Expression of sodium-iodide symporter mRNA in the thyroid gland of *Xenopus laevis* tadpoles: developmental expression, effects of antithyroidal compounds, and regulation by TSH

Robert Opitz, Achim Trubiroha, Claudia Lorenz, Ilka Lutz, Sabine Hartmann, Tobias Blank, Thomas Brauneck and Werner Kloas

Department of Inland Fisheries, Leibniz-Institute of Freshwater Ecology and Inland Fisheries, Mueggelseedamm 310, D-12587 Berlin, Germany

1Aquatic Ecology and Toxicology, Department of Zoology, University of Heidelberg, D-69120 Heidelberg, Germany

2Department of Endocrinology, Institute of Biology, Humboldt University, D-10115 Berlin, Germany

(Requests for offprints should be addressed to W Kloas; Email: werner.kloas@igb-berlin.de)

Abstract

The uptake of iodide represents the first step in thyroid hormone synthesis by thyroid follicular cells and is mediated by the sodium-iodide symporter (NIS). In mammals, expression of NIS is stimulated by TSH and transcription of the NIS gene involves regulation by the thyroid-specific transcription factors Pax8 and Nkx2.1. In this study, we examined the mRNA expression of NIS, Pax8 and Nkx2.1 in the thyroid gland of *Xenopus laevis* tadpoles by semi-quantitative reverse transcriptase (RT)-PCR. During spontaneous metamorphosis, NIS mRNA expression was low in premetamorphic tadpoles, increased throughout metamorphosis, and peaked at climax stage 60. Analysis of TSH β-subunit (TSHβ) mRNA in the pituitary of the same tadpoles revealed a close temporal relationship in the expression of the two genes during metamorphosis, suggesting a regulatory role of TSH in the developmental expression of NIS. Treatment of tadpoles with goitrogenic compounds (sodium perchlorate and ethylendithiourea) increased TSHβ mRNA expression (approximately twofold) and caused thyroid gland hyperplasia, confirming that feedback along the pituitary–thyroid axis was operative. Analysis of gene expression in the thyroid gland revealed that goitrogen treatment was correlated with increased expression of NIS mRNA (~20-fold). In the thyroid gland organ culture experiments, bovine TSH (bTSH; 1 mU/ml) strongly induced NIS mRNA expression. This effect was mimicked by co-culture of thyroid glands with pituitaries from stage 58 tadpoles and by agents that increase intracellular cAMP (forskolin, dibutyryl-cAMP). In addition, it could be shown that thyroid glands of *X. laevis* tadpoles express Pax8 and Nkx2.1 mRNA in a developmentally regulated manner and that *ex vivo* treatment of thyroid glands with bTSH, forskolin, and cAMP analogs increased the expression of Pax8 and Nkx2.1 mRNA. This is the first report on developmental profiles and hormonal regulation of thyroid gland gene expression in amphibian tadpoles and, together, results reveal a critical role of TSH in the regulation of NIS mRNA expression in the thyroid gland of *X. laevis* tadpoles.


Introduction

Thyroid hormones (THs) are critically important for the regulation of diverse biological processes associated with vertebrate growth, development, and metabolism (Yen 2001). In vertebrates, the *de novo* synthesis of the two major THs, 3,5,3′,5′-tetraiodothyronine (T4) and 3,5,3′-triiodothyronine (T3), is restricted to the thyroid gland. Since THs are iodinated thyronine derivatives, active concentration of iodide from the bloodstream represents a crucial step in their biosynthesis. A remarkable capability of the thyroid gland is to concentrate iodide by a factor of 20–40 over blood plasma iodide concentrations (Dohan et al. 2003). This active uptake of iodide by thyroid follicular cells is an energy-dependent process that is mediated by the sodium-iodide symporter (NIS), a glycoprotein located in the basolateral membrane of thyroid follicular cells (Dohan et al. 2003). The driving force for NIS-mediated iodide transport is the inwardly directed Na⁺ gradient generated by Na⁺K⁺ ATPase (Paire et al. 1998). The pivotal role of NIS in mediating thyroidal iodide uptake and thus facilitating TH synthesis is highlighted by several key findings. Competitive inhibition of NIS-mediated iodide uptake (e.g., by thiocyanate or perchlorate anions) not only blocks thyroidal iodide uptake but impairs TH synthesis (Alexander & Wolff 1966, Wolff 1998, Tonacchera et al. 2004). In addition, clinical studies of patients with congenital iodide transport defect, a condition characterized by low iodide uptake, hypothyroidism, and goiter, revealed that specific
mutations of the NIS protein are involved in the etiology of this disease (Pohlenz & Refetoff 1999, De La Vieja et al. 2000). The first cDNA encoding for rat NIS was cloned in 1996 by Dai et al. (1996). Subsequently, the regulation of NIS mRNA expression in thyroid follicular cells was extensively investigated in various mammalian model systems (reviewed in De La Vieja et al. 2000, Dohan et al. 2003). Together, these studies demonstrated that thyroid-stimulating hormone (TSH) stimulates NIS activity via up-regulation of NIS mRNA and protein expression in thyroid follicular cells (Kogai et al. 1997, Saito et al. 1997a, Selmi-Ruby et al. 2003). Treatment of thyroid follicular cells with forskolin and analogs of cAMP could reproduce the effects of TSH on NIS expression, thus demonstrating that TSH effects are mediated via the cAMP-protein kinase A (PKA) pathway (Saito et al. 1997a, Ohno et al. 1999, Trapasso et al. 1999). Three different transcription factors, including the paired box gene Pax8, the homeo-domain-containing protein Nkx2.1 (also called TTF-1 for thyroid transcription factor 1) and the forkhead domain-containing protein FoxE1 (also called TTF-2 for thyroid transcription factor 2) have been implicated in the regulation of thyroid-specific gene expression in mammals (Damante et al. 2001). Although each of these transcription factors is also expressed in other tissues, their co-expression is unique to the thyroid gland. Moreover, functional analyses of NIS promoters in mammalian species strongly suggest important roles for both Pax8 and Nkx2.1 in the regulation of NIS gene transcription in the thyroid gland (Endo et al. 1997, Ohno et al. 1999, Altmann et al. 2005).

In amphibians, THs play a pivotal role during postembryonic development (metamorphosis), as these hormones are the primary morphogen-regulating diverse processes associated with tissue transformations from a larval to the adult phenotype (Shi 1999). Studies on thyroid system function during amphibian metamorphosis have so far been mainly concerned with the action of TH in peripheral tissues (Shi 1999), while knowledge about the thyroid gland function during metamorphic development is limited to the description of morphological and biochemical aspects of thyroid gland activity (Regard 1978, Wright et al. 1995). Early studies in amphibians showed that, similar to mammals, treatment with mammalian TSH preparations leads to increased thyroidal iodide uptake (Lynn & Dent 1961, Hourdry & Regard 1975), whereas treatment with perchlorate and thiocyanate reduced thyroidal iodide uptake (Lynn & Dent 1960, Norris & Platt 1973). The vulnerability of the amphibian thyroid system to perchlorate has also been demonstrated in recent studies showing that long-term treatment of tadpoles with perchlorate inhibits TH-dependent development in Xenopus laevis tadpoles and induces thyroid follicular cell hyperplasia (Goleman et al. 2002, Tietge et al. 2005). Little attention has so far been given to the molecular analysis of thyroid gland function in amphibians. Recently, cDNAs encoding for X. laevis NIS, Pax8, and Nkx2.1 have been cloned (Heller & Brändli 1999, Hollemann & Pieler 2000, Klein et al. 2002), but the expression of the corresponding mRNAs in the thyroid gland of metamorphosing X. laevis tadpoles has so far not been examined.

