Ontogenic and morphological study of gonadal formation in genetically-modified sex reversal XYPOS mice

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ABSTRACT. Mammalian sexual fate is determined by the presence or absence of sex determining region of the Y chromosome (Sry) in the “bipotential” gonads. Recent studies have demonstrated that both male and female sexual development are induced by distinct and active genetic pathways. Breeding the Y chromosome from Mus m. domesticus poschiavinus (POS) strains into C57BL/6J (B6J) mice (B6J-XYPOS) has been shown to induce sex reversal (75%; bilateral ovary, 25%; true hermaphrodites). However, our B6N-XYPOS mice, which were generated by backcrossing of B6J-XYPOS on an inbred B6N-XX, develop as males (36%; bilateral testis with fertility as well as bilateral ovary (34%), and the remainder develop as true hermaphrodites. Here, we investigated in detail the expressions of essential sex-related genes and histological features in B6N-XYPOS mice from the fetal period to adulthood. The onsets of both Sry and SRY-box 9 (Sox9) expressions as determined spatiotemporally by whole-mount immunohistochemistry in the B6N-XYPOS gonads occurred 2–3 tail somites later than those in B6N-XYB6 gonads, but earlier than those in B6J-XYPOS, respectively. It is possible that such a small difference in timing of the Sry expression underlies testicular development in our B6N-XYPOS mice. The ability of the Sry protein, which starts at 11 ts and ends with the last Sry-positive cells detectable at 30 ts, and ceases entirely by 34 ts [6, 46], which corresponds to a time window of only 6 hr after the normal onset of Sry expression in the XY gonad [21]. Reduced or delayed Sry expression impairs testis development, highlighting the importance of its accurate spatiotemporal regulation and implying a potential role for SRY dysregulation in human intersex disorders [27]. On the other hand, despite its important roles, the Sry protein structure except for the HMG box varies across some mammalian species. Mouse Sry has a particularly unusual structure in comparison with other mammals. The N-
terminal domain has only 2 amino acids, and the C-terminal domain includes a glutamine (Q)-rich domain that is derived from degenerate CAG repeats. Moreover, there is a “bridge domain” situated between the HMG box and the Q-rich domain [37]. Although it was previously considered that the HMG box is the only functional domain involved in the activation of Sox9, recent studies demonstrated that the Q-rich domain also has important roles in protein stabilization and transcriptional activation, both of which are essential for male sex determination [48].

The Q-rich domain is known to be less conserved in mice than in other species, and its sequence and length are different. For example, three main subspecies of the genus Mus. (Mus m. musculus; e.g. 129, B6, DBA/2J; Mus m. domesticus; e.g. POS, TIR, CD1, AKR; Mus m. castaneus; e.g. Southeast Asian house or wild mouse) exist, and the length of the Q-stretch in Mus. m. domesticus is approximately half of that in Mus. m. musculus, due to a premature stop codon [37]. Moreover, the transfer of the Y chromosome from the mouse species Mus. m. domesticus poschiavinus (XYPOS) to the genome of the C57BL/6J (B6J) inbred strain causes disruption of the normal testis determination process and results in the partial or complete sex reversal of XY individuals. These XYPOS mice have been produced using a standard backcrossing method. After several generations of backcrossing, half of the XY individuals developed as females with ovarian tissue and half developed as hermaphrodites. Some hermaphrodites were fertile, having functional testicular tissue to masculinize their internal and external genitalia and produce sufficient numbers of sperm to fertilize eggs [13, 16].

The progeny of our XYPOS mice, which were originally obtained from the Jackson Laboratory [16], also express various combinations of females with ovaries and ambiguous individuals, such as hermaphrodites (unilateral or bilateral ovotestis) or individuals with ovotestes and males with bilateral testes. However, the frequency of male progeny was higher than that of the other phenotypes, and these males appeared normal with fertility. From the above, it is possible that our mice were slightly different from those reported in 1982. However, if this is true, what causes the formation of testes in our mice? Otherwise, what protects against XYPOS mice on an inbred C57BL/6J (B6N) (purchased from Japan SLC, Inc., Hamamatsu, Japan) background were generated by backcrossing for more than 11 generations. The phenotypes have been produced by the same ratio during these generations. Their offspring having only the Sry allele from Mus. m. domesticus poschiavinus (SryPOS) were selected and are the subject of this paper. All mice were maintained in individual 40.5 × 20.5 × 18.5-cm ventilated cages (Sealsafe Plus Mouse; Tecniplast S.p.A., Buguggiate, Italy) under specific pathogen-free conditions with controlled temperature (23 ± 2°C) and humidity (50 ± 10%) on a 12-hr light/dark cycle at the Kobe University Life-Science Laboratory with ad libitum access to water and a pellet diet (DC-8; Clea Japan, Inc., Tokyo, Japan). This study was approved by the Institutional Animal Care and Use Committee (Permission #25-06-03) and carried out according to the Kobe University Animal Experimental Regulation.

