Female-enriched and thermosensitive expression of steroidogenic factor-1 during gonadal differentiation in *Pleurodeles waltl*

S Kuntz, D Chardard, C-I Ko, H Dumond, M Ducatez, M Callier, S Flament and A Chesnel

EA 3442: Aspects Cellulaires et Moléculaires de la Reproduction et du Développement, Université Henri Poincaré-Nancy 1, Faculté des Sciences, BP239, Boulevard des Aiguillettes, 54506 Vandœuvre les nancy CEDEX, France

(Requests for offprints should be addressed to S Flament; Email: Stephane.Flament@scbiol.uhp-nancy.fr)

Abstract

In the urodele amphibian *Pleurodeles waltl*, sex differentiation is genetically controlled, that is, ZZ male vs ZW female, but may be influenced in other species, such as the interrenal tissue in amphibians (Mayer et al. 2002) as well as brain and gonad (Val et al. 2003). SF-1 plays a key role in the development of both the hypothalamic-pituitary-adrenal and hypothalamic-pituitary-gonadal axes (Ikeda et al. 1993), since mice with a SF-1 gene homozygous disruption show complete adrenal and gonadal agenesis and ventromedial hypothalamus dysgenesis (Luo et al. 1994, Ikeda et al. 1995, Shinoda et al. 1995). A failure of gonad and adrenal development has also been detected in a human case of male-to-female sex reversal exhibiting a heterozygote mutation in the SF-1 gene (Achermann et al. 1999). Furthermore, the SF-1(+/−) XY mice have a female phenotype (Luo et al. 1994). These results agree with an early expression of SF-1 in the genetic ridges of both sexes throughout the undifferentiated stage (Ikeda et al. 1994), leading to adrenal formation and gonadal differentiation (Schnabel et al. 2003). At a later stage of development, as histologic sex differentiation of the gonad begins, several vertebrate species exhibit a sexually dimorphic gonadal expression of SF-1 in their developing gonads. A higher level of SF-1 mRNA is found in the male differentiating gonad in mouse (Ikeda et al. 1994), rat (Hatano et al. 1994), man (Hanley et al. 2000), pig (Pilon et al. 1998) and turtle (Wibbels et al. 1998), whereas an opposite situation is observed in chicken (Smith et al. 1999), alligator (Western et al. 2000) and American bullfrog (Mayer et al. 2002). In mammals, SF-1 controls the expression of many enzymes required for steroid hormone production, including aromatase (Parker & Schimmer 2002). For instance, in rat and man, SF-1 binds to the aromatase promoter and activates its transcription (Lynch et al. 1993, Michael et al. 1995). SF-1-binding sites have also

Introduction

The steroidogenic factor-1 gene (SF-1) encodes a nuclear orphan receptor belonging to the nuclear receptor superfamily (Lala et al. 1992, Whitfield et al. 1999). In various species, SF-1 is known to be expressed in several tissues involved in steroidogenesis and/or reproduction, such as the adrenal glands in mammals and corresponding organs in other species, such as the interrenal tissue in amphibians (Mayer et al. 2002) as well as brain and gonad (Val et al. 2003). SF-1 plays a key role in the development of both the hypothalamic-pituitary-adrenal and hypothalamic-pituitary-gonadal axes (Ikeda et al. 1993), since mice with a SF-1 gene homozygous disruption show complete adrenal and gonadal agenesis and ventromedial hypothalamus dysgenesis (Luo et al. 1994, Ikeda et al. 1995, Shinoda et al. 1995). A failure of gonad and adrenal development has also been detected in a human case of male-to-female sex reversal exhibiting a heterozygote mutation in the SF-1 gene (Achermann et al. 1999). Furthermore, the SF-1(+/−) XY
been identified in the promoter region of aromatase gene in chicken (Kudo et al. 1996), Xenopus (Akatsuka et al. 2005), and many teleost fishes (Tanaka et al. 1995, Tong & Chung 2003, Yoshiura et al. 2003, Gardner et al. 2005). Alternatively, estrogen could also control SF-1 transcription, as suggested in the red-eared slider turtle model (Fleming & Crews 2001), in which estradiol treatment was shown to produce SF-1 upregulation, although it was not proved that the effect was direct or indirect.

In the urodele amphibian Pleurodeles walti, steroid hormones play a role in sex differentiation since the application of estradiol to the rearing water during a hormone-sensitive period induces ZZ genetic male larvae to differentiate into functional neofemales (Gallien 1951). Moreover, a similar treatment performed with an aromatase inhibitor can induce a complete female-to-male sex reversal (Chardard & Dournon 1999), demonstrating that the aromatase enzymatic complex plays a very important part in the process of female differentiation (Kuntz et al. 2003a). Indeed, aromatase activity measurements in gonad revealed up to 40-fold higher activity in ZW larvae than in their ZZ counterparts at the onset of ovarian differentiation (Chardard et al. 1995). However, the gonadal level of endogenous aromatase transcripts in ZW larvae was only 1.5-fold higher than in ZZ, suggesting the involvement of an unknown post-transcriptional regulation (Kuntz et al. 2003b).

Temperature can also interfere with the ZZ/ZW genetic sex determination and sex ratio, since ZW larvae reared at 32 °C during the thermosensitive period (TSP) differentiate into functional neomasculine (Dournon & Houillon 1984). The masculinizing temperature was shown to inhibit aromatase activity (Chardard et al. 1995) and could act as a direct or indirect repressor of estrogen synthesis, since estradiol benzoate can counteract the masculinizing effect of a high rearing temperature (Zaborski 1986).