Given the importance of thyroidal iodide uptake for TH synthesis, the aims of this study were to examine the expression of NIS mRNA during metamorphosis and to characterize the putative role of TSH in the regulation of NIS mRNA in the thyroid gland of X. laevis tadpoles. We show that NIS mRNA is expressed in the thyroid gland of X. laevis tadpoles and characterize the developmental expression profile of NIS mRNA during metamorphosis. Experimental induction of goiter by in vivo treatment of tadpoles with sodium perchlorate and ethylenethiourea (ETU) and ex vivo organ culture experiments of X. laevis thyroid glands were used as models to reveal the stimulating effects of TSH on thyroidal NIS expression. In addition, developmental and treatment-related changes in mRNA expression were determined for the thyroid transcription factors Pax8 and Nkx2.1.

Materials and Methods

Reagents

Bovine TSH (bTSH) (lot 064K1172, 1·8 IU/mg protein), forskolin, dibutyryl-cAMP (db-cAMP), ETU, sodium perchlorate, dimethylsulfoxide and aminoesterbenzoic acid (MS-222) were obtained from Sigma. Dulbecco’s modified Eagle’s medium (DMEM) was purchased from Invitrogen.

Animals and husbandry

All experiments were carried out with X. laevis tadpoles obtained from in-house breeding of adult animals. During all phases of the in vivo experiments described below, tadpoles were reared in a synthetic culture medium at 22±1°C and pH 7·0±0·5 as described previously in Opitz et al. (2005). All rearing tanks were continuously aerated by airstones. A 12 h light:12 h darkness cycle was used. Starting at day 5 postfertilization, tadpoles were fed daily with Sera Micron (Sera, Heinsberg, Germany). Developmental stages of the tadpoles were determined according to the normal table of X. laevis (Nieuwkoop & Faber 1994). All experimental aspects were conducted in compliance with the institutional guidelines for the care and use of animals.

In vivo experiments

To study the developmental changes in various thyroid system-related parameters, tadpoles at developmental stage 48 were placed in 11 l glass aquaria (culture medium volume 10 l) and were raised without any additional treatment until complete tail resorption at stage 66. The larval density was maintained at 20–25 tadpoles per 101 culture medium. The medium was changed completely three times per week and
tadpoles were fed daily with Sera Micron. At distinct developmental stages (see Results), tadpoles were collected from the stock population and anesthetized in 100 mg/l MS-222. Pituitary and thyroid glands were dissected and separately collected in 15 μl of RNALater reagent (Qiagen). Tissue samples were stored at −80 °C until RNA extraction. In addition, lower jaw tissue was sampled from a subset of tadpoles and fixed in Bouin’s solution (Sigma) for thyroid gland histology and morphometry.

For experimental induction of goiter tadpoles, tadpoles at developmental stage 52 were placed in 11 l glass aquaria (volume of test solution was 10 l) containing 20 mg/l sodium perchlorate, 50 mg/l ETU, and culture medium alone (controls). The test solutions were replaced completely three times per week and tadpoles were fed daily with Sera Micron. After treatment for a total of 12 days, tadpoles were anesthetized in 100 mg/l MS-222 and pituitaries and thyroid glands were collected in RNALater reagent. Lower jaw tissue was collected from a subset of test animals and fixed in Bouin’s solution for thyroid gland histology.

**Organ culture**

Before tissue removal for organ culture, stage 56/57 tadpoles were immersed in the *in vivo* culture medium supplemented with 200 μg/ml streptomycin (Cambrex, Verviers, Belgium) and 200 U/ml penicillin (Cambrex) for 24 h. Tadpoles were not fed during the 24 h treatment with antibiotics. All procedures related to the subsequent *ex vivo* culture of thyroid glands were done under sterile conditions in a tissue culture hood and the protocol used was based on the technique described by Denver (1988), with some modifications. DMEM was diluted to two-thirds strength and supplemented with 0.1% BSA (Invitrogen), 1·1 mM L-glutamine (Cambrex), 50 U/ml penicillin, 50 μg/ml streptomycin and 50 U/ml neomycin (Sigma). Tadpoles were anesthetized in 100 mg/l MS-222 and decapitated. Following removal of the cranium and the upper jaw, the lower jaw was briefly rinsed in sterile distilled water and ethanol (70%). Ventrail skin and muscle tissue were removed and the paired thyroids were dissected out together with a small piece of the underlying hyoid bone. Thyroid glands were then rinsed in 1 ml ice-cold DMEM for 30 s, annealing (30 s), and extension (72 °C, 40 s) and a final extension step (72 °C, 10 min). The nucleotide sequences of the primers, cycle numbers, and annealing temperatures used in PCR are listed in Table 1. Amplified PCR products (7 μl per sample) were electrophoresed on a 1·8% agarose gel and stained with ethidium bromide-stained gels were taken using the GelDoc 2000 system (BioRad) and densitometric analyses were performed with Quantity One software (BioRad). Densitometric values for elongation factor 1α (EF) were used to normalize NIS, Pax8, Nkx2·1, and TSHβ values for variations in cDNA loading. Results from triplicate analyses of individual RNA samples for target gene expression were averaged, yielding a single value for each RNA sample to be used in the statistical analysis. PCR products were extracted from agarose gels using QIAquick kit (Qiagen), and the identity of the PCR products was confirmed by sequence analysis (Sequence Laboratories, Göttingen, Germany).