Dissection, staging and genotyping of fetal mouse gonads: Timed matings were used for all embryonic experiments. Noon of the day of vaginal plug detection was designated as 0.5 dpc. The gonads and mesonephroi that were removed from the embryos between 11.5 and 12.5 dpc were precisely staged by counting the number of ts: 11.5 dpc is ~18 ts, and 12.5 dpc is ~30 ts [19]. The sexual phenotype of weaning-age mice was determined by examining the distance from the anus to the genitalia (anogenital distance; AGD). Fetal sex and the presence of the SryPOS and Sry129 alleles were determined by multiplex PCR (polymerase chain reaction). The chromosomal sex of each fetus was confirmed by PCR using the primer pair 5′-GGG ACT CTA AGC TTC AAT CA and 5′-TGG AGG AGG AAG AAA AGC AA to detect the interleukin-3 (IL-3) region as an internal control, and the primer pair 5′-CCC CTT TCT TCT AAG CAC AGG AGG AAA AGC AA to detect Y-specific B10-derived sequences (YB-10), a region located on the long arm of Y chromosome. The amplified products were electrophoresed in 2% agarose gel, dyed by ethidium bromide and visualized with a UV transilluminator.

Sry alleles: In addition to the primer pairs described above, a region of the Sry HMG box was amplified from genomic DNA using 5′-TGG GAC TGG TGA CAA TTG TC and 5′-GAG TAC AGG GAG AAG AAA AGC AA to detect the SryPOS allele contains an Mbo I recognition site, resulting in two fragments of 23 and 130 bp, while the Sry129 allele lacks the Mbo I recognition site, resulting in an undigested 153 bp fragment.

Tissue preparation: Genital tissues were fixed in 4% paraformaldehyde in 0.1 M phosphate buffer (pH 7.4) for 24 hr at 4°C. The specimens were dehydrated with an ethanol series followed by xylene and then embedded in paraffin. Then, 4-μm-thick sections were cut by a sliding microtome (SM2000R; Leica Microsystems, Wetzlar, Germany) and placed on slide glasses (Platinum; Matsunami Glass Ind., Ltd., Kishiwada, Japan).

Histological and immunohistochemical analyses: For the general histological analyses, tissue sections were stained with hematoxylin and eosin. Immunostaining was performed for Sox9 and IL-3, the former acting as an internal control and the latter as an antibody that could be used for sexual differentiation (B10-derived sequences).
with hematoxylin and eosin (HE; Merck Ltd., Japan, Tokyo, Japan) after their deparaffinization and hydration. To detect Nr5a1 (a generous gift from Dr. K. Morohashi, Kyushu University, Japan), Sox9 (Santa Cruz Biotechnology, Inc., Santa Cruz, CA, U.S.A.) and forkhead box L2 (Foxl2) (Affinity Bioreagents, Golden, CO, U.S.A.), we performed the following immunohistochemical protocol by using anti-Nr5a1 rabbit polyclonal antibody (1:16,000), anti-Sox9 rabbit polyclonal antibody (1:300) and anti-Foxl2 rabbit polyclonal antibody (1:500). The sections were immersed in absolute methanol and 0.5% H2O2 for 30 min at room temperature (RT) to quench the endogenous peroxidase activity. They were then incubated with Blocking One Histo (Nacalai Tesque, Inc., Kyoto, Japan) for 1 hr at RT for protein blocking and then incubated with each primary antibody in phosphate-buffered saline (PBS) containing 0.05% Tween-20 (PBST; pH 7.4) for 18 hr at 4°C. After being washed with PBST, the sections were reacted with Dako EnVision+ system-HRP (horseradish peroxidase) labeled polymer (EnVision+; Dako Japan, Tokyo, Japan) in Tris-HCl buffer (pH 7.6) for 1 hr at RT. Immunoreactivity was then detected by incubation with 3,3′-diaminobenzidine solution (EnVision+ kit/HRP[DAB]; Dako). The sections were counterstained lightly with hematoxylin solution for 1 min. Finally, the sections were placed in a graded series of ethanol, dehydrated with absolute ethanol, cleared by xylene and coverslipped with Eukitt (O. Kindler, GmbH, Freiburg, Germany).