Since the aromatase gene is differentially expressed during sexual differentiation and considering that this expression can be indirectly affected by temperature, we focused our attention on SF-1, a known potential regulator of aromatase. We first isolated SF-1 cDNA containing a putative open reading frame. Expression analysis during gonadal development of ZZ and ZW larvae revealed the presence of SF-1 mRNA early during the TSP in the gonad–mesonephros-interrenal complex (GMI), either when aromatase mRNA is present in low amounts in the undifferentiated gonad (Gd) or at the time of aromatase expression increase in ZW larvae. A transient, female-specific upregulation of SF-1 expression was observed at the end of TSP, not only in Gd but also in the mesonephros-interrenal (MI), suggesting a role of SF-1 in the differentiating ovary and in mesonephric or interrenal steroid synthesis. Amounts of SF-1 mRNAs were significantly decreased in ZW larvae subjected to long-term sex-reversing heat treatment, in either Gd or MI, but not in the brain. However, these changes in SF-1 gene expression, rather than being directly regulated by temperature during the TSP, seem to be related to changes in aromatase mRNA expression and activity leading to low estrogen levels. Indeed, estradiol benzoate treatments of ZZ larvae clearly induce upregulation of SF-1 mRNA expression. Therefore, SF-1 does not appear to be directly involved in temperature-dependent sex-reversal in Pleurodeles.

Materials and methods

Animals

Adult P. walti were reared in fresh water at a controlled temperature of 20 ± 2 °C in our laboratory (standard ZW and ZZ20). The ZW or ZZ, sexual genotype was determined by electrophoretic patterning of the two W- and/or Z-linked peptidase-1 isozymes, as described previously (Chardard et al. 1995). Developmental stages were determined by macroscopic observation according to Gallien and Durocher (1957). Stage 55 lasts about 2 months and was chronologically subdivided into stage 55, stage 55+15 days (5515d) and stage 55+30 days (5530d). The TSP from stage 42 to 54 is defined as the period while ZW larvae must be reared at 32 °C in order to obtain 100% sex reversal (Dournon & Houillon 1984). Heat treatment of ZW larvae was run at 32 °C (ZW32) during the TSP while other ZW or ZZ larvae were maintained at 20 ± 2 °C as a control (ZW20, ZZ20). Heat shocks of 32 °C were applied to ZW larvae (ZWbas) for 48 h at stages 55 and 55+30d. Hormonal treatment was run by rearing ZZ larvae at stages 55 and 55+30d for 48 h in fresh water containing estradiol benzoate (100 µg/l). Before dissection, animals were anesthetized in a solution of benzocaine (0.03%), and the brain, Gd, MI or GMI was dissected for further analysis. Due to their small size, Gd could not be isolated from the MI before stage 5515d.

SF-1 cDNA isolation

Total RNA (1 µg) from adult testis was reverse transcribed with oligo(dT18) primers and Superscript II reverse transcriptase (Invitrogen). An aliquot of the reaction was amplified by PCR with the degenerated primers SF1, SF2 and SF4 (Table 1). The amplification was performed in the presence of 0·1 unit Taq DNA polymerase (Invitrogen) in PCR buffer containing 25 mM of each dNTP and 3·5 mM MgCl2. A 60 °C to 40 °C touchdown PCR program was run at 94 °C for 3 min followed by 20 cycles at 94 °C for 1 min, annealing for 1 min and 72 °C for 1 min. Amplification was then

www.endocrinology-journals.org
pursued with 30 cycles at 94 °C for 1 min, 40 °C for 1 min and 72 °C for 1 min. Two independent PCR products of 657 and 800 bp were obtained by using two different sets of primers, Sf2/Sf4 and Sf1/Sfδ respectively (Table 1). After separation on agarose gel electrophoresis, the expected fragments were purified, inserted into the plasmid pCR2 (Invitrogen) and transfected in E. coli INVα strain (Invitrogen), and both were sequenced (Genome Express, Meylan, France).

The 5’ and 3’ rapid amplification of cDNA ends (RACE) system (SMART RACE cDNA amplification kit; Clontech) was used to amplify the 5’-end and 3’-end of SF-1 cDNA synthesized from 1 µg total RNA isolated from adult testis according to the manufacturer’s instructions. PCR was performed with 1 unit Taq DNA polymerase (Advantage 2 Polymerase Mix; Clontech) and specific primer for each amplification in the 5’-end and 3’-end regions (Sf1–5R and Sf1–3R respectively) (Table 1). The reaction mixture was heated at 94 °C for 3 min and amplified for the first five cycles as follows: 94 °C for 30 s and 72 °C for 3 min. The next five cycles were 94 °C for 30 s, 70 °C for 30 s and 72 °C for 3 min. The remaining 30 cycles of PCR were carried out at 94 °C for 30 s, 68 °C for 30 s and 72 °C for 3 min, with a final extension at 72 °C for 10 min. Two fragments of 0.9 and 1.2 kb, isolated from the 5’ and 3’ regions respectively, were purified (QiaEX II Kit; Qiagen), inserted into the plasmid pGEM-T Easy (Promega), transfected into E. coli TG1 strain and sequenced (Genome Express).