**Thyroid gland histology and morphometry**

Lower jaw tissue samples containing the paired thyroid gland were dehydrated in a graded series of alcohol, embedded in paraffin and sectioned in a transverse plane from dorsal to ventral at 5 μm thickness. Serial sections were mounted on glass slides and stained with hematoxylin and eosin. For each

---

**Semi-quantitative RT-PCR**

Extraction of RNA was performed for individual thyroid gland and pituitary tissue samples, with the exception of stage 51 tadpoles, where tissue samples from two animals were always pooled before RNA extraction. Total RNA was extracted using RNase-free DNase (Qiagen) according to the manufacturer’s protocol. Total RNA content was measured using the Ribogreen RNA quantitation kit (Invitrogen) according to the manufacturer’s protocol in a Spectrafluor plus microplate reader (Tecan, Crailsheim, Germany). cDNA was reverse transcribed from 10 ng total RNA using 3·5 pmol oligo(dT) primer (Biometra, Göttingen, Germany), 7·5 nmol of each dNTP (Biometra), and 5 units Avian Myeloblastosis Virus RT (Biometra). The cDNA was diluted 1:16 prior to PCR amplification in a thermal cycler (Biometra). PCR was performed in a 25 μl reaction using 2 μl of cDNA solution as template. PCR products were electrophoresed on 1·8% agarose gel and stained with ethidium bromide. The nucleotide sequences of the primers, cycle numbers, and annealing temperatures used in PCR are listed in Table 1. Amplified PCR products (7 μl per sample) were electrophoresed on a 1·8% agarose gel and stained with ethidium bromide (Gibco). Images of ethidium bromide-stained gels were taken using the GelDoc 2000 system (BioRad) and densitometric analyses were performed with Quantity One software (BioRad). Densitometric values for elongation factor 1α (EF) were used to normalize NIS, Pax8, Nkx2·1, and TSHβ values for variations in cDNA loading.
tadpole, five sections of the central portion of the right thyroid lobe were histologically examined and epithelial cell height measurements were performed as described in Optiz et al. (2006a). A single mean value for epithelial cell height was calculated for each animal, and a total of five tadpoles were analyzed at each developmental stage.

Statistical analysis

Epithelial cell heights and densitometric data from RT-PCR assays were log-transformed to satisfy the criteria of normality and homogeneity of variance. Densitometric data were then analyzed by Dunnett’s test to compare control data to all other treatment groups or by Tukey-Kramer’s multiple comparison test for pair-wise comparisons to identify significant differences among experimental groups. Developmental stage data were analyzed using the nonparametric Kruskal-Wallis test followed by Dunn’s multiple comparison test to determine whether significant differences existed between the developmental stage composition of treatment groups. Statistical analyses were performed using the software package SigmaStat 2.0 (SPSS-Jandel Scientific, Erkrath, Germany). Differences were considered significant at $P<0.05$.

Results

Determination of NIS, Pax8, and Nkx2·1 mRNA by RT-PCR

Using total RNA, isolated from thyroid gland tissue of stage 57/58 tadpoles, PCR products of the expected length were detected by gel electrophoresis following RT-PCR with primers designed for amplification of NIS (585 bp), Pax8 (307 bp), Nkx2·1 (409 bp), and EF (285 bp) cDNAs (Fig. 1). Sequence analysis of the PCR products confirmed the successful amplification of all four transcripts from thyroid gland RNA. To further validate our RT-PCR protocols, total RNA isolated from different tissues of stage 57/58 tadpoles was analyzed for expression of NIS, Pax8, Nkx2·1, and EF mRNA by qualitative RT-PCR. Figure 1 shows that extrathyroideal NIS mRNA expression was detected in stomach and kidney tissue but not in liver, heart, or lung tissue. Among the tissues analyzed, extrathyroideal expression of Pax8 and Nkx2·1 mRNA was limited to kidney and lung tissue respectively, whereas EF mRNA was successfully detected in all tissues examined (Fig. 1). For semi-quantitative RT-PCR analysis of NIS, Pax8, Nkx2·1 mRNAs in thyroid and TSHβ mRNA in pituitary, PCR cycle numbers were then empirically determined to ensure detection within the log-linear range of the PCR (Fig. 2). Preliminary experiments showed a wide range of thyroidal NIS mRNA expression and, therefore, cycle experiments were separately performed with cDNA obtained from tissue samples displaying low and high expression levels of NIS in order to determine cycle numbers at which log-linear phases overlap (Fig. 2C). Optimized assay conditions finally applied in the semi-quantitative RT-PCR experiments are summarized in Table 1.

Developmental profiles of NIS, Pax8, and Nkx2·1 mRNA

The developmental profiles of NIS, Pax8, and Nkx2·1 mRNA expression were studied in thyroid glands of tadpoles

<table>
<thead>
<tr>
<th>Gene</th>
<th>GenBank Accession no.</th>
<th>Forward (F) and reverse (R) primer</th>
<th>$T_a$(°C)</th>
<th>Cycles</th>
<th>Product size (bp)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sodium-iodide symporter</td>
<td>BC077614</td>
<td>F: TAAACgggAgACAATgCAGCA</td>
<td>58</td>
<td>31–33</td>
<td>585</td>
</tr>
<tr>
<td>Pax8</td>
<td>AJ010504</td>
<td>R: TgggCATTCATgCTT</td>
<td>58</td>
<td>30–32</td>
<td>307</td>
</tr>
<tr>
<td>Nkx2·1</td>
<td>AF250347</td>
<td>F: CggCggATgAAACAgAgAgTCT</td>
<td>58</td>
<td>29–31</td>
<td>409</td>
</tr>
<tr>
<td>Thyroid-stimulating hormone (β-subunit)</td>
<td>L07618</td>
<td>R: ggAgggATgAAACAgAgAgTCT</td>
<td>62</td>
<td>23–24</td>
<td>191</td>
</tr>
<tr>
<td>Elongation factor 1α</td>
<td>M25504</td>
<td>F: AgAgAgAgAgAgAgACCTT</td>
<td>59</td>
<td>22–24</td>
<td>285</td>
</tr>
</tbody>
</table>

$T_a$, annealing temperature.
beginning at premetamorphic stage 51 throughout the end of metamorphosis at stage 66 (Fig. 3). Expression of NIS mRNA in the thyroid gland was low in premetamorphic tadpoles (stages 51–53). A first statistically significant increase of NIS mRNA expression was detected between late premetamorphic stage 53 and the onset of prometamorphosis at stage 57/58. For NIS-specific PCR (C), cDNA of thyroid tissue from tadpoles at different developmental stages was used to determine overlap of log-linear amplification phases. Each cycle experiment was performed in triplicate. Mean values are shown and standard error bars are omitted to reduce clutter.

Figure 2 Determination of the log-linear phase of PCR with gene-specific primers for sodium-iodide symporter (NIS), Pax8, Nkx2-1, TSHβ subunit, and elongation factor 1α (EF). PCR was performed as described in Materials and Methods with cDNA generated from pituitary (A) and thyroid tissue (B) of stage 57/58 tadpoles. For NIS-specific PCR (C), cDNA of thyroid tissue from tadpoles at different developmental stages was used to determine overlap of log-linear amplification phases. Each cycle experiment was performed in triplicate. Mean values are shown and standard error bars are omitted to reduce clutter.