**Whole-mount immunohistochemistry:** Gonad/mesonephros complexes were fixed in 4% paraformaldehyde in 0.1 M phosphate buffer (pH 7.4) for 24 hr at 4°C. The specimens were dehydrated with 100% methanol for 8 hr at 4°C; then passed through three cycles of chilling in 1% H2O2 dissolved in absolute methanol to −80°C in a freezer and thawing to 4°C to break down the cell membranes and quench the endogenous peroxidase activity. Next, the specimens were rinsed with 50% methanol in 0.1 M PBS for 1 hr, followed by 0.1 M PBS alone for 1 hr, then incubated with 0.1% albumin serum in Blocking One Histo (Nacalai Tesque, Inc.) at 4°C for 18 hr and reacted with anti-Sry rabbit polyclonal antibody (a generous gift from Dr. D. Wilhelm, Monash University, Australia; 1:800) or anti-Sox9 rabbit polyclonal antibody (1:600) at 4°C for 24 hr. The tissues were washed with PBS three times for 2 hr each and incubated with a Dako EnVision+ system-HRP labeled polymer (Dako) at 4°C for 42 hr. After washing with PBS as described above, they were incubated with 0.17% DAB and 0.3% H2O2 in the Tris-HCl buffer at 4°C for 2 hr. Immunoreactivities were visualized by using 0.17% DAB and 0.3% H2O2 in the Tris-HCl (pH 7.6). Negative controls, in which the primary antibodies were replaced with nonimmunized serum, did not show nonspecific staining.

**Sequence analysis:** The Sry coding sequence (CDS) was analyzed by direct sequencing of PCR products by the capillary electrophoresis systems. A total of 100–150 ng of genomic DNA was extracted from liver tissue using a QIAamp DNA Microkit (Qiagen, Hilden, Germany). Genomic DNA was used as a template for the primers mSry-933: 5′-GCA

**Quantification of ovarian follicles:** The number of follicles was counted in individual tissue sections. If one follicle was present in several continuous sections by using ocular micrometer under light microscopy, it was only counted in the first section in order to avoid repetition. The means were calculated, and the data are presented as the means ± standard deviation (SD).

**Fertility test:** Each B6N-XYPOS male or B6N-XYPOS female offspring (5–8 weeks of age) was housed with a B6N-XX or B6N-XYB6 mouse (6–10 weeks of age) that was known to be fertile. The presence or absence of copulation plugs was examined between 9:00 and 10:00 a.m. every morning up to 7 days. If copulation plugs were not found, mating was repeated two more times. The female mouse that had copulated was housed singly until the expected delivery day. If pregnancy was not confirmed after 12 days of delivery, this process was repeated two more times.

**Statistical analysis:** Statistical analyses were performed with Excel Statistics 2012 (SSRI, Ltd., Tokyo, Japan). All data were analyzed by two-way analysis of variance (ANOVA) followed by Tukey-Kramer’s post hoc test. The results were considered significant when the P-value was <0.05.

**Table 1. Primers used for Sry sequencing**

<table>
<thead>
<tr>
<th>Name</th>
<th>Forward/Reverse</th>
<th>Primer sequence (5’ to 3’ direction)</th>
</tr>
</thead>
<tbody>
<tr>
<td>mSry-537</td>
<td>Forward</td>
<td>CGTACACGGCAAAAGAACCTA</td>
</tr>
<tr>
<td>mSry-328</td>
<td>Forward</td>
<td>GAGGAGGGGATAAATTTTCTTTACA</td>
</tr>
<tr>
<td>mSry-97</td>
<td>Forward</td>
<td>AGATCTGATTTTAGTGTTG</td>
</tr>
<tr>
<td>mSry+162</td>
<td>Forward</td>
<td>TTCCAGAGGCCAGAGATT</td>
</tr>
<tr>
<td>mSry+320</td>
<td>Forward</td>
<td>CCCACATGCAATACGACATA</td>
</tr>
<tr>
<td>mSry+410</td>
<td>Forward</td>
<td>TATCCCCGCTGGGACACCT</td>
</tr>
<tr>
<td>mSry+1083 Reverse</td>
<td>GGAATT</td>
<td>GGAATT</td>
</tr>
<tr>
<td>mSry+1132 Forward</td>
<td>CCAAGAGGAACGAGAGCA</td>
<td></td>
</tr>
<tr>
<td>mSry+1195 Reverse</td>
<td>GTGTTCGATAGGTAGGAAAGAAG</td>
<td></td>
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</tbody>
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RESULTS