### Table 1 List of PCR primers used

<table>
<thead>
<tr>
<th>Gene(*)</th>
<th>Name</th>
<th>Primer sequence</th>
</tr>
</thead>
<tbody>
<tr>
<td>SF-1</td>
<td>Sf1</td>
<td>5'-TGYAARGGTTTYYAARMGIACT-3'</td>
</tr>
<tr>
<td>SF-1</td>
<td>Sf2</td>
<td>5'-AARTTYYGICCIATGTAYAA-3'</td>
</tr>
<tr>
<td>SF-1</td>
<td>Sf4</td>
<td>5'-TCISWCCARCATTTYG-3'</td>
</tr>
<tr>
<td>SF-1</td>
<td>Sf1-5R</td>
<td>5'-CTGTCGCGCCATCTTGCACTAGGCC-3'</td>
</tr>
<tr>
<td>SF-1</td>
<td>Sf1-3R</td>
<td>5'-CTGAAGCCTGTCGAGCAGAG-3'</td>
</tr>
<tr>
<td>SF-1</td>
<td>Sf1-1</td>
<td>5'-GGTTACACCTAACCACCTT-3'</td>
</tr>
<tr>
<td>SF-1</td>
<td>Sf1-5</td>
<td>5'-TCTTGGGCTGTAGCAGGG-3'</td>
</tr>
<tr>
<td>Aromatase</td>
<td>Arom-1</td>
<td>5'-ATTCAGGCACCTGACAGAT-3'</td>
</tr>
<tr>
<td>Aromatase</td>
<td>Arom-6</td>
<td>5'-TTGGTGCTGATGCTTCTCAA-3'</td>
</tr>
<tr>
<td>GAPDH</td>
<td>fwd</td>
<td>5'-ACTCAAAAGGACTAGTCCAGG-3'</td>
</tr>
<tr>
<td>GAPDH</td>
<td>rev</td>
<td>5'-CCGTTATTGCACTCAACGACC-3'</td>
</tr>
</tbody>
</table>

(*) Aromatase and GAPDH primers were used as a control in RT–PCR analysis of SF-1 expression.

Reverse transcription–polymerase chain reaction (RT–PCR) analyses

The detailed protocol for RT has been previously described (Kuntz et al. 2003b). Total RNA was extracted from dissected tissues with TRIzol reagent (Invitrogen) and quantified (BioPhotometer; Eppendorf, Le Pecq, France). Total RNA (1 µg) was reverse transcribed with random hexanucleotide primers and 100 units MMLV reverse transcriptase in a total volume of 25 µl. A 2 µl aliquot of resultant cDNA was PCR amplified with 0·1 unit of Taq DNA Polymerase (Invitrogen) in PCR buffer containing 25 mM of each dNTP, 2·5 mM MgCl2 and 0·4 pM of each primer in a total volume of 25 µl. RT–PCR analyses were performed on ‘n’ samples (n is given in figures and tables), each sample comprising a pool of four or five individuals. Specific primers for P. walli were Sf1–1 and Sf1–5, leading to a PCR product of 462 bp in length. The specific primers for the aromatase cDNA were Arom-1 and Arom-6, and the resulting PCR product was 510 bp in length. All the PCR products encompassed one exon/intron boundary based on other vertebrate gene alignments (not shown). To ensure that the RNA was not degraded and to prevent poor transcription quality, GAPDH cDNA was used as a control (see primer sequence in Table 1). The PCR conditions were 30-s denaturation at 94 °C, and 30-s annealing and 2-min elongation at 72 °C, and led to a 290 bp fragment. Annealing temperatures were 52 °C for GAPDH and aromatase primers, and 60 °C for SF-1 primers. We performed 35 cycles for qualitative analyses and 26 or 28 cycles for semiquantitative analyses in Gd and brain respectively. PCR products were then separated in a 1% agarose gel and transferred to nylon membrane (Hybond-N, Amersham) before hybridization with DIG-labeled probes and detection by chemiluminescence under previously described conditions (Kuntz et al. 2003b). Semiquantitative RT–PCR analysis was performed by running 28 or 30 PCR cycles for mRNA from Gd or MI respectively. PCR products were separated in agarose gel and compared with GAPDH level. In all cases, amplification was verified to take place in the linear phase of the PCR, and the intensity of the hybridization signal or agarose gel band was normalized to GAPDH by using the GelDoc 2000 (Bio-Rad) and a software package (Quantity One v. 4.3.1; Bio-Rad).
Statistical analysis
The relative intensities of SF-1 and aromatase mRNAs were compared after normalization to GAPDH mRNA levels. The results are expressed as mean ± S.E.M. of several measurements performed on different pools for each group, as indicated in the text. The variation of relative SF-1 mRNA expression between sexes (ZZ20 and ZW20 groups) was analyzed by comparison of means with Student’s t-test. The statistical significance of SF-1 and aromatase mRNA expression regarding to temperature (ZW32 or ZWhs and ZW20 groups) was estimated by comparing means of the relative SF-1 and aromatase mRNA expression from each group by analysis of variance (one-way ANOVA) followed by the Bonferroni multiple comparison procedure with SPSS 11.5 software (SPSS Inc., Chicago, IL, USA).