Figure 3 Developmental mRNA expression profiles of sodium-iodide symporter (NIS), Pax8, Nkx2-1, and elongation factor 1α (EF) in thyroid glands of *Xenopus laevis* tadpoles during spontaneous metamorphosis. Total RNA was extracted from thyroid gland tissue sampled at the indicated stages of development (Nieuwkoop & Faber 1994) and analyzed by semi-quantitative RT-PCR. PCR products were separated on a 1.8% agarose gel stained with ethidium bromide. (A) Representative agarose gel images of amplified cDNA fragments for each gene. (B) Results from densitometric analyses of scanned agarose gels. NIS, Pax8, and Nkx2-1 values were normalized by EF values. For graphical presentation, results were expressed relative to the expression level determined at stage 51 (arbitrarily set at 1.0). Data are shown as mean ± S.E. (n = 6 RNA samples per stage). Within each graph shown, different letters denote means that are significantly different (P < 0.05; Tukey–Kramer multiple comparison test).
stage 54 ($P<0.05$). The signal intensity of the separated bands increased further during prometamorphosis, reaching peak levels at climax stage 60. A sharp and highly significant increase in NIS mRNA expression was observed between stages 58 and 60 ($P<0.001$). NIS mRNA expression remained high during metamorphic climax and pairwise multiple comparison tests did not detect significant differences in the expression between stages 60 and 64. However, between stages 64 and 66, NIS mRNA expression showed a distinct and significant decline ($P<0.01$) to levels comparable to prometamorphic stage 58. Similar to NIS, only weak mRNA expression was determined for the transcription factors Pax8 and Nkx2·1 at prometamorphic stages 51 and 53 (Fig. 3). A significant up-regulation of mRNA expression was detected for both genes at stage 54 ($P<0.01$). Pax8 mRNA expression was maximal between late prometamorphic stage 58 and late climax stage 64 but dropped significantly between stages 64 and 66 ($P<0.01$). Nkx2·1 mRNA expression was maximal between late prometamorphic stage 58 and early climax stage 60 but decreased significantly between stage 60 and stage 62 ($P<0.05$) and expression remained at a reduced level throughout the remaining climax phase.

**Developmental profiles of thyroid follicular cell height**

In addition to the determination of developmental mRNA expression profiles in the thyroid gland, a subset of animals was analyzed morphometrically at distinct developmental stages for changes in the thyroid follicular cell height as a histological marker of thyroid follicular cell activity (Kalisnik 1972). The height of thyroid follicular cells showed a distinct developmental profile throughout metamorphosis (Fig. 4A). At premetamorphic stages, follicular cells had a cuboidal shape and a mean cell height of $5·5\pm 1·1\,\mu m$. Pairwise multiple comparison tests showed that the cell height increased significantly at the onset of metamorphosis ($9·2\pm 2·0\,\mu m$ at stage 54, $P<0.05$) followed by a constant but less pronounced increase to peak values at early climax stages ($11·5\pm 2·8\,\mu m$ at stage 60). A slight decrease in follicular cell height was noted at stage 64 ($11·0\pm 2·3\,\mu m$) and the completion of metamorphosis at stage 66 ($9·4\pm 2·3\,\mu m$).

**Developmental profile of TSHβ mRNA**

Thyroid gland activity is primarily stimulated by TSH, which is produced and secreted by thyrotropic cells of the pituitary (Vassart & Dumont 1992). In order to relate our observations on developmental expression profiles of genes in the thyroid gland to changes in pituitary TSH synthesis, we additionally determined the mRNA expression of TSHβ in the pituitary tissue collected from the same animals being sampled for thyroid gland gene expression analyses (Fig. 4B and C). Expression of TSHβ mRNA was low in premetamorphic tadpoles (stages 51–53) but increased markedly between metamorphic stages 54 and 56. Levels of TSHβ mRNA increased further during prometamorphosis and reached peak values at late prometamorphic stage 58 (approximately eightfold higher than stage 51). From stage 60 towards the end of metamorphosis, there was a steady decrease in TSHβ mRNA expression and at stage 66, the expression level was

---

**Figure 4** Developmental changes in thyroid epithelial cell height and mRNA expression of thyroid-stimulating hormone β-subunit (TSHβ) during spontaneous metamorphosis. (A) Results from densitometric analyses of thyroid gland tissue sampled at the indicated stages (Nieuwkoop & Faber 1994). Note that epithelial cell height was not analyzed (n.a.) for stage 53 tadpoles. Columns and bars represent means and S.D. ($n=5$ animals per stage). For determination of TSHβ mRNA expression, total RNA was extracted from pituitaries sampled at the indicated stages of development and analyzed by semi-quantitative RT-PCR. PCR products were separated on a 1·8% agarose gel stained with ethidium bromide. (B) Representative agarose gel images of amplified cDNA fragments for TSHβ and elongation factor 1α (EF). (C) Results from densitometric analyses of scanned agarose gels. TSHβ values were normalized by EF values. For graphical presentation, results were expressed relative to the expression level determined at stage 51 (arbitrarily set at 1·0). Data are given as mean ± S.E. ($n=6$ RNA samples per stage). Within each graph shown, different letters denote means that are significantly different ($P<0.05$; Tukey–Kramer multiple comparison test).
Effects of ETU and perchlorate treatment on thyroid gland gene expression

The goitrogen treatment model has been successfully used in various mammalian studies to elucidate TSH-dependent changes in thyroidal gene expression (Uyttersprot et al. 1997, Viglietto et al. 1997, Suzuki et al. 1999). Stage 52 tadpoles were treated with 50 mg/l ETU or 20 mg/l sodium perchlorate for 12 days to study in vivo the effects of TSH overexpression on gene expression in the thyroid gland. Because ETU inhibits iodide organification (Doerge & Takazawa 1990) and perchlorate inhibits thyroidal iodide uptake (Wolf 1998), these treatments were both expected to inhibit TH synthesis, thereby inducing a compensatory rise in TSH production and release. The presence of TH-deficient conditions in the treated tadpoles was assessed via examination of tadpole development, TSHβ mRNA expression in pituitary tissue, and thyroid gland histology (Figs 5 and 6). Whereas untreated control tadpoles showed development to stage 57/58 within 12 days, tadpoles exposed to either ETU or sodium perchlorate were developmentally arrested at stage 55 (Fig. 5A). Analysis of TSHβ mRNA expression in pituitary tissue by semi-quantitative RT-PCR demonstrated 2.1- and 2.0-fold higher TSHβ expression in sodium perchlorate and ETU-treated tadpoles respectively, compared to the controls (Fig. 5B and C). In the ETU and perchlorate treatment groups, gross morphological examination showed a marked enlargement of the thyroid gland and histological analysis of thyroid gland sections revealed marked hyperplasty and hyperplasia of follicular epithelial cells in ETU- and perchlorate-treated tadpoles (Fig. 6). When total RNA of thyroid glands was analyzed by semi-quantitative RT-PCR for changes in gene expression (Fig. 7), a strong up-regulation of NIS mRNA was detected in tadpoles treated with sodium perchlorate (~21-fold) and ETU (~18-fold) compared to controls (Fig. 7B). The up-regulation was significant (P<0·001) and highly consistent among individuals from each of the two goitrogen treatment groups. In contrast, no significant differences in the expression of Pax8 and Nkx2·1 mRNA were detectable between the treatment groups (Fig. 7C and D).