Sexual development of B6N-XY^POS^ mice: When analyzing B6N-XY^POS^ mice, which had been established by a cross between a male B6J-XY^POS^ transgenic mouse with the 14.6 kb DNA fragment containing the Sry^129^ males and a B6N-XX females, we found a broad range of gonadal phenotypes, but typically four types of external and internal genitalia—i.e., genitalia with bilateral testes (T/T), bilateral ovaries (O/O), bilateral ovotestes (OT/OT) and a testis on one side and an ovary on another (O/T, hermaphrodite)—with the same genotype (Fig. 1A). Hermaphrodites and individuals with unilateral testis or ambiguous gonads had both nipples and penises (Fig. 1A). Notably, O/T mice had a right ovary and left testis with extraordinary frequency at few years since assignation from the Jackson Laboratory (Fig. 1A). The frequency of these phenotypes in the growing stages (pre-SM: pre-sexual maturation at the ages of 2 weeks; SM: sexual maturation at the ages of 9 weeks; post-SM: post-sexual maturation at the ages of 18 weeks) showed that over 36% of our B6N-XY^POS^ mice displayed normal sex differentiation (T/T individuals) (Fig. 1B) and some of them were fertile. The boundary of these phenotypes seemed ill-defined, and some B6N-XY^POS^ individuals had ambiguous gonads. Although the B6N-XY^POS^ testes and accessory reproductive glands looked similar to those of the B6N-XY^B6^, some B6N-XY^POS^ testes were smaller. Individuals with bilateral ovaries had nipples and vaginal openings, and no penises. The ovaries and accessory reproductive glands looked similar to those of the B6N-XX. The AGD of these animals was the same as that of the B6N-XX and shorter than that of the B6N-XY^B6^ mice. They also had male accessory reproductive glands (Fig. 1C).

Gonadal descent was detected in T/T, OT/OT and O/T individuals, but not in O/O mice, even in the post-SM period. The body weights and AGDs in mice with gonadal descent were significantly higher than those in mice without gonadal descent (data not shown).

Histological and immunohistological findings: Histopa-
thology was evaluated using cross-sections of gonads stained with HE by light microscopy. To investigate the etiology of sex reversal, we examined the expression of Nr5a1, which is a critical regulator of sexual development and reproduction [33], the testicular Sertoli cell marker Sox9 [24] and the ovarian somatic cell marker Foxl2 [29]. Because the B6N-XYPOS T/T individual testes showed normal cell arrangements with well-developed seminiferous tubules consisting of spermatogonia, spermatocytes, spermatids and sperm according to each sexual development stage, the gonads contained no Foxl2-positive cells, but only Sox9-positive cells (Fig. 2A), indicating that the testes were normal and thus that there was no failure of the testis-determining pathway. While some seminiferous tubular structures in the testis of O/T individuals had abnormal vacuoles and no sperm (Fig. 2B), the pre-SM testis showed Foxl2-positive oocyte-like cells, but without a pellucid zone or follicular epithelium (Fig. 2B). The number of ovarian follicles was quite small in the ovaries of the O/T mice, and some follicles exhibited blood leakage or intrafollicular shedding of cells, while Sox9-positive cells were observed in some of the seminiferous tubule-like structures (Fig. 2C). Many secondary ovarian follicles as well as primary ones were observed in the pre-SM B6N-XYPOS females (O/O mouse), but no vesicular ovarian follicles were detected (Fig. 3A). These follicles were rare in the SM and post-SM sexual developing stages (Fig. 3A). The measurement of the number of ovarian follicles revealed a rapid decrease of germ cells at between 2 and 9 weeks of age (Fig. 3B).