Results
SF-1 is conserved in P. waltl

Pleurodeles SF-1 cDNA sequence (accession no. AY540336, not shown) was obtained by RT–PCR from total RNA extracted from adult testes. Two independent clones of 657 and 800 bp were obtained by degenerated PCR, using different set of primers (Table 1). Then, 5′ and 3′ RACE was performed in order to isolate the full-length SF-1 mRNA containing a putative 1407 bp open reading frame. The deduced amino-acid sequence was compared with SF-1 sequences from several species: Rana rugosa, Trachenys scripta, chicken, mouse and man (Fig. 1). The putative encoded polypeptide is composed of 468 amino acids and is related to that of R. rugosa although slightly longer than that of T. scripta (466 residues), mouse (462 residues) and man (461 residues). Overall sequence identity with T. scripta was 81%, with R. rugosa 79%, and with mouse and man 63% (Fig. 1). The conserved regions were identified by comparison with the corresponding regions in other species: the first and second zinc fingers corresponding to the DNA binding domain (residues 13–78), the Ad4 BP/SF-1 box (residues 79–106), region II (residues 274–315), region III (residues 364–387) and the AF-2 domain (residues 458–463). The identity rate of each functional domain in SF-1 was also examined. In contrast to the second zinc finger, the first one is highly conserved between species, except for P. waltl, which exhibits a single 15-valine-to-alanine amino-acid substitution. Nevertheless, the Pbox ESCKG localized in the first zinc finger was conserved in our model. SF-1 box, region II and region III present also a high degree of identity among most species (75–100%) while the AF-2 motif, essential for transcriptional activation, is entirely conserved. A proline stretch of 7–8 consecutive amino acids is present in the mammalian SF-1 but absent in chicken, turtle, frog and Pleurodeles.

SF-1 is expressed during early gonadal development
The SF-1 mRNA expression pattern in the urogenital system of Pleurodeles larvae during the TSP was examined. Qualitative RT–PCR analysis in GMI from ZZ20, ZW20 and ZW32 larvae selected at different stages of their development showed that SF-1 is expressed early in the three types of larvae: SF-1 mRNAs are detected since stage 42, and their expression is maintained thereafter in a sex-independent manner through the whole TSP that ends at stage 54 (Fig. 2). Thus, SF-1 expression occurs before gonadal differentiation, which can be assessed at stage 53 by histologic examination. Besides, temperature appeared to have no silencing effect on SF-1 during this period of development.

Sex- and tissue-specificity of SF-1 expression during gonadal differentiation
SF-1 mRNA expressions were then compared by semiquantitative RT–PCR analyses performed from total RNA isolated either from GMI at stages 54 and 55, or from isolated Gd and MI taken at various subsets of stage 55 during which metamorphosis proceeds, and at stage 56 at which animals are metamorphosed (Table 2). The results were compared with those obtained in brain, another important, steroid-producing organ.

At stage 54, no significant difference could be detected between GMI from ZW20 and ZZ20 larvae. Then, SF-1 expression in GMI was higher in ZW20 individuals with a 2.14-fold higher mRNA level at the beginning of stage 55. After this stage, the Gd was big enough to allow their dissection and their study independently of MI. We observed the expression of SF-1 to be higher in the ovary at stages 5515d (1.55-fold) and 5530d (1.19-fold). This female-enriched expression was transient, since, at stage 56, there was no significant difference between ZW20 and ZZ20 animals. Surprisingly, a high SF-1 expression was observed in female MI at stage 5515d (2.13-fold), whereas no significant difference was found at stages 5515d and 56. In the brain of ZW20 larvae, SF-1 mRNA level observed inside and outside TSP, that is, at stages 54 and 5515d respectively, was not significantly different from those in ZZ20 ones.

Tissue-specific inhibition of SF-1 expression after long-term heat treatment
In order to test whether SF-1 mRNA expression is regulated by temperature, the SF-1 mRNA level in ZW32 larvae was compared with those measured in ZW20 ones in Gd, MI, GMI and brain as before.
Figure 1 Alignment of the amino-acid sequences of SF-1 cDNAs from several vertebrate species. Amino-acid identity with *Pleurodeles* sequence is shown in gray. The conserved regions, zinc finger I, zinc finger II, Ad4BP (Ad4 binding protein)/SF-1 box, region II, region III and AF-2, are framed. The mammalian proline stretch is in boldface.
At stage 54, no difference in SF-1 mRNA level was detected in GMI between ZW 32 and ZW 20 larvae, whereas at stage 5515d, a reduced expression (1·6-fold) was observed (Table 3). In Gd of larvae at the same stage (5515d), a higher difference was observed between heat-treated larvae and controls, heat treatment leading to a 3·7-fold lower expression of SF-1. The inhibitory effect of heat treatment on gonadal SF-1 expression was confirmed at stage 5530d (2·2-fold lower SF-1 mRNA level). Interestingly, at this stage, a similar situation was observed in MI: there was a 3·4-fold lower expression of SF-1 in this organ in ZW32 larvae. Therefore, heat treatment performed from stage 42 to 54 affects SF-1 expression not only in Gd but also in MI. Besides, this effect appears late, after the end of the TSP. In the brain, SF-1 transcription is not temperature-sensitive either during the TSP (stage 54) or after the end of TSP (stage 5515d).