**Organ culture experiments**

To gain further insight into the hormonal regulation of NIS mRNA expression in the thyroid gland, we devised a series of organ culture experiments with thyroid glands collected from stage 56/57 tadpoles. In all organ culture experiments conducted during this study, a rapid decline in basal NIS mRNA expression levels was observed during the 16 h preincubation period of thyroid glands that was performed after organ dissection. After preincubation, NIS mRNA was barely detectable by RT-PCR in cultured control thyroid glands (Fig. 8A). Thyroid glands incubated for 48 h in DMEM containing various concentrations of bTSH (0·1–10 mU/ml) revealed strong up-regulation of NIS mRNA by 1·0 and 10 mU/ml bTSH but not at the lowest concentration of 0·1 mU/ml bTSH (Fig. 8B). In contrast to NIS, expression of Pax8 and Nkx2·1 mRNA was always detectable in

**Figure 5** Effects of treatment of stage 52 Xenopus laevis tadpoles with 20 mg/l sodium perchlorate (PER) and 50 mg/l ethylenethiourea (ETU) on development and thyroid-stimulating hormone β-subunit (TSHβ) mRNA expression. (A) The distribution of developmental stages (Nieuwkoop & Faber 1994) in the different treatment groups at day 12 (n=15 tadpoles per treatment). Columns represent median values, and maximum (circles) and minimum (triangles) stages observed in each treatment group are indicated. Statistically significant differences from the control group (Ctrl) are marked by asterisks (P<0·05, Dunn’s test). For RT-PCR determination of TSHβ mRNA expression, total RNA was extracted from eight individual pituitaries per treatment group sampled on treatment day 12. PCR products were separated on a 1·8% agarose gel stained with ethidium bromide. (B) Representative agarose gel images of amplified cDNA fragments for TSHβ and elongation factor 1α (EF). (C) Results from densitometric analyses of scanned agarose gels. TSHβ values were normalized by EF values. For graphical presentation, results were expressed relative to control group values (arbitrarily set at 1·0). Data are shown as mean ± s.e. (n=8 RNA samples per treatment). Statistically significant differences in TSHβ mRNA expression from the control group are marked by asterisks (P<0·05, Dunnett’s test).
cultured thyroid glands by RT-PCR. Treatment of cultured glands with 1·0 and 10 mU/ml bTSH caused a moderate increase in the expression of both genes (approximately twofold), whereas 0·1 mU/ml bTSH failed to affect the expression of both transcription factors (Fig. 8C and D). A concentration of 1·0 mU/ml bTSH was then used to study the time-course of bTSH effects on NIS mRNA expression during 48 h of thyroid gland culture. As illustrated in Fig. 9,

Figure 6 Histological changes in thyroid glands of Xenopus laevis tadpoles after treatment with 20 mg/l sodium perchlorate (PER) and 50 mg/l ethylenethiourea (ETU). Treatment of tadpoles was initiated at stage 52 (Nieuwkoop & Faber 1994), and thyroid gland histology was examined after 12 days of treatment. In comparison to the control group (A), tadpoles treated with PER (B) and ETU (C) showed remarkable enlargement of thyroid glands displaying follicular cell hypertrophy and hyperplasia. In PER-treated tadpoles, collapsed follicles devoid of colloid and lined by high columnar epithelia predominated while glands from ETU-treated tadpoles displayed distended follicles with enlarged lumina containing small amounts of foamy colloid. Sections of 5 μm thickness were stained with hematoxylin and eosin, and light micrographs were taken at 20× magnification.

Figure 7 Effects of treatment of Xenopus laevis tadpoles with 20 mg/l sodium perchlorate (PER) and 50 mg/l ethylenethiourea (ETU) on thyroid gland gene expression. Total RNA was extracted from eight individual thyroid glands per treatment group sampled on treatment day 12. Expression of sodium-iodide symporter (NIS), Pax8, Nkx2·1 mRNA, and elongation factor 1α (EF) was analyzed by semi-quantitative RT-PCR and PCR products were separated on a 1·8% agarose gel stained with ethidium bromide. (A) Representative agarose gel images of amplified cDNA fragments for each gene. (B–D) Results from densitometric analyses of scanned agarose gels. Densitometric values for NIS, Pax8, and Nkx2·1 were normalized by EF values. For graphical presentation, results were expressed relative to control group (Ctrl) values (arbitrarily set at 1·0). Data are given as mean±s.e. (n=8 RNA samples per treatment). Statistically significant differences from the control group are marked by asterisks (P<0·05, Dunnett’s test).
while NIS mRNA was not detectable in untreated glands, induction of NIS mRNA expression was seen as early as 6 h after initiation of bTSH treatment. Peak expression of NIS mRNA was observed after 12 h of bTSH treatment, but NIS mRNA expression was still maintained at elevated levels throughout the 48 h of organ culture. In another set of experiments, thyroid glands were co-incubated for 24 h with freshly dissected pituitary glands of stage 58 X. laevis tadpoles or 1–0 mU/ml bTSH. Results shown in Fig. 10A demonstrate that co-culture of thyroid glands with pituitary glands could fully reproduce the effects of 1–0 mU/ml bTSH on NIS mRNA expression. In order to examine whether the effects of TSH on NIS mRNA expression are mediated via the cAMP–PKA pathway, thyroid glands were cultured for 48 h in the presence of bTSH (1–0 mU/ml), forskolin (10 μM) or db-cAMP (2 mM), and the expression of NIS

Figure 8 Effects of various concentrations of bovine TSH (bTSH) (0–1–10 mU/ml) on mRNA expression of sodium-iodide symporter (NIS), Pax8 and Nkx2·1 in cultured thyroid glands of Xenopus laevis tadpoles. The paired thyroid glands were dissected from stage 56/57 tadpoles, preincubated for 16 h in TSH-free medium and treated with the indicated TSH concentration for a total of 48 h. Total RNA was extracted from thyroid gland tissue and analyzed by semi-quantitative RT-PCR for target gene expression. PCR products were separated on a 1–8% agarose gel stained with ethidium bromide. (A) Representative agarose gel images of amplified cDNA fragments for each gene. (B–D) Results from densitometric analyses of scanned agarose gels. Densitometric values for NIS, Pax8 and Nkx2·1 were normalized by elongation factor 1α values (EF). For graphical presentation, results were expressed as a percentage of the experimental group with the highest expression level (arbitrarily set at 100%). Results from two independent experiments (each containing at least three replicates per treatment) were averaged. Note that NIS mRNA expression could not be reproducibly detected in the 0 and 0–1 mU/ml TSH treatment groups.

Figure 9 Ethidium bromide-stained gels showing RT-PCR analysis of sodium-iodide symporter (NIS) and elongation factor 1α (EF) expression in cultured Xenopus laevis thyroid glands after various incubation times. The paired thyroid glands were dissected from stage 56/57 tadpoles and preincubated for 16 h in TSH-free medium. Total RNA was extracted from thyroid glands cultured thereafter for the indicated periods of time in the absence or presence of 1 mU/ml TSH. Two independent experiments (each containing three replicates per experimental group) were performed with tadpoles from different spawns and yielded similar results. Note that NIS mRNA expression could not be detected in the control group.
mRNA was determined by semi-quantitative RT-PCR. Figure 10B shows that treatment of thyroid glands with forskolin or db-cAMP could reproduce the NIS-inducing effect of 1·0 mU/ml bTSH.