The results of immunoreactive analysis in the genital ridges at 11.5 dpc are shown in Fig. 4. The immunoreexpression of Nr5a1 in the genital ridges of B6N-XYPOS mice was compared to that in the B6N-XYB6 males and females. Nr5a1 positivity was detected in the epithelium and internal somatic cells but not in the germ cells, and no difference was found in the staining properties (Fig. 4A). Although Sox9 was expressed in a diffusely-arranged manner in both the right and left gonads of the B6N-XYB6, the level of Sox9 expression in the B6N-XYPOS gonads was much lower than that in the B6N-XYB6 (Fig. 4B). In addition, a bilateral difference or very few Sox9-positive cells were demonstrated in B6N-XYPOS gonads (data not shown). By contrast, no immunopositive cells were detected in the B6N-XX (Fig. 4B). No Foxl2 immunoreactivity was detected in the genital ridges of both B6N-XYB6 and B6N-XX, but extremely-weak reactivity was seen in the B6N-XYPOS (Fig. 4C).

*Spatiotemporal expression of Sry:* We found no expression at 11 ts in either the B6N-XYB6 or B6N-XYPOS gonads (Fig. 5a and 5h). Weakly positive cells were observed chiefly in the central region of the 13 ts B6N-XYB6 gonad (Fig. 5b). Getting to 15 ts, positive cells were expanded toward both the cranial and the caudal region, and the expression level in the central region was stronger than that in both acral regions (Fig. 5c). From 16 ts to 21 ts, strongly positive cells were seen throughout the gonad (Fig. 5d). Sry expression began to decrease from the central region after 23 ts, and then, it became limited by 25 ts (Fig. 5e). Few positive cells were observed in the thickening gonads at 26 ts (Fig. 5f), and there were no positive cells at 27 ts (Fig. 5g). Briefly, Sry expression of B6N-XYB6 gonads starts from the central region at 12–13 ts, rises toward a peak at 17–21 ts and then falls to a low level at 23–27 ts (Fig. 5a–5g).

On the other hand, Sry expression of B6N-XYPOS was not detected beyond 13 ts (Fig. 5h and 5i). Weakly positive cells were wholly observed in the 15 ts B6N-XYPOS gonad (Fig. 5j). At 17 ts, positive cells were seen throughout the gonad, though the expression level was weak around the caudal region (Fig. 5k). The expression level became strong at 19–26 ts (Fig. 5l and 5m), and it was reduced beyond 28 ts (Fig. 5n). Although there were few positive cells from the cranial to the central region at 30 ts, many strongly positive cells remained in the caudal region (Fig. 5o). In brief, Sry expression of B6N-XYPOS gonads starts from the central region at 14–15 ts, rises toward a peak at 19–26 ts and then falls to a low level after 28 ts (Fig. 5h–5o).

*Spatiotemporal expression of Sox9:* Weakly positive cells emerged chiefly in the central region of the 15 ts B6N-XYB6 gonad (Fig. 6a). At 17 ts, positive cells were seen throughout the gonad, though the expression level was significantly low around the caudal region (Fig. 6b). Strongly positive cells were seen at 18–22 ts (Fig. 6c–6e). By the 20 ts stage, Sox9 expression was seen throughout the gonad (Fig. 6d–6g). An increase in positive cells and gonadal thickening were observed after 22 ts, and testis cords including positive cells were observed after 26 ts (Fig. 6e–6g). Briefly, Sox9 expression of B6N-XYB6 gonads starts from the central region at 14–15 ts and expands to all regions at 18 ts, and then, the number of Sox9-positive cells increases, causing gonadal thickening and testis cords formation (Fig. 6a–6g).

By contrast, typically, Sox9 expression was not detected in B6N-XYPOS gonads at 16 ts (Fig. 6h), though expression in a small number of cells was sometimes seen in the central region (data not shown). Weakly positive cells started to expand toward both acral regions from 17 ts to 20 ts, but the number of positive cells in B6N-XYPOS gonads increased more moderately than that in the B6N-XYB6 gonads (Fig. 6i–6k). The number of positive cells continued to rise in the central region, and no increase was observed at either acral region after 22 ts (Fig. 6l and 6m). Thickening was observed only in the center of the gonads at 26 ts (Fig. 6n). Although the gonads had developed to the same level as the B6N-XYB6 gonads at 30 ts, they formed no testis cords and contained very few positive cells at either acral region. Moreover, the coelomic epithelium invaginated into the gonads at 30 ts, and weakly positive cells were eccentrically located at the mesonephric side (Fig. 6n). In brief, then, the Sox9 expression of B6N-XYPOS gonads starts from the central region at 16–17 ts, and then, it expands to all regions by 20 ts. The number of positive cells in B6N-XYPOS gonads increased more moderately than that in the B6N-XYB6 gonads. Gonads at 30 ts have less positive cells at both acral regions, which results in no formation of testis cords (Fig. 6h–6n).

