like growth factor-II in the development of a radioimmunoassay in rainbow trout (*Oncorhynchus mykiss*). *Gen. Comp. Endocrinol.*, 104: 156-167.
- GOMEZ J.M., WEIL C., OLLITRAULT M., LE BAIL P.-Y., BRETON B. & F. LE GAC, 1999. - Growth hormone (GH) and gonadotropin subunit gene expression and pituitary and plasma changes during spermatogenesis and oogenesis in rainbow trout (*Oncorhynchus mykiss*). *Gen. Comp. Endocrinol.*, 113: 413-428.
- GRAY E.S., KELLEY K.M., LAW S., TSAI R., YOUNG G. & H.A. BERN, 1992. - Regulation of hepatic growth hormone receptors in coho salmon (*Oncorhynchus kisutch*). *Gen. Comp. Endocrinol.*, 88: 243-252.

- GREENE M.W. & T.T. CHEN, 1997. - Temporal expression pattern of insulin-like growth factor mRNA during embryonic development in a teleost, rainbow trout (*Onchorynchus mykiss*). *Mol. Mar. Biol. Biotechnol.*, 6: 144-151.
- GREENE M.W. & T.T. CHEN, 1999. - Quantitation of IGF-I, IGF-II, and multiple insulin receptor family member messenger RNAs during embryonic development in rainbow trout. *Mol. Reprod. Dev.*, 54: 348-361.
- GUILLEN I., LLEONART R., AGRAMONTE A., MORALES R., MORALES A., HERNÁNDEZ C.A., VÁZQUEZ M.M., DIAZ M., HERRERA M.T., ALVAREZ-LAJONCHERE L., HERNÁNDEZ O. & J. DE LA FUENTE, 1998. - Physiological changes in the juvenile euryhaline teleost, the tilapia *Oreochromis hornorum*, injected with *E. coli*-derived homologous growth hormone. *J. Mar. Biotech.*, 6: 142-151.
- HIGGS D.A., FAGERLUND U.H.M., MCBRIDE J.R. & J.G. EALES, 1979. - Influence of orally administered L-thyroxine on growth, food consumption, and food conversion of underyearling coho salmon (*Oncorhynchus kisutch*). *Can. J. Zool.*, 57: 1974-1979.
- HIRANO T., 1991. - Hepatic receptors for homologous growth hormone in the eel. *Gen. Comp. Endocrinol.*, 81: 383-390.
- HOLLOWAY A.C. & J.F. LEATHERLAND, 1998. - Neuroendocrine regulation of growth hormone secretion in teleost fishes with emphasis on the involvement of gonadal sex steroids. *Rev. Fish. Biol. Fish.*, 8: 409-429.
- HOLLOWAY A.C., SHERIDAN M.A., VANDERKRAAK G. & J.F. LEATHERLAND, 1999. - Correlations of plasma growth hormone with somatostatin, gonadal steroid hormones and thyroid hormones in rainbow trout during sexual recrudescence. *Comp. Biochem. Physiol. B, Biochem Mol. Biol.*, 123: 251-260.
- JONES I., KILLE P. & G. SWEENEY, 2001. - Cadmium delays growth hormone expression during rainbow trout development. *J. Fish Biol.*, 59: 1015-1022.
- KAJIMURA S., HIRANO T., VISITACION N., MORIYAMA S., AIDA K. & E.G. GRAU, 2003. - Dual mode of cortisol action on GH/IGF-I/IGF binding proteins in the tilapia, *Oreochromis mossambicus*. *J. Endocrinol.*, 178: 91-99.
- KELLEY K.M., DESAI P., ROTH J.T., HAIGWOOD J.T., AROPE S.A., FLORES R.M., SCHMIDT K.E., PEREZ M., NICHOLSON G.S. & W.W. SONG, 2000. - Evolution of endocrine growth regulation: The insulin like growth factors (IGFs), their regulatory binding proteins (IGFBPs), and IGF receptors in fishes and others ectothermic vertebrates. In: *Aquaculture* (Fingerman M. & R. Nagabhushanam, eds), pp. 189-228. New Delhi: Oxford and IBH Publishing.