Discussion

THs are the primary morphogen initiating and regulating tissue remodeling during amphibian metamorphosis (Shi 1999). During premetamorphosis (stages 36/37 to 53 in X. laevis), the thyroid gland still undergoes development into a functional gland and TH secretion is very low (Leloup & Buscaglia 1977, Regard 1978). The onset of metamorphosis (stage 54 in X. laevis) is characterized by an increase in circulating TH plasma levels and peak levels of TH in blood plasma are present during mid climax (stages 60–62 in X. laevis). The distinct changes reported for blood plasma TH levels during X. laevis metamorphosis (Leloup & Buscaglia 1977) are closely correlated to alterations in histological and biochemical markers of thyroid gland activity (Regard 1978). Given the central role of NIS for normal thyroid gland function, we devised a number of experiments to examine the expression of NIS mRNA in the thyroid gland of X. laevis tadpoles under different physiological conditions.

An initial qualitative RT-PCR analysis of NIS mRNA tissue distribution in stage 57/58 tadpoles revealed detectable levels in thyroid, stomach, and kidney tissue but failed to demonstrate expression in liver, heart, or lung tissue. These results corroborate the recent demonstration of NIS mRNA expression in stomach and kidney of X. laevis (Carr et al. 2003), whereas the detection of NIS in X. laevis thyroid tissue represents a novel finding. The physiological meaning of NIS expression in stomach and kidney of X. laevis is not yet clear. The tissue distribution of NIS mRNA observed in X. laevis tadpoles is in accordance with several mammalian studies reporting increased NIS expression in thyroid and gastric mucosa but very low or undetectable levels in liver, heart, and lung (Perron et al. 2001, Bruno et al. 2004). Inconsistent results have been obtained in mammalian studies of NIS expression in the kidney. Spitzweg et al. (2001) reported positive detection of NIS mRNA in human kidney by RT-PCR and ribonuclease protection assay, whereas other studies failed to detect NIS in kidney using various techniques (Perron et al. 2001, Bruno et al. 2004).

During spontaneous development, the level of NIS mRNA expression in thyroid glands of X. laevis tadpoles showed distinct changes. The observation of weak mRNA expression of NIS at premetamorphic stages is in accordance with earlier studies that reported low rates of thyroidal iodide uptake in the premetamorphic amphibian thyroid gland (Saxen et al. 1957, Regard 1978). Furthermore, the increase in NIS mRNA expression observed during prometamorphosis to peak expression levels at early climax stages followed by a distinct decline towards the end of metamorphosis correlates well with developmental profiles reported for thyroidal iodide uptake in X. laevis tadpoles (Leloup & Buscaglia 1977, Kran & Denver 2004). In addition, our own morphometric measurements of follicular cell height, considered as a histological marker of thyroid follicular cell activity (Kalisnik 1972), suggest a relationship between NIS mRNA expression and thyroid follicular cell activity during metamorphosis. Together, these data implicate that the increase in NIS mRNA expression coincides temporally with the onset of elevated iodide-trapping, TH synthesis, and secretion. Although the present study determined only the expression

---

Figure 10 Ethidium bromide-stained gels showing RT-PCR analysis of sodium-iodide symporter (NIS) and elongation factor 1α (EF) expression in cultured Xenopus laevis thyroid glands after pituitary (Pit) co-culture for 24 h (A) or treatment with dibutyryl-cAMP (db-cAMP) and forskolin for 48 h (B). The paired thyroid glands were dissected from stage 56/57 tadpoles and preincubated for 16 h in TSH-free medium. Thereafter, glands were co-incubated with freshly dissected pituitaries (pit) from stage 58 tadpoles or treated with 2 mM db-cAMP and 10 μM forskolin. Thyroid glands incubated in the absence (Ctrl) or presence of 1 μM/ml bovine TSH served as negative and positive controls in these experiments respectively. A treatment group with 0·1% dimethylsulfoxide (DMSO) served as a solvent control for the forskolin treatment. Data are representative of two independent experiments (each containing three replicates per experimental group) respectively.
of NIS mRNA and not the functional protein, our data strongly suggest that the increases in thyroidal iodide uptake during metamorphic development, as observed in previous studies (Saxen et al. 1957, Regard 1978), are mediated at least in part by increased transcription of the NIS gene.

TSH is the primary hormonal regulator of thyroid gland function and mammalian studies have shown that most effects of TSH are mediated by modulation of thyroid-specific gene expression (Vassart & Dumont 1992, Yamazaki et al. 2003). In previous studies with amphibian tadpoles, mammalian TSH preparations have been shown to stimulate thyroid iodide uptake (Lynn & Dent 1961, Hourdry & Regard 1975) but the effects of TSH on NIS gene expression have not been examined in any amphibian species so far. We first wished to characterize the role of TSH in the developmental regulation of NIS mRNA expression during metamorphosis. Since an anti-TSH antibody to examine TSH plasma concentrations in tadpoles is not yet available for X. laevis, we determined TSHβ mRNA expression in pituitary tissue of the same tadpoles that were sampled for thyroid gland gene expression analysis. Comparison of pituitary TSHβ mRNA and thyroidal NIS mRNA expression patterns revealed a close correlation between the developmental profiles of both genes. Notably, the first induction of increased thyroidal NIS mRNA and pituitary TSHβ mRNA expression occurred at the same developmental stage (stage 54 in this study), peak expression of pituitary TSHβ mRNA (stage 58) shortly precedes the maximum expression of thyroidal NIS mRNA (stage 60), and the expression of both genes is down-regulated towards the end of the metamorphosis. Although the precise relationship between pituitary TSHβ mRNA expression and circulating TSH concentrations remains to be elucidated in X. laevis tadpoles, these data suggest a role of increased TSH synthesis and secretion in the up-regulation of NIS mRNA expression during metamorphic development.

Further support for this hypothesis was obtained from in vivo experiments involving 12-day treatment of X. laevis tadpoles with known anti-thyroidal compounds to induce hypothyroidism and goiter development. With sodium perchlorate and ETU, we selected two goitrogenic compounds that inhibit thyroid gland function via different modes of action; the perchlorate anion inhibits thyroidal iodide uptake, whereas ETU inhibits organification of iodide (Doerge & Takazawa 1990, Wolff 1998). The test concentrations for these compounds are known to severely suppress TH-dependent development, while inducing thyroid gland hyperplasia in X. laevis tadpoles (Tietge et al. 2005, Opitz et al. 2006a). In the present study, treatment of tadpoles for 12 days with sodium perchlorate and ETU induced a significantly increased expression of TSHβ mRNA in the pituitary. Further histological examination of thyroid gland sections from perchlorate- and ETU-treated tadpoles provided evidence for glandular enlargement, follicular cell hyperplasia, and hyperplasia, most likely resulting from stimulation of thyroid follicular cells by elevated TSH plasma levels. It should be noted, however, that thyroid gland histology also revealed marked differences in the follicular architecture induced by these two compounds. Irrespective of the different modes of perchlorate and ETU action on thyroid gland function, both treatments led to a marked increase in thyroidal NIS mRNA expression. Results from this experiment are, thus, in accordance with data from recent mammalian studies showing that experimental induction of goiter is associated with increased pituitary TSH expression and concomitant up-regulation of thyroidal NIS expression (Levy et al. 1997, Uyttersprot et al. 1997). Moreover, results from this study suggest that goitrogen-induced overexpression of TSH in X. laevis tadpoles provides a meaningful model to study TSH-dependent gene expression in amphibian thyroid glands in an in vivo context. In turn, the results of the present study suggest that analysis of gene expression in the thyroid gland may provide a meaningful endpoint measurement in amphibian bioassays for detection of xenobiotics with thyroid system-disrupting activities (Klos 2002, Opitz et al. 2006a, 2006b).