**Gonadal SF-1 expression is not inhibited by 48-h heat shock**

The inhibition of SF-1 expression described above is observed after sex-reversing heat treatment is completed, suggesting that temperature does not act directly on SF-1 expression. In order to get more information about the relationship between temperature and SF-1 expression, a 48-h 32 °C heat shock was applied to ZW larvae.
then, aromatase and SF-1 mRNA levels were measured and compared with those in ZW20 larvae in GMI at stage 55 and in Gd or MI at stage 5530d (Fig. 3). As previously described (Kuntz et al. 2003b), aromatase was absent from MI (not shown), and its expression in Gd was insensitive to heat shock when applied after the TSP (Fig. 3A). Conversely, SF-1 mRNA level (Fig. 3B) is slightly reduced under heat shock in GMI at early stage 55 (1·2-fold; \( P = 0·355 \)) and in MI at stage 55 30d (1·34-fold; \( P = 0·127 \)), but not in the isolated Gd at stage 5530d, wherein it appears to be significantly upregulated (1·18-fold; \( P = 0·026 \)). This result suggests that *Pleurodeles* SF-1 is not directly downregulated by temperature. Rather, raising temperature can increase SF-1 mRNA level, at least at stage 5530d, by an unknown tissue-dependent mechanism.

**Estrogen sensitivity of SF-1 expression after the end of the TSP**

The female-enriched expression of SF-1 occurs after the female-specific increase in aromatase expression. Besides, a decreased SF-1 expression is observed after long-term heat treatment, which is known to

### Table 2 ZW\(^{20}\)/ZZ\(^{20}\) SF-1 mRNA expression ratio in gonad and/or mesonephros-interrenal and brain

<table>
<thead>
<tr>
<th>Stage of larval development(^{(2)})</th>
<th>GMI(^{(3)})</th>
<th>Gonad</th>
<th>Mesonephros-interrenal</th>
<th>Brain</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stage 54</td>
<td>0·78(^{(4)})</td>
<td>ND(^{(5)})</td>
<td>ND</td>
<td>0·95</td>
</tr>
<tr>
<td></td>
<td>( P = 0·434^{(6)} )</td>
<td></td>
<td>( P = 0·671 )</td>
<td></td>
</tr>
<tr>
<td></td>
<td>( n (ZW^{20}) = 5 ; n (ZZ^{20}) = 6 )</td>
<td></td>
<td>( n (ZW^{20}) = 5 ; n (ZZ^{20}) = 6 )</td>
<td></td>
</tr>
<tr>
<td>Stage 55(^{15d})</td>
<td>2·14 ( P = 0·001 )</td>
<td>ND</td>
<td>ND</td>
<td></td>
</tr>
<tr>
<td></td>
<td>( n (ZW^{20}) = 6 ; n (ZZ^{20}) = 5 )</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Stage 55(^{30d})</td>
<td>ND</td>
<td>1·55 ( P = 0·021 )</td>
<td>1·29 ( P = 0·123 )</td>
<td>0·91</td>
</tr>
<tr>
<td></td>
<td>( n (ZW^{20}) = 4 ; n (ZZ^{20}) = 5 )</td>
<td>( n (ZW^{20}) = 4 ; n (ZZ^{20}) = 5 )</td>
<td>( n (ZW^{20}) = 4 ; n (ZZ^{20}) = 4 )</td>
<td></td>
</tr>
<tr>
<td>Stage 56</td>
<td>ND</td>
<td>2·15 ( P = 0·022 )</td>
<td>2·15 ( P = 0·003 )</td>
<td>ND</td>
</tr>
<tr>
<td></td>
<td>( n (ZW^{20}) = 4 ; n (ZZ^{20}) = 4 )</td>
<td>( n (ZW^{20}) = 4 ; n (ZZ^{20}) = 4 )</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>0·98 ( P = 0·956 )</td>
<td>1·03 ( P = 0·890 )</td>
<td>ND</td>
<td></td>
</tr>
<tr>
<td></td>
<td>( n (ZW^{20}) = 6 ; n (ZZ^{20}) = 6 )</td>
<td>( n (ZW^{20}) = 6 ; n (ZZ^{20}) = 6 )</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

(1) SF-1 mRNA/GAPDH mRNA expression ratio measured in ZW\(^{20}\) larvae and divided by those measured in ZZ\(^{20}\) larvae. (2) More details about developmental stages are in Materials and methods. (3) Gonad and mesonephros-interrenal attached (see Materials and methods). (4) Significant values (\( P \leq 0·05 \)) are in bold face. (5) Not determined. (6) The mean of relative SF-1 mRNA level from each group, \( n (ZW^{20}) \) and \( n (ZZ^{20}) \), was compared (Student’s \( t \)-test).