- KELLEY K.M., SCHMIDT K.E., BERG L., SAK K., GALIMA M.M., GILLESPIE C., BALOGH L., HAWAYEK A., REYES J.A. & M. JAMISON, 2002. - Comparative endocrinology of the insulin-like growth factor-binding protein 16. *J. Endocrinol.*, 175: 3-18.
- KIESS W., YANG Y., KESSLER U. & A. HOEFLICH, 1994. - Insulin-like-growth factor II (IGF-II) and the IGF-II/mannose-6-phosphate receptor: The myth continues. *Horm. Res.*, 41: 66-73.
- KWAIN W., 1975. - Embryonic development, early growth and meristic variation in rainbow trout (*Salmo gairdneri*) exposed to combinations of light intensity and temperature. *J. Fish. Res. Bd Canada*, 32: 397-402.
- LARSEN D.A., BECKMAN B.R. & W.W. DICKHOFF, 2001. - The effect of low temperature and fasting during the winter on metabolic stores and endocrine physiology (Insulin, insulin-like growth factor-I and thyroxine) of coho salmon, *Oncorhynchus kisutch*. *Gen. Comp. Endocrinol.*, 123: 308-323.
- LE BAIL P.-Y., GENTIL V., NOEL O., GOMEZ J.M., CARRE F., LE GOFF P. & C. WEIL, 1998. - Structure, function, and regulation of insulin-like growth factors in fish. *Ann. N.Y. Acad. Sci.*, 839: 157-161.
- LE BAIL P.-Y., PÉREZ-SÁNCHEZ J., YAO H. & G. MAISSE, 1993. - Effect of GH treatment on salmonid growth: Study of the variability of response. In: *Aquaculture: Fundamental and applied Research* (Lahlou B. & P. Vitiello, eds), pp. 173-197. Washington: American Geophysical Union.
- LE BAIL P.-Y., SUMPTER J.P., CARRAGHER J.F., MOUROT B., NIU P.D. & C. WEIL, 1991. - Development and validation of a highly sensitive radioimmunoassay for chinook salmon (*Oncorhynchus tshawytscha*) growth hormone. *Gen. Comp. Endocrinol.*, 83: 75-85.
- LE GAC F., BLAISE O., FOSTIER A., LE BAIL P.-Y., LOIR M., MOUROT B. & C. WEIL, 1993. - Growth hormone (GH) and reproduction: A review. *Fish. Physiol. Biochem.*, 11: 219-232.
- LEE L.T.O., NONG G., CHAN Y.H., TSE D.L.Y. & C.H.K. CHENG, 2001. - Molecular cloning of a teleost growth hormone receptor and its functional interaction with human growth hormone. *Gene*, 270: 121-129.
- LEROITH D., BONDY C., YAKAR S., LIU J.L. & A. BUTLER, 2001. - The somatomedin hypothesis: 2001. *Endocr. Rev.*, 22: 53-74.
- LIN X. & R.E. PETER, 2001. - Somatostatin and their receptors in fish. *Comp. Biochem. Physiol. B, Biochem. Mol. Biol.*, 129: 543-550.
- LIN X.W., OTTO C.J., CARDENAS R. & R.E. PETER, 2000. - Somatostatin family of peptides and its receptors in fish. *Can. J. Physiol. Pharmacol.*, 78: 1053-1066.
- MAL A.O., SWANSON P. & W.W. DICKHOFF, 1989. - Immunocytochemistry of the developing salmon pituitary gland. *Am. Zool.*, 29: 94A p.
- MARCHANT T.A. & R.E. PETER, 1986. - Seasonal variations in body growth rates and circulating levels of growth hormone in the goldfish, *Carassius auratus*. *J. Exp. Zool.*, 237: 231-239.
- MARCHANT T.A., COOK A.F. & R.E. PETER, 1986. - The relation between circulating growth hormone levels and somatic growth in a teleost species, *Carassius auratus* L. *Aquaculture*, 43-54.