**Fertility:** All fertility-tested B6N-XYPOS female mice were infertile. Although all (four) B6N-XYPOS females that had been placed with B6N-XYB6 mated as evidenced by the presence of copulation plugs, none of them were pregnant on
Fig. 2. General histology and immunohistochemistry in the B6N-XYPOS mice in each sexual developmental stage. (A) Hematoxylin and eosin staining (HE) and Sox9 immunostaining on transversal sections at pre-sexual maturation (pre-SM), SM and post-SM in T/T individuals. The testis shows a luminal structure and normal cell arrangements including elongated spermatids in the wall of seminiferous tubules in the SM and post-SM (a–c). Clusters of Leydig cells are present in the intertubular space (arrows, a–c). Sox9-positive Sertoli cells are observed (arrowheads, d–f). St: seminiferous tubule. (B) Abnormal structures and immunoreactivities of the testis in O/T individuals. Deformed seminiferous tubules and Foxl2-positive oocyte-like cells are seen in the lumen of the seminiferous tubules in the pre-SM (asterisk, g and k). Clusters of Leydig cells are present in the intertubular space (arrows, h–j). Detachment of Sox9-positive Sertoli cells (arrowheads) is also seen in the degenerated seminiferous tubules in the SM and post-SM (l–m). Sperm masses are present in the seminiferous tubules without spermatogonia, spermatocytes, spermatids and Sertoli cells (j). The boxed areas are shown at higher magnification (n). (C) Degenerated structures and immunoreactivities of the ovary in O/T individuals. Slight primordial follicles and primary oocytes were observed in the pre-SM stage (o). Vesicular follicles, corpus luteum and blood leakage (large arrows) in the SM stage (p), and secondary and vesicular follicles and corpus luteum in the post-SM stage (q). Moreover, blood leakage and intrafollicular shedding (large arrows) of cells were also seen (u, v). Oocyte (arrowhead) and follicular epithelium (arrow) slightly positive for Sox9 (r) and positive for Foxl2 (s) were seen in the pre-SM. Clusters of Sox9-positive cells (small arrows) were observed at SM (t). *primordial follicles; **primary follicles; ***secondary follicles; ****vesicular follicles; §corpus luteum.
day 12 after copulation. In contrast, some of the B6N-XYPOS males that had functional seminiferous tubes mated with B6N-XXB6, and most of them carried the pregnancy to full term. To date, no pups have been obtained from B6N-XYPOS (O/O individuals).

Sry CDS sequence: To determine whether our B6N-XYPOS mouse had a normal Mus. domesticus-derived Sry allele, we sequenced SryPOS CDS and found the same sequence as previously reported for SryPOS [1]. While SRYB6 is composed of 395 amino acids, SRYPOS is composed of 230 amino acids because of the point mutation creating a TAG stop codon in CAG repeats. In addition, the Q-rich domain of SRYB6 consists of 21 blocks of glutamine residues, and that of SRYPOS consists of 8 blocks.

DISCUSSION

In recent years, not only the sex-determining gene Sry, but also some other genes have been identified as important factors involved in sex determination and sex differentiation. It is already known that knocking such genes out causes gonadal sex reversal in mice [45]. For example, XY gonadal sex reversal has been described in cases of homozygous deletion of a number of testis-determining genes, including Sox9 [5, 8, 28], Fgf9 [10], Fgfr2 [4, 25], Cbx2 (M33) [23] and Wt1 (+KTS) [20]. A number of additional cases of XY sex reversal in the mouse depend on the presence of a Mus m. domesticus Y chromosome and the B6J genetic background: i.e., so-called B6J-XYDOM sex reversal [1, 16]. B6J-XYPOS mice carrying a Mus m. domesticus poschiavinus-derived Y chromosome show sex reversal, which was one of the B6J-XYDOM sex reversal, and 75% of them develop as females (ovaries) while the remainder develop ovotestes; none develop a testis [14]. However, when we analyzed offspring of B6N-XYPOS mice in our laboratory, they had a broad range of gonadal phenotypes that could be divided into four types (T/T, O/O, OT/OT and O/T), and the frequency of the T/T animals, which displayed normal sex differentiation and were fertile, was over 30%. This implies that the B6N-XYPOS mice in our laboratory were somewhat different from those reported initially [16].
Accordingly, Sry CDS sequence analysis was carried out to investigate whether our B6N-XYPOS mouse has a different Sry allele from Mus m. domesticus poschiavinus. However, the results showed that our SryPOS was identical to that reported previously [1], which means that they have the same published Mus m. domesticus poschiavinus-derived Sry allele. This suggests that the gonadal phenotypic divergence between our present data and the results published previously was not due to the Sry CDS.