Using ex vivo thyroid gland culture experiments, we could demonstrate a marked up-regulation of NIS mRNA by bTSH. The effect of bTSH on NIS gene expression was rapid as NIS mRNA induction was observed already after 6 h of bTSH treatment. Moreover, in the presence of bTSH, elevated expression of NIS mRNA was maintained for up to 48 h in cultured thyroid glands. Similar temporal induction characteristics, i.e., rapid and persistent induction of NIS mRNA by TSH treatment, have recently been reported in different rat thyroid follicular cell lines (Kogai et al. 1997, Trapasso et al. 1999). In contrast, NIS induction by TSH was delayed in primary porcine thyrocytes, suggesting the existence of species-specific differences in time-courses of NIS up-regulation (Selmi-Ruby et al. 2003). The up-regulation of NIS mRNA by bTSH could be fully reproduced if thyroid glands were co-cultured with freshly dissected pituitary glands, demonstrating that pituitaries from X. laevis tadpoles secrete a bTSH-mimicking factor, which is most likely endogenous TSH. However, at present, we cannot exclude the possibility that other pituitary hormones such as gonadotropins and prolactin contribute also to the regulation of thyroid-specific gene expression (Regard 1978, Sakai et al. 1991). Another remarkable characteristic of the ex vivo thyroid gland culture model was the rapid disappearance of NIS mRNA in thyroid glands cultured in TSH-free culture medium. A similar disappearance of NIS mRNA has previously been reported for FRTL–5 cells (Kogai et al. 1997) and primary porcine thyrocytes cultured in TSH-free medium (Selmi-Ruby et al. 2003). The expression of thyroid peroxidase and thyroglobulin mRNA was much less drastically reduced during incubation of X. laevis thyroid glands in TSH-deprived medium (unpublished observations). These observations suggest that the maintenance of NIS mRNA might be more strictly dependent on the presence of TSH compared to other thyroid-specific genes, an interpretation that is also supported by recent studies on mammalian NIS expression (Marians et al. 2002). Experiments using real-time quantitative RT-PCR, as applied in other studies.
(Wagner et al. 2002), are currently in progress to further examine the kinetics of NIS mRNA down-regulation after TSH withdrawal from culture medium.

In mammalian thyroid follicular cells, cAMP-dependent activation of PKA has been shown to be the most important signaling pathway of TSH to induce changes in gene expression (Vassart & Dumont 1992, Kimura et al. 2001). The demonstration that the adenylyl cyclase agonist forskolin and the cAMP analog db-cAMP mimic the stimulatory effects of bTSH on NIS mRNA expression in X. laevis thyroid glands suggests that the cAMP-dependent control of NIS gene transcription is conserved in amphibian thyrocytes. Given the known stimulatory action of db-cAMP and forskolin on PKA activity in X. laevis tissues (Liou et al. 2001), our data on NIS mRNA expression indicate similar regulatory mechanisms in the amphibian thyroid gland compared to what has been reported in a large number of mammalian studies. However, further studies examining TSH-dependent changes in cellular cAMP content (Bidey et al. 1981) and the effects of specific inhibitors of PKA activity on NIS expression (Taki et al. 2002) will be required to confirm PKA activation and to delineate TSH-induced signaling cascades, leading to increased NIS mRNA expression in X. laevis thyrocytes. Another issue that needs to be addressed is NIS protein expression and targeting of NIS to the plasma membrane in amphibian thyroid cells.

Three thyroid-specific transcription factors, Pax8, Nkx2-1, and FoxE1, have been shown to mediate the TSH/cAMP effects on gene transcription in mammalian thyroid follicular cells (Damante et al. 2001), but very little is known about the role of thyroid-specific transcription factors in nonmammalian vertebrates (Wendt et al. 2002, Elsalini et al. 2003). Using the whole mount in situ hybridization, Nkx2-1 mRNA expression has been observed in the thyroid primordium of X. laevis embryos (Hollemann & Pieler 2000, Small et al. 2000), but expression of Nkx2-1 mRNA in thyroid glands of metamorphosing tadpoles has not been resolved. Moreover, Heller & Brändli (1999) noted that they failed to detect Pax8 mRNA expression in the region of the thyroid anlage of X. laevis embryos by whole mount in situ hybridization. Using semi-quantitative RT-PCR, we successfully detected both Nkx2-1 and Pax8 mRNA expression in the thyroid gland of X. laevis tadpoles from premetamorphic stage 51 throughout metamorphosis. It should be noted that our observation of Pax8 mRNA expression in the thyroid gland is not necessarily contradictory to the results of Heller & Brändli (1999), since the developmental stages examined in the two studies do not overlap. Moreover, results from our qualitative RT-PCR analysis of Pax8 and Nkx2-1 tissue distribution are in accordance with previous reports on restricted extrathyroidal expression domains for Pax8 (kidney) and Nkx2-1 (lung) in mammals (Damante et al. 2001) and X. laevis (Heller & Brändli 1999, Hollemann & Pieler 2000, Small et al. 2000).

Pax8 and Nkx2-1 mRNA expression increased rapidly during metamorphosis and elevated expression levels were maintained throughout metamorphosis. The temporal coincidence of elevated Pax8 and Nkx2-1 mRNA expression and increased thyroid gland activity during prometamorphosis and climax stages suggests a role for these transcription factors in the regulation of thyroid gland function as previously shown for mammalian species. The factors that stimulate the onset of increased expression of Pax8 and Nkx2-1 mRNA in the thyroid gland during the transition from pre- to prometamorphic stages are currently unknown. A primary candidate for the regulation of Pax8 mRNA expression might be TSH. In mammalian thyroid cell cultures, TSH has been shown to up-regulate Pax8 mRNA and protein expression in a cAMP-dependent manner (Fabbro et al. 1998, Mascia et al. 2002). Results from our X. laevis thyroid gland culture experiments are in line with these observations, since moderate increases in Pax8 mRNA were consistently detected after TSH treatment. Notably, in vivo treatment of tadpoles with perchlorate or ETU failed to increase thyroid gland Pax8 expression over control levels. However, taking into account the different developmental stages of the sampled test animals and the developmental expression profile observed for Pax8 during spontaneous metamorphosis, it appears that the goitrogen-treated tadpoles displayed higher levels of Pax8 mRNA expression as one would expect for their early developmental stage.