### Table 3 ZW\(^{32}\)/ZW\(^{20}\) SF-1 mRNA expression ratio in gonad and/or mesonephros-interrenal and brain

<table>
<thead>
<tr>
<th>Stage of larval development(^{(2)})</th>
<th>GMI(^{(3)})</th>
<th>Gonad</th>
<th>Mesonephros-interrenal</th>
<th>Brain</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stage 54</td>
<td>1·33(^{(4)})</td>
<td>ND(^{(5)})</td>
<td>ND</td>
<td>0·95</td>
</tr>
<tr>
<td></td>
<td>( P = 0·954^{(6)} )</td>
<td></td>
<td>( P &gt; 0·999 )</td>
<td></td>
</tr>
<tr>
<td></td>
<td>( n (ZW^{32}) = 4 ; n (ZW^{20}) = 5 )</td>
<td></td>
<td>( n (ZW^{32}) = 4 ; n (ZW^{20}) = 4 )</td>
<td></td>
</tr>
<tr>
<td>Stage 55(^{15d})</td>
<td>0·61 ( P = 0·008 )</td>
<td>0·27 ( P = 0·001 )</td>
<td>0·27 ( P = 0·001 )</td>
<td>1·08</td>
</tr>
<tr>
<td></td>
<td>( n (ZW^{32}) = 4 ; n (ZW^{20}) = 5 )</td>
<td>( n (ZW^{32}) = 3 ; n (ZW^{20}) = 4 )</td>
<td>( n (ZW^{32}) = 4 ; n (ZW^{20}) = 4 )</td>
<td></td>
</tr>
<tr>
<td>Stage 55(^{30d})</td>
<td>ND</td>
<td>0·45 ( P &gt; 0·001 )</td>
<td>2·9 ( P &gt; 0·001 )</td>
<td>ND</td>
</tr>
<tr>
<td></td>
<td>( n (ZW^{32}) = 4 ; n (ZW^{20}) = 4 )</td>
<td>( n (ZW^{32}) = 4 ; n (ZW^{20}) = 4 )</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

(1) SF-1 mRNA/GAPDH mRNA expression ratio measured in ZW\(^{32}\) larvae and divided by those measured in ZW\(^{20}\) larvae. (2) More details about developmental stages are in Materials and methods. (3) Gonad and mesonephros-interrenal attached (see Materials and methods). (4) Significant values are in bold face. (5) Not determined. (6) The mean of relative SF-1 mRNA level from each group, \( n (ZW^{32}) \) and \( n (ZW^{20}) \), was compared (ANOVA followed by Bonferroni test).
downregulate aromatase expression in ZW larvae. These results strongly suggest a relationship between estrogens and SF-1 expression in *Pleurodeles*. To test this hypothesis, we performed 48-h estrogen treatments of ZZ larvae (ZZE2). The mRNA expression of both aromatase and SF-1 was compared with those in ZW20 and ZZ20 larvae in GMI at stage 55 and in Gd or MI at stage 55+30d (Fig. 4). We confirmed our previous studies showing the absence of aromatase expression in MI (Kuntz et al. 2003b). In Gd, we observed aromatase mRNA expression to be increased in ZZE2 versus ZZ20 larvae (2·1-fold; $P=0·003$) when estradiol benzoate was applied at stage 55 (Fig. 4A). Such a sensitivity was not observed when the hormonal treatment was performed at stage 55+30d. As observed for aromatase, SF-1 mRNA expression was upregulated in GMI (2·4-fold; $P=0·002$) when estradiol benzoate was applied at stage 55 (Fig. 4B). When the treatment was performed at stage 55+30d, such an increase was not observed in Gd, while a significant difference was still observed in MI between ZZ20 and ZZE2 larvae (1·8-fold; $P=0·008$). Moreover, in all cases shown in Fig. 4, the SF-1 mRNA level in ZZE2 larvae was not significantly different from that in ZW20 ones. Taken together, these results suggest that mesonephric and/or interrenal SF-1 expression can be increased by circulating estrogens after gonadal differentiation, that is, after the ovarian rise in the level of aromatase expression and activity.

Discussion

Little is known about SF-1 in amphibians, and its involvement in the regulation of steroid hormone synthesis has still to be demonstrated in *P. wallii*. Whether SF-1 is involved in the transcriptional regulation of aromatase in *P. wallii* is one of the questions we address here. This work was also performed in order to

---

**Figure 3** Heat-shock analysis of SF-1 and aromatase mRNA level in gonad (Gd), mesonephros-interrenal (MI) and gonad-mesonephros-interrenal complex (GMI). Expression during early sexual differentiation (stages 55 and 55+30d) was measured in ZW20 and compared with those in ZW larvae submitted to a 48-h 32 °C heat shock (ZWhs). Total RNA from a pool of four or five larvae was reversed transcribed and amplified by PCR for 28 cycles. PCR products were agarose gel fractionated, and relative amounts of aromatase (A) and SF-1 (B) mRNAs were normalized to GAPDH mRNA level. Values are means of four or six replicates: the number of pools is indicated by ‘$n$’. Vertical bars indicate the mean standard error. To calculate the $P$ value, the mean of relative SF-1 mRNA level from each group, $n$ (ZWhs) and $n$ (ZW20), was compared (ANOVA followed by the Bonferroni test). *$P<0·05$ vs ZW20.

**Table 1** Summary of the effects of estradiol benzoate on the expression of aromatase (A) and SF-1 (B) mRNAs in Gd, MI and GMI at stage 55, and ZW20 and ZWhs.

<table>
<thead>
<tr>
<th>Stage</th>
<th>Aromatase</th>
<th>SF-1</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stage 55</td>
<td>2·1-fold</td>
<td>2·4-fold</td>
</tr>
<tr>
<td>Stage 55+30d</td>
<td>Non-significant</td>
<td>Non-significant</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Stage 55</th>
<th>ZW20</th>
<th>ZWhs</th>
</tr>
</thead>
<tbody>
<tr>
<td>ZW20</td>
<td>1·8-fold</td>
<td></td>
</tr>
<tr>
<td>ZWhs</td>
<td>Non-significant</td>
<td></td>
</tr>
</tbody>
</table>
determine whether SF-1 could itself constitute an upstream target of the masculinizing temperature which leads to downregulation of aromatase expression (Kuntz et al. 2003b).