- MARCHANT T.A., DULKA J.G. & R.E. PETER, 1989. - Relationship between serum growth hormone levels and the brain and pituitary content of immunoreactive somatostatin in the goldfish, *Carassius auratus* L. *Gen. Comp. Endocrinol.*, 73: 458-468.
- MARCHELIDON J., SCHMITZ M., HOUEBINE L.M., VIDAL B., LE BELLE N. & S. DUFOUR, 1996. - Development of a radioimmunoassay for European eel growth hormone and application to the study of silvering and experimental fasting. *Gen. Comp. Endocrinol.*, 102: 360-369.
- MARTI-PALANCA H. & J. PÉREZ-SÁNCHEZ, 1994. - Developmental regulation of growth hormone binding in the gilthead sea bream, *Sparus aurata*. *Growth Regul.*, 4: 14-19.
- MATTHEWS S.J., KINHULT A.K., HOEBEN P., SARA V.R. & T.A. ANDERSON, 1997. - Nutritional regulation of insulin-like growth factor-I mRNA expression in barramundi, *Lates calcarifer*. *J. Mol. Endocrinol.*, 18: 273-276.
- MAURES T., CHAN S.J., XU B., SUN H., DING J. & C.M. DUAN, 2002. - Structural, biochemical, and expression analysis of two distinct insulin-like growth factor I receptors and their ligands in zebrafish. *Endocrinology*, 143: 1858-1871.
- MAURES T.J. & C. DUAN, 2002. - Structure, developmental expression, and physiological regulation of zebrafish IGF binding protein-1. *Endocrinology*, 143: 2722-2731.

- MCCORMICK S.D., KELLEY K.M., YOUNG G., NISHIOKA R.S. & H.A. BERN, 1992. - Stimulation of coho salmon growth by insulin-like growth factor I. *Gen. Comp. Endocrinol.*, 86: 398-406.
- MCCORMICK S.D., MORIYAMA S. & B.T. BJORNSSON, 2000. - Low temperature limits photoperiod control of smolting in atlantic salmon through endocrine mechanisms. *Am. J. Physiol.*, 278: R1352-R1361 p.
- MCCORMICK S.D., SHRIMPSON J.M., MORIYAMA S. & B.T. BJORNSSON, 2002. - Effects of an advanced temperature cycle on smolt development and endocrinology indicate that temperature is not a zeitgeber for smolting in Atlantic salmon. *J. Exp. Biol.*, 205: 3553-3560.
- MCLEAN E. & E.M. DONALDSON, 1993. - The role of growth hormone in the growth of poikilotherms. *In: The Endocrinology of Growth, Development, and Metabolism in Vertebrates* (Schreibman M.P., Scanes C.G. & P.K.T. Pang, eds), pp. 43-71. San Diego: Academic Press.
- MELROE G.T., EHRMAN M.M., KITTILSON J.D. & M.A. SHERIDAN, 2000. - Glucose regulates pancreatic preprosomatostatin I expression. *FEBS Lett.*, 465: 115-118.
- MENDEZ E., PLANAS J.V., CASTILLO J., NAVARRO I. & J. GUTIERREZ, 2001. - Identification of a type II insulin-like growth factor receptor in fish embryos. *Endocrinology*, 142: 1090-1097.
- MINGARRO M., VEGA-RUBIN d.C., ASTOLA A., PENDON C., VALDIVIA M.M. & J. PÉREZ-SÁNCHEZ, 2002. - Endocrine mediators of seasonal growth in gilthead sea bream (*Sparus aurata*): The growth hormone and somatolactin paradigm. *Gen. Comp. Endocrinol.*, 128: 102-111.
- MOMMSEN T.P. & T.W. MOON, 2001. - Hormonal regulation of muscle growth. *In: Muscle Development and Growth* (Sänger A.M. & W. Stoiber, eds), pp. 251-308. San Diego: Academic Press.