The moderate up-regulation of Nkx2-1 mRNA by TSH in our organ culture experiments would similarly indicate a role for TSH in the positive control of Nkx2-1 mRNA expression. Results from mammalian studies on TSH regulation of Nkx2-1 expression are contradictory as either no effects (Fabbro et al. 1998) or a down-regulation of Nkx2-1 expression by TSH has been reported (Saito et al. 1997b). The latter response has been suggested to contribute to a short intra-thyroidal feedback loop, fine-tuning the responsiveness of thyroid follicular cells to TSH stimulation (Suzuki et al. 1999). For the FRTL-5 cell line, a recent study by Medina et al. (2000) demonstrated that TSH effects on Nkx2-1 expression were dependent on the hormonal background of the media used for incubation, since down-regulation of Nkx2-1 by TSH required the presence of insulin in the medium. Further studies are needed to clarify the potential modulating effects of insulin supplementation on the response of Nkx2-1 expression to TSH treatment in cultured thyroid glands of X. laevis tadpoles.

In conclusion, the present study provides the first characterization of the developmental profile and hormonal regulation of NIS, Pax8 and Nkx2-1 gene expression in the amphibian thyroid gland. The developmental NIS mRNA expression profile in the thyroid gland was closely related to the plasma membrane in amphibian thyroid cells. Another issue that needs to be addressed is NIS protein expression and targeting of NIS to the plasma membrane in amphibian thyroid cells. Three thyroid-specific transcription factors, Pax8, Nkx2-1, and FoxE1, have been shown to mediate the TSH/cAMP effects on gene transcription in mammalian thyroid follicular cells (Damante et al. 2001), but very little is known about the role of thyroid-specific transcription factors in nonmammalian vertebrates (Wendt et al. 2002, Elsalini et al. 2003). Using the whole mount in situ hybridization, Nkx2-1 mRNA expression has been observed in the thyroid primordium of X. laevis embryos (Hollemann & Pieler 2000, Small et al. 2000), but expression of Nkx2-1 mRNA in thyroid glands of metamorphosing tadpoles has not been resolved. Moreover, Heller & Brändli (1999) noted that they failed to detect Pax8 mRNA expression in the region of the thyroid anlage of X. laevis embryos by whole mount in situ hybridization. Using semi-quantitative RT-PCR, we successfully detected both Nkx2-1 and Pax8 mRNA expression in the thyroid gland of X. laevis tadpoles from premetamorphic stage 51 throughout metamorphosis. It should be noted that our observation of Pax8 mRNA expression in the thyroid gland is not necessarily contradictory to the results of Heller & Brändli (1999), since the developmental stages examined in the two studies do not overlap. Moreover, results from our qualitative RT-PCR analysis of Pax8 and Nkx2-1 tissue distribution are in accordance with previous reports on restricted extrathyroidal expression domains for Pax8 (kidney) and Nkx2-1 (lung) in mammals (Damante et al. 2001) and X. laevis (Heller & Brändli 1999, Hollemann & Pieler 2000, Small et al. 2000).

Pax8 and Nkx2-1 mRNA expression increased rapidly during metamorphosis and elevated expression levels were maintained throughout metamorphosis. The temporal coincidence of elevated Pax8 and Nkx2-1 mRNA expression and increased thyroid gland activity during prometamorphosis and climax stages suggests a role for these transcription factors in the regulation of thyroid gland function as previously shown for mammalian species. The factors that stimulate the onset of increased expression of Pax8 and Nkx2-1 mRNA in the thyroid gland during the transition from pre- to prometamorphic stages are currently unknown. A primary candidate for the regulation of Pax8 mRNA expression might be TSH. In mammalian thyroid cell cultures, TSH has been shown to up-regulate Pax8 mRNA and protein expression in a cAMP-dependent manner (Fabbro et al. 1998, Mascia et al. 2002). Results from our X. laevis thyroid gland culture experiments are in line with these observations, since moderate increases in Pax8 mRNA were consistently detected after TSH treatment. Notably, in vivo treatment of tadpoles with perchlorate or ETU failed to increase thyroid gland Pax8 expression over control levels. However, taking into account the different developmental stages of the sampled test animals and the developmental expression profile observed for Pax8 during spontaneous metamorphosis, it appears that the goitrogen-treated tadpoles displayed higher levels of Pax8 mRNA expression as one would expect for their early developmental stage.

The moderate up-regulation of Nkx2-1 mRNA by TSH in our organ culture experiments would similarly indicate a role for TSH in the positive control of Nkx2-1 mRNA expression. Results from mammalian studies on TSH regulation of Nkx2-1 expression are contradictory as either no effects (Fabbro et al. 1998) or a down-regulation of Nkx2-1 expression by TSH has been reported (Saito et al. 1997b). The latter response has been suggested to contribute to a short intra-thyroidal feedback loop, fine-tuning the responsiveness of thyroid follicular cells to TSH stimulation (Suzuki et al. 1999). For the FRTL-5 cell line, a recent study by Medina et al. (2000) demonstrated that TSH effects on Nkx2-1 expression were dependent on the hormonal background of the media used for incubation, since down-regulation of Nkx2-1 by TSH required the presence of insulin in the medium. Further studies are needed to clarify the potential modulating effects of insulin supplementation on the response of Nkx2-1 expression to TSH treatment in cultured thyroid glands of X. laevis tadpoles.
TSH-dependent changes in thyroid gland gene expression in X. laevis. To this end, the results from the organ culture experiments led us to conclude that TSH, presumably acting via the cAMP–PKA pathway, is a potent stimulator of NIS mRNA expression in the amphibian thyroid gland. Based on the findings of the present study, it will be interesting to develop an antibody to X. laevis NIS in order to study the regulation of NIS expression at the protein level.

Acknowledgements

This study was supported by the German Federal Environmental Agency under contract no. 204 67 454. The authors thank G Adam and M Simon for help with performing the histological analyses and Prof. J Köhle for critical comments on an earlier draft of the manuscript. The authors declare that there is no conflict of interest that would prejudice the impartiality of this scientific work.

References


Mariani RS, Nig L, Blair HC, Unger P, Groves PN & Davies TF 2002 Defining thyrotropin-dependent and -independent steps of thyroid hormone synthesis by using thyrotropin receptor-null mice. PNAS 99 15776–15781.


sodium/iodide symporter gene and participates in both thyroid-specific and cyclic-AMP-dependent transcription. Molecular and Cellular Biology 19 2051–2060.


Pohljen J & RefettoFS 1999 Mutations in the sodium/iodide symporter (NIS) gene as a cause for iodide transport defects and congenital hypothyroidism. Biochimica 81 469–476.

Regard E 1978 Cytophysiology of the amphibian thyroid gland through larval development and metamorphosis. International Review of Cytology 52 81–118.


Yen PM 2001 Physiological and molecular basis of thyroid hormone action. Physiological Reviews 81 1097–1142.

Received in final form 27 March 2006
Accepted 29 March 2006
Made available online as an Accepted Preprint
25 April 2006