We first cloned from adult testis *Pleurodeles* SF-1 cDNA containing an open reading frame that could encode a protein of 468 amino acids. Sequence identity of the deduced protein compared with polypeptides found in other vertebrates showed a high homology, ranging from 81% in *T. scripta* to 63% in man and mouse. As expected, the regions that correspond to known functional domains in the nuclear receptor family showed higher amino-acid identity than for the protein as a whole. These results suggest that biologic SF-1 function can be conserved in *Pleurodeles* species.

SF-1 was described as a transcription factor expressed in several tissues involved in reproduction and/or steroidogenesis and is currently detected in brain, testis, ovary, and interrenal or adrenal tissue in mouse, chicken, *T. scripta* and frog (Ingraham et al. 1994, Kawano et al. 1998, Fleming et al. 1999, Smith et al. 1999, Mayer et al. 2002). As in other species, *Pleurodeles* SF-1 transcripts were detected in all adult steroidogenic tissues (Kuntz et al. 2004a) as well as in spleen, as

---

**Figure 4** Effect of estradiol benzoate on aromatase and SF-1 mRNA level in gonad (Gd), mesonephros-interrenal (MI) and gonad-mesonephros-interrenal complex (GMI). Total RNA was extracted from ZZ larvae reared in 100 µg/l estradiol benzoate for 48 h (ZZE2) at stages 55 and 55°d. (A) As a control, aromatase mRNA expression, absent in MI, is shown in GMI and Gd. (B) RT–PCR analysis of SF-1 expression was examined in the conditions described in Fig. 3. Amounts of SF-1 and aromatase mRNAs were normalized to GAPDH mRNA level, and values were analyzed as described in Fig. 3 by comparing the mean of relative mRNA level of the two groups: n(ZZ20) and n(ZZE2).
observed in *R. rugosa* (Kawano *et al.* 1998), and, surprisingly, in lung, where aromatase activity is also present (Kuntz *et al.* 2004a). These results suggest a role for SF-1 in the steroid hormone synthesis pathway, as in chicken (Kudo *et al.* 1996), and *Xenopus* (Akatsuka *et al.* 2005) and teleost (Gardner *et al.* 2005) species, where SF-1 consensus binding sites are conserved in aromatase 5'-flanking region. However, *Pleurodeles* SF-1 cis-acting targets in the aromatase gene promoter remain to be discovered.

Then we examined *P. wallii* SF-1 expression during sexual differentiation. Qualitative expression analysis revealed the presence of an SF-1 transcriptional activity as early as stage 42, in ZZ$^{20}$ and ZW$^{20}$ or ZW$^{32}$, and this sex- and temperature-independent signal was observed at all stages of the TSP. This result is consistent with those obtained in mouse, where SF-1 transcripts are present in the undifferentiated urogenital ridge in both sexes before the onset of *Sry* expression (Ikeda *et al.* 1993). Such a gonadal expression pattern, prior to sexual differentiation, is also observed in chicken (Smith *et al.* 1999), turtle (*T. scripta*) (Fleming *et al.* 1999), alligator (Western *et al.* 2000) and frog (*R. catesbeiana*) (Mayer *et al.* 2002). This early presence of SF-1 mRNA in *Pleurodeles* GMI is correlated with its role in the first differentiation steps of the two primary steroidogenic organs: the Gd and interrenal tissue, as demonstrated in other species (Luo *et al.* 1994). Furthermore, gonadal SF-1 expression occurs before expression of its steroidogenic target genes (Parker & Schimmer 2002). However, the question of whether SF-1 is expressed during the TSP in Gd, MI or both in *P. wallii* awaits an answer from in situ hybridization studies. Such histologic investigations would also determine whether SF-1 expression and activity are localized in aromatase-producing cells.

After the onset of gonadal sex differentiation, the SF-1 expression pattern becomes sexually dimorphic among species. In mouse embryos, SF-1 expression persists during testicular differentiation, but it declines during ovarian differentiation (Ikeda *et al.* 1994). A similar pattern was found in other mammals (Hatano *et al.* 1994, Pilon *et al.* 1998, Hanley *et al.* 2000) and in turtle (*T. scripta*) (Fleming *et al.* 1999), but not in chicken (Smith *et al.* 1999), alligator (Western *et al.* 2000), frog (*R. catesbeiana*) (Mayer *et al.* 2002) or *P. wallii*. In the last mentioned, our semiquantitative analysis showed a transient increase of the SF-1 transcript level in the ovary after the beginning of its differentiation. This sexually dimorphic expression was detected at stages 55$^{15d}$ and 55$^{30d}$, which develop after the first evidence of histologic sex differentiation that takes place at stage 53. The female-enriched expression was higher at stage 55$^{15d}$ than at stage 55$^{30d}$, whereas no significant difference was observed at stage 56. The ovarian specific increase in SF-1 expression could appear as early as stage 55, since a 2·14-fold higher expression was detected in GMI at this stage. However, since at this stage as well as earlier ones, we could not separate Gd from MI, and since both tissues express SF-1, this hypothesis cannot be validated. Surprisingly, in MI, a similar transient increase in SF-1 expression in ZW$^{20}$ larvae was observed, but it appeared at stage 55$^{30d}$, that is, later than in Gd. The delay observed for the maximum SF-1 expression in MI suggests that the SF-1 gene may be more directly activated in Gd, where aromatase is expressed, than in MI, where aromatase is not transcribed. We note that expression of SF-1 in mesonephros or interrenal tissue is very poorly described in the literature; to our knowledge, there are no data about it during the period of sex differentiation. It appears that SF-1 gene transcription can be positively regulated by estrogen in *Pleurodeles*. Indeed, we observed that upregulation of SF-1 mRNA expression can be triggered by exogenous stimulation with estradiol benzoate. In Gd, the local production of these hormones can stimulate SF-1 expression earlier than in MI, which does not produce estrogen and is sensitive to the sole circulating hormones. In *T. scripta*, estrogen was also shown to modulate the regulation of SF-1 transcription, since treatment with estradiol applied at a male-producing temperature resulted in upregulation of gonadal SF-1 and female hatching (Fleming & Crews 2001). However, whether estrogens have a direct or indirect effect on SF-1 expression is not known. Therefore, in *P. wallii*, SF-1 expression could be correlated with the high level of steroidogenic activity necessary to support female sexual development, as in chicken embryos, where the developing ovary displays a higher steroidogenic activity than the testis (Woods & Erton 1978, Guichard *et al.* 1979), while the opposite is observed in mammals (Jost 1970). In *Pleurodeles*, the aromatase and SF-1 expression patterns appear to be closely related, both increasing, during ovarian differentiation, respectively at stages 54 (Kuntz *et al.* 2003b) and 55 (this work). However, SF-1 expression decrease at stage 56 cannot be explained by a reduction in aromatase activity, which is still high at this moment (Chardard & Dournon 1999). Instead, this decrease may be related to the end of the hormone-sensitive period, at which aromatase expression is no longer activated by estradiol.