- MONTELL C., BIRNBAUMER L. & V. FLOCKERZI, 2002. - The TRP channels, a remarkably functional family. *Cell*, 108: 595-598.
- MORIYAMA S., 1995. - Increased plasma insulin-like growth factor-I (IGF-I) following oral and intraperitoneal administration of growth hormone to rainbow trout, *Oncorhynchus mykiss*. *Growth Regul.*, 5: 164-167.
- MORIYAMA S., SWANSON P., NISHII M., TAKAHASHI A., KAWAUCHI H., DICKHOFF W.W. & E.M. PLISETSKAYA, 1994. - Development of a homologous radioimmunoassay for coho salmon insulin-like growth factor-I. *Gen. Comp. Endocrinol.*, 96: 149-161.
- MURRAY R.W., 1971. - Temperature receptors. *In: Sensory System and Electric Organs* (Hoar W.S. & D.J. Randall, eds), pp. 121-133. New York: Academic Press.
- NAITO N., JESUS E.G.D., NAKAI Y. & T. HIRANO, 1993. - Ontogeny of pituitary cell-types and the hypothalamo-hypophysial relationship during early development in chum salmon, *Oncorhynchus keta*. *Cell Tissue Res.*, 272: 429-437.
- NATHANAILIDES C., LOPEZ-ALBORS O. & N.C. STICKLAND, 1995. - Influence of pre-hatch temperature on the development of muscle cellularity in post-hatch Atlantic salmon (*Salmo salar*). *Can. J. Fish. Aquat. Sci.*, 52: 675-680.
- NAVARRO I., LEIBUSH B., MOON T.W., PLISETSKAYA E.M., BAÑOS N., MENDEZ E., PLANAS J.V. & J. GUTIERREZ, 1999. - Insulin, insulin-like growth factor-I (IGF-I) and glucagon: the evolution of their receptors. *Comp. Biochem. Physiol. B, Biochem. Mol. Biol.*, 122: 137-153.
- NG T.B., LEUNG T.C., CHENG C.H.K. & N.Y.S. WOO, 1992. - Growth hormone binding sites in Tilapia (*Oreochromis mossambicus*) liver. *Gen. Comp. Endocrinol.*, 86: 111-118.
- PENG C. & R.E. PETER, 1997. - Neuroendocrine regulation of growth hormone secretion and growth in fish. *Zool. Stud.*, 36: 79-89.
- PÉREZ-SÁNCHEZ J., MARTI-PALANCA H. & S.J. KAUSHIK, 1995. - Ration size and protein intake affect circulating growth hormone concentration, hepatic growth hormone binding and plasma insulin-like growth factor I in a marine teleost, the gilthead sea bream (*Sparus aurata*). *J. Nutr.*, 125: 546-552.
- PÉREZ-SÁNCHEZ J., MARTI-PALANCA H. & P.-Y. LE BAIL, 1994a. - Homologous growth hormone (GH) binding in gilthead sea bream (*Sparus aurata*). Effect of fasting and refeeding on hepatic GH-binding and plasma somatomedin-like immunoreactivity. *J. Fish Biol.*, 44: 287-301.
- PÉREZ-SÁNCHEZ J., MARTI-PALANCA H. & P.-Y. LE BAIL, 1994b. - Seasonal changes in circulating growth hormone (GH), hepatic GH-binding protein and plasma insulin-like growth factor-I immunoreactivity in a marine fish, gilthead sea bream, *Sparus aurata*. *Fish Physiol. Biochem.*, 13: 199-208.
- PÉREZ-SÁNCHEZ J., WEIL C. & P.-Y. LE BAIL, 1992. - Effects of human insulin-like growth factor-I on release of growth hormone by rainbow trout (*Oncorhynchus mykiss*) pituitary cells. *J. Exp. Zool.*, 262: 287-290.
- PETER R.E. & J.P. CHANG, 1999. - Brain regulation of growth hormone secretion and food intake in fish. *In: Neural Regulation in the Vertebrate Endocrine System* (Prasada R. & R.E. Peter, eds), pp. 55-67. New York: Kluwer Academic/Plenum Publishers.