Sry expression expands from the central region to the poles along the anteroposterior axis of the XY gonad [6, 40], and testis cord formation subsequently proceeds in a similar gradient manner [39]. The study of Bullejos and Koopman (2005) [7] clearly indicates that a delay of expression of SryDOM relative to B6J-Sry underlies B6J-XYDOM sex reversal, and Sry must act during a critical time window to appropriately activate Sox9 and effect male sex determination before the onset of the ovarian-determining pathway. Their findings also showed that the expression of SryPOS reached a peak level only after the expression of SryB6 had all but ceased; this represents a delay of 4 ts (approximately 9.6 hr), and the onset of Sox9 expression is delayed by a period corresponding to 6 ts (approximately 14.4 hr) compared with B6N-XYB6. In contrast, the spatiotemporal expressions of Sry and Sox9 examined using whole-mount immunohistochemistry in the present study showed that the onsets of both Sry and Sox9 expressions in the B6N-XYPOS gonads were 2–3 ts later than those in B6N-XYB6 gonads. These results suggest that the onset of SryPOS expression is earlier than that reported previously, that is, our SryPOS expression seemed more similar to that in B6N-XYB6 gonads. Furthermore, it is possible that such a small difference in timing of
the Sry expression underlies testicular development in our B6N-XYPOS mice. At the same time, even at 30 ts B6N-XYPOS gonads, Sox9-positive cells were limited at the central region and were not seen at the cranial and caudal regions, which results in no formation of testis cords at both acral regions. Sox9 expression normally persists throughout life in Sertoli cells, suggesting that Sox9 executes and maintains their differentiation and aspects of their function [39]. It suggests that the failure of expressing Sox9 at both acral regions of the gonad leads to the formation of ambiguous gonads seen in OT/OT individuals of B6N-XYPOS. Actually, it is mentioned that testicular tissue in ovotestis was invariably concentrated in the mid region of the gonad, with ovarian tissue distributed at the cranial and caudal poles [22].

Most studies on XYPOS mice have not focused on histological and immunohistochemical findings, so we provide indication of normality or abnormality of adult tissues (pre-SM, SM and post-SM) in detail. In T/T individuals, the testes showed normal cell arrangement and sperm formation, which is the histological evidence supporting fertility in our XYPOS male mice. On the other hand, the gonads in O/T individuals showed abnormal structures, especially in the testes, where the seminiferous tubular structures had abnormal vacuoles and no sperm. The pre-SM testes showed Foxl2-positive oocyte-like cells, but without a pellucid zone or follicular epithelium. Foxl2, a forkhead transcription factor, is expressed in fetal and adult ovarian follicular cells and involved in ovarian development and maintenance [9]. Testicular oocytes are also observed in MRL/MpJ XY mice with fertility, although they are surrounded by a pellucid zone and follicular epithelium unlike in the present case [36]. The ovaries in our O/T individuals had quite small follicles, and Sox9-positive cells were observed in the seminiferous tubule-like structures. Our studies are the first to histologically show the expression and localization of a female-related gene in the B6N-XYPOS testes and a male-related gene in the B6N-XYPOS ovaries. The ectopic expressions of such transcriptional factors as Foxl2 in the testes and Sox9 in the ovaries suggest that the normal differentiation system in B6N-XYPOS gonads is disturbed due to an imbalance between the male and female pathway sinceFoxl2 and SOX9 oppose each other’s actions and thereby ensure the establishment and maintenance of the different female and male supporting cell types, respectively [43].

We have indicated that delayed Sry and Sox9 expressions disrupt normal testicular development, as described previously [7]. However, in the B6N-XYPOS gonads, Nrg5α1 expression, which regulates Sry expression, was at the same level as in the B6N-XYB6 gonads. Several studies suggest that the C57BL/6J background is sensitized to disruptions to testis determination due to the relatively delayed expression of testis-determining genes and higher levels of expression of ovari-determining genes; in addition, most sex-reversing mouse mutants examined, B6J increases the amount of ovarian tissue that forms in mutant XY embryos [11, 34, 44]. Therefore, there may be some interactions between autosomal factors specific to the B6J background and the domesticus-derived Y chromosome.