Whether the SF-1 gene, as a possible regulator of aromatase, is a target of temperature in *Pleurodeles* temperature-dependent sex reversal is another question we address. Our results obtained under heat treatment differ from those obtained in *T. scripta*, in which SF-1 mRNAs increase at male-producing temperature but decline at female-producing temperature (Fleming *et al.* 1999), but are closer to those obtained in *R. rugosa*, in which SF-1 mRNA level remains unchanged in the female-to-male sex reversal, while that of P450 aromatase declines (Kato *et al.* 2004). Indeed, in our
model, we detected a significant decrease in SF-1 expression in Gd of ZW\textsuperscript{32} larvae at stages 55\textsuperscript{1std} and 55\textsuperscript{30th} with regard to that observed in ZW\textsuperscript{20} ones. Such a significant decrease is also observed in MI at stage 55\textsuperscript{30th}. According to the results of estrogen treatments, this inhibition of the female-specific peak of SF-1 mRNA in both Gd and MI could be due to the previously described defect in aromatase expression and estrogen synthesis induced under the effect of heat treatment leading to sex reversal (Chardard et al. 1995). These results support the hypothesis of a regulation of SF-1 gene expression by estrogen level rather than by a direct effect of temperature. This is strengthened by the fact that, when larvae are submitted to a 48-h heat shock, the SF-1 mRNA response is quite different from that observed after long-term heat treatment, since a weak but not significant inhibition of SF-1 transcription can be observed in MI, while mRNA level is significantly increased in Gd. Since this test was run after TSP, this does not mean that SF-1 could be a target of the masculinizing temperature in the course of sex reversal.

Recently, the brain has been suggested to be involved in sex determination in a turtle exhibiting temperature sex determination (TSD), such as Malaclemys terrapin, in which temperature-dependent SF-1 mRNA level rises earlier in female than in male brain before gonadal differentiation (Jeyasuria & Place 1997). In T. scripta, the brain also seems to be the site of aromatase response to temperature, since differential aromatase activity was detected in brain during the TSP, whereas no differential activity was observed in Gd (Willingham et al. 2000, Crews et al. 2001). In Pleurodeles, our semiquantitative RT–PCR analysis did not show any differential expression of SF-1 in brain from ZZ\textsuperscript{20}, ZW\textsuperscript{20} and ZW\textsuperscript{32} larvae taken at the beginning of sex-specific gonadal differentiation. This result is similar to that observed for aromatase expression (Kuntz et al. 2004b), suggesting that brain does not significantly interfere in the sexual determination or differentiation of the Gd in P. waltli and would not be considered to play a role in temperature-dependent sex reversal.

This work sheds a new light on the agents involved in Pleurodeles gonadal differentiation, although aromatase and estrogen seem to remain, at that time, the most important pieces of the puzzle. However, additional results will be necessary to understand the overall regulation of estrogen synthesis and the actual involvement of SF-1 in the complex path of ovarian differentiation and/or determination.

**Acknowledgements**

We thank Jean-Charles Olry and Alain Iuréttig for animal rearing, and Henri Schroeder for valuable help in statistical analysis of results. The authors declare that there is no conflict of interest that would prejudice the impartiality of this scientific work.

**Funding**

This work was supported by grants from the Ligue Contre le Cancer, comités de la Meurthe et Moselle, de la Meuse et des Vosges, the Association pour la Recherche sur le Cancer, the Université Henri Poincaré-Nancy 1 (BQR), and the Conseil Régional de Lorraine. S K is a recipient of a grant from the French Ministère de l’Education Nationale, de l’Enseignement Supérieur et de la Recherche.

**References**


Lala DS, Rice DA & Parker KL 1992 Steroidogenic factor I, a key regulator of steroidogenic enzyme expression, is the mouse homolog of fushi tarazu-factor I. *Molecular Endocrinology* 6:1249–1258.