- PETERSON R.H., SPINNEY H.C.E. & A. SREEDHARAN, 1977. - Development of Atlantic salmon (*Salmo salar*) eggs and alevins under varied temperature regimes. *J. Fish Res. Bd Can.*, 34: 31-43.
- PIERCE A.L., BECKMAN B.R., SCHEARER K.D., LARSEN D.A. & W.W. DICKHOFF, 2001. - Effects of ration on somatotrophic hormones and growth in coho salmon. *Comp. Biochem. Physiol. B, Biochem. Mol. Biol.*, 128: 255-264.
- PLANAS J.V., MENDEZ E., BAÑOS N., CAPILLA E., CASTILLO J., NAVARRO I. & J. GUTIERREZ, 2000. - Fish insulin, IGF-I and IGF-II receptors: A phylogenetic approach. *Am. Zool.*, 40: 223-233.
- PLISETSKAYA E.M., DUGUAY S.J. & C. DUAN, 1994. - Insulin and insulin-like growth factor I in salmonids: Comparison of structure, function, and expression. *In: Perspectives in comparative Endocrinology* (Davey K.G., Peter R.E. & K. Tobe, eds), pp. 226-233. Ottawa: National Research Council of Canada.
- RICORDEL M.J., SMAL J. & P.-Y. LE BAIL, 1995. - Application of a recombinant cichlid growth hormone radioimmunoassay to measure native GH in tilapia (*Oreochromis niloticus*) bred at different temperatures. *Aquat. Living Res.*, 8: 153-160.
- RODGERS B.D., HELMS L.M. & E.G. GRAU, 1992. - Effects of fasting, medium glucose, and amino acid concentrations on prolactin and growth hormone release, *in vitro*, from the pituitary of the tilapia *Oreochromis mossambicus*. *Gen. Comp. Endocrinol.*, 86: 344-351.
- ROUSSEAU K., HUANG Y.S., LEBELLE N., VIDAL B., MARCHELIDON J., EPELBAUM J. & S. DUFOUR, 1998. - Long-term inhibitory effects of somatostatin and insulin-like growth factor 1 on growth hormone release by serum-free primary culture of pituitary cells from european eel (*Anguilla anguilla*). *Neuroendocrinology*, 67: 301-309.
- SAGA T., OOTA Y., NOZAKI M. & P. SWANSON, 1993. - Salmonid pituitary gonadotrophs III. Chronological appearance of GTH I and other adeno-hypophysial hormones in the pituitary of the developing rainbow trout (*Oncorhynchus mykiss irideus*). *Gen. Comp. Endocrinol.*, 92: 233-241.

- SHAMBLOTT M.J., CHENG C.M., BOLT D. & T.T. CHEN, 1995. - Appearance of insulin-like growth factor mRNA in the liver and pyloric caeca of a teleost in response to exogenous growth hormone. *Proc. Natl Acad. Sci. U.S.A.*, 92: 6943-6946.
- SHIMIZU M., HARA A. & W.W. DICKHOFF, 2003. - Development of an RIA for salmon 41 kDa IGF-binding protein. *J. Endocrinol.*, 178: 275-283.
- SILVERSTEIN J.T., SHEARER K.D., DICKHOFF W.W. & E.M. PLISETSKAYA, 1998. - Effects of growth and fatness on sexual development of chinook salmon (*Oncorhynchus tshawytscha*) parr. *Can. J. Fish Aquat. Sci.*, 55: 2376-2382.
- SILVERSTEIN J.T., WOLTERS W.R., SHIMIZU M. & W.W. DICKHOFF, 2000. - Bovine growth hormone treatment of channel catfish: Strain and temperature effects on growth, plasma IGF-I levels, feed intake and efficiency and body composition. *Aquaculture*, 190: 77-88.