Let us consider these factors individually. First, there is the issue of the C57BL/6 background. Because testicular tissue develops in DBA/2J or 129S1/SvJmJ (129) mice containing the poschiavinus-derived Y chromosome, sex reversal in B6J-XYPOS mice is attributable to the genetic background of B6J [15]. Previous studies of gene expression within B6J and another non-sex-reversing strain, 129S1, in developing testes showed that, compared to 129-XY129 gonads, B6J-XYB6 gonads had a higher average expression of “female”-related genes and a lower expression of “male”-related genes [34, 35]. Moreover, the B6 mouse, a common inbred strain of laboratory mouse, is classified into Mus m. musculus. However, commonly used classical inbred mouse strains have mosaic genomes with sequences from different subspecific origins, and with regard to B6, their genomes are derived predominantly from the Western European subspecies Mus m. domesticus, with the remaining sequences derived mostly from the Japanese subspecies Mus m. molosinus [42]. Molosinus-derived autosomal factors in B6 may provide sensitivity to sex reversal, because some other inbred strains, such as AKR, that are classified into Mus m. domesticus do not show sex reversal [7]. Furthermore, although they derive from the same B6 strains, B6J and B6N are genetically and phenotypically different because their breeding stocks have been maintained separately for a long period of time, allowing genetic differences to accumulate due to individual variety and genetic drift [30, 49]. At the beginning of our breeding, B6J-XX were mated to B6J-XYPOS Tg (129) mice over five generations, with the result that only individuals with ovaries or hermaphrodites were produced, which is the same result as reported in 1982. However, B6N-XX were mated to B6J-XYPOS Tg (129) mice subsequently, and the frequency of their progeny was the subject of this paper. Thus, it was suggested that the difference between B6J and B6N may be responsible for the phenotypes in our B6N-XYPOS mice.

Secondly, we would like to focus on attention to the epigenetic factors upstream of Sry. Jumonji domain-containing 1a (Jmjd1a) (also called Tsga/Jhdm2a/Kdm3a) acts as a H3K9 demethylase, and Jmjd1a-deficient mice frequently show XY sex reversal [26]. The phenotypes of these animals have a broad range that is quite similar to that of our B6N-XYPOS mice. Jmjd1a directly and positively controls Sry expression by regulating H3K9me2 marks, which reveals that certain epigenetic factors, such as histone demethylation, have an important role in mammalian sex determination. Interestingly, the generation and comparison of XY Jmjd1a-deficient mice, which carried the Y chromosome from either CBA (YCB) or B6 (YB6) on a B6N autosomal background, revealed that the sex-reversal phenotype was dependent on not only the loss of Jmjd1a but also the genetic origin of the Y chromosome combined with the B6 background [26]. In the case of the XY female in humans, without a functional mutation in SRY, pericentric inversion of the Y chromosome causes XY females: if SRY is inverted and relocated to the center of the heterochromatic region, this positional variegation will lead to SRY gene silencing, inducing XY female development [17, 31, 32]. These facts indicate that, even if
Sry is intact, the interaction between Sry and other genes will cause sex reversal because Sry expression is regulated in a strictly temporal and spatial manner.

Finally, a recent study on B6J-XyPOS mice showed that the non-coding congenic region on chromosome 11 (110 region) that protects against B6J-XyPOS sex reversal is located within the Sox9 promoter and promotes the expression of Sox9, thereby driving testis development within the B6J-YPOS background. B6J-XyPOS males which we originally believed to be “XYPOS” were heterozygous for this 110 region derived from Mus m. domesticus poschiavius, and heterozygosity for this region was sufficient to prevent the formation of complete embryonic B6J-YPOS ovaries. However, heterozygosity for the 110 region does not result in fully normal embryonic testis, with the majority of gonads showing some degree of ovarian formation [3]. This suggests that the Sox9 promoter region of our B6N-XyPOS mice has a similar congenic region that protects against B6J-XyPOS sex reversal to a certain degree. By contrast, our B6N-XyPOS progeny show a broad range of gonadal phenotypes even in littermates, and the frequency of T/T progeny is as high as that of O/O progeny. Our B6N-XyPOS mice may have a similar autosomal non-coding region that prevents sex reversal in a dose-dependent manner. Therefore, further experiments will be needed to analyze the promoter regions of Sry and Sox9 or the expression of sex-related genes affected by epigenetic regulations.

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