- STICKLAND N.C., WHITE R.N., MESCALL P.E., CROOK A.R. & J.E. THORPE, 1988. - The effect of temperature on myogenesis in embryonic development of the Atlantic salmon (*Salmo salar* L.). *Anat. Embryol.*, 178: 253-257.
- STORY G.M., PEIER A.M., REEVE A.J., EID S.R., MOSBACHER J., HRICIK T.R., EARLEY T.J., HERGARDEN A.C., ANDERSSON D.A., HWANG S.W., MCINTYRE P., JEGLA T., BEVAN S. & A. PATAPOUTIAN, 2003. - ANKTM1, a TRP-like channel expressed in nociceptive neurons, is activated by cold temperatures. *Cell*, 112: 819-829.
- SUMPTER J.P., LE BAIL P.-Y., PICKERING A.D., POTTINGER T.G. & J.F. CARRAGHER, 1991. - The effect of starvation on growth and plasma growth hormone concentrations of rainbow trout, *Oncorhynchus mykiss*. *Gen. Comp. Endocrinol.*, 83: 94-102.
- SWIFT D.R., 1954. - Influence of mammalian growth hormone on rate of growth of fish. *Nature*, 173: 1096.
- SWIFT D.R. & G.E. PICKFORD, 1965. - Seasonal variations in the hormone content of the pituitary gland of the perch, *Perca fluviatilis* L. *Gen. Comp. Endocrinol.*, 5: 354-365.
- USHER M.L., STICKLAND N.C. & J.E. THORPE, 1994. - Muscle development in Atlantic salmon (*Salmo salar*) embryos and the effect of temperature on muscle cellularity. *J. Fish Biol.*, 44: 953-964.
- VERNIER J.M., 1969. - Table chronologique du développement embryonnaire de la truite arc en ciel, *Salmo gairdneri*. *Ann. Embryol. Morphol.*, 2: 495-520.
- WEBER G.M. & E.G. GRAU, 1999. - Changes in serum concentrations and pituitary content of the two prolactins and growth hormone during the reproductive cycle in female tilapia, *Oreochromis mossambicus*, compared with changes during fasting. *Comp. Biochem. Physiol. C, Pharmacol. Toxicol. Endocrinol.*, C124: 323-335.
- YADA T. & T. HIRANO, 1992. - Inhibition of growth hormone synthesis by somatostatin in cultured pituitary of rainbow trout. *J. Comp. Physiol. B*, 162: 575-580.
- YADA T., URANO A. & T. HIRANO, 1991. - Growth hormone and prolactin gene expression and release in the pituitary of rainbow trout in serum-free culture. *Endocrinology*, 129: 1183-1192.
- YANG B.Y., GREEN M. & T.T. CHEN, 1999. - Early embryonic expression of the growth hormone family protein genes in the developing rainbow trout, *Oncorhynchus mykiss*. *Mol. Reprod. Dev.*, 53: 127-134.
- YAO K., 1993. - Caractérisation des récepteurs hépatiques de l'hormone de croissance (GH) chez la truite arc en ciel (*Oncorhynchus mykiss*) et étude préliminaire de leur régulation par le niveau d'alimentation et par la température. Thèse de Doctorat, 163 p. Univ. Rennes I.
- YAO K. & P.-Y. LE BAIL, 1999. - Biochemical characterization of growth hormone receptor in rainbow trout (*Oncorhynchus mykiss*) before and after purification. *Fish Physiol. Biochem.*, 21: 111-120.
- YAO K., NIU P.D., LE GAC F. & P.-Y. LE BAIL, 1991. - Presence of specific growth hormone binding sites in rainbow trout (*Oncorhynchus mykiss*) tissues: Characterization of the hepatic receptor. *Gen. Comp. Endocrinol.*, 81: 72-82.
- ZHANG Y. & T.A. MARCHANT, 1996. - Characterization of growth hormone binding sites in the goldfish, *Carassius auratus*: Effects of hypophysectomy and hormone injection. *Fish Physiol. Biochem.*, 15: 157-165.

Reçu le 25 novembre 2003.

Accepté pour publication le 14 juin 2004.