WNT4 and RSPO1 together are required for cell proliferation in the early mouse gonad

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SUMMARY

The gonad arises from the thickening of the coelomic epithelium and then commits into the sex determination process. Testis differentiation is activated by the expression of the Y-linked gene Sry, which promotes cell proliferation and differentiation of Sertoli cells, the supporting cells of the testis. In absence of Sry (XX individuals), activation of WNT/CTNNB1 signalling, via the upregulation of Rspo1 and Wnt4, promotes ovarian differentiation. However, Rspo1 and Wnt4 are expressed in the early undifferentiated gonad of both sexes, and Axin2-lacZ, a reporter of canonical WNT/CTNNB1 signalling, is expressed in the coelomic region of the E11.5 gonadal primordium, suggesting a role of these factors in early gonadal development. Here, we show that simultaneous ablation of Rspo1 and Wnt4 results in a reduced number of Sertoli cells and the formation of a hypoplastic testis exhibiting few seminiferous tubules. Hence, this study identifies Rspo1 and Wnt4 as two new regulators of cell proliferation in the early gonad regardless of its sex, in addition to the specific role of these genes in ovarian differentiation.

KEY WORDS: Gonad, Proliferation, Rspo1, Wnt4, Mouse

INTRODUCTION

In mammals, the gonadal primordium is a unique tissue able to undergo two divergent fates leading to the formation of either a testis or an ovary. In mice, the primordial gonads arise as linear ridges from the ventromedial surface of the mesonephroi between 8 and 16 tail somites (ts) [corresponding to 10.5 and 11.2 day post coitum (E10.5-E11.2) (Karl and Capel, 1998)]. It has been shown that the supporting and interstitial cells derive from the coelomic epithelium, a cell layer covering the coelomic cavity, including the gonadal primordium (DeFalco et al., 2011; Karl and Capel, 1998). The first coelomic cells entering the gonads are precursors of Sertoli cells and their fate depends on the expression of Sry, the sex-determining factor located on the Y chromosome (Karl and Capel, 1998; Koopman et al., 1991; Lovell-Badge and Robertson, 1990). Sry expression starts at E10.5 (11-12 ts), peaks at E11.5 (18 ts) and ceases at E12.5 (Bullejos and Koopman, 2001; Hacker et al., 1995; Jeske et al., 1995) in a center-to-poles wave (Hiramatsu et al., 2009). Moreover, Sry expression is restricted to the precursors of the supporting cells (Albrecht and Eicher, 2001; Sekido et al., 2004; Wilhelm et al., 2005). One of the earliest consequences of Sry expression is a dramatic increase in somatic cell proliferation, resulting in an increase in size of the embryonic testis relative to the embryonic ovary (Schmahl and Capel, 2003). Whereas somatic cell proliferation in XX gonads is constant between 8 and 29 ts, and localized to the coelomic region, in XY gonads, SF1-positive somatic cells of the coelomic region are highly proliferative between 16 and 18 ts (Schmahl et al., 2000).

The molecular signals regulating the early proliferation of the coelomic region are still unknown and are the main issue of the present study. Several genes regulate the expression of Sry to reach levels that are required for testis determination (for a review, see Kashimada and Koopman, 2010; Sekido and Lovell-Badge, 2009). So far, no direct effects of Sry on cell proliferation have been shown. Indeed, the main function of Sry is to activate directly the expression of Sox9 (Sekido and Lovell-Badge, 2008), a transcription factor required for the differentiation of the supporting cells into Sertoli cells (Barrionuevo et al., 2006; Chaboissier et al., 2004). A crucial threshold number of Sertoli precursors is necessary to initiate testis differentiation (Palmer and Burgoyne, 1991) and mutations affecting the Sertoli cell threshold establishment can trigger sex reversal (Polanco and Koopman, 2007). Sertoli cells produce signalling molecules such as FGF9 (Colvin et al., 2001; Kim et al., 2006), which promotes further coelomic cell proliferation (Bagheri-Fam et al., 2008; Bradford et al., 2009; Kim et al., 2007; Schmahl et al., 2004). These cells will become additional Sertoli cells. Then, SF1-negative cells in this region proliferate between 19 and 25 ts (after 11.5 dpc) to give interstitial cells (Schmahl et al., 2000). Schmahl and Capel (Schmahl and Capel, 2003) have shown that inhibition of the early proliferation (between E10.8 and 11.2) results in smaller testes and reduced numbers of testis cords. From E12.0, the vascularisation of the XX gonads is involved in the formation of the testis cords (Combes et al., 2009; Coveney et al., 2008).

In XX gonads, there is no significant increase in proliferation during early embryogenesis (Schmahl et al., 2000). The simplest explanation is the absence of Sry. However, this might alternatively be associated with the female-specific expression of cell-cycle inhibitors (Nef et al., 2005). Ovarian differentiation is induced by activation of the WNT/CTNNB1 canonical signalling pathway (Maatouk et al., 2008) by Rspo1 and Wnt4 (Parma et al., 2006; Vainio et al., 1999). In mice, Wnt4 is expressed in the undifferentiated gonad before becoming upregulated in the XX
gonad after E11.5 (Jeays-Ward et al., 2004; Kim et al., 2006; Vainio et al., 1999). Similarly, Rspo1 is specifically upregulated in XX foetal gonads at E11.5 (Nef et al., 2005; Parmar et al., 2006). Loss of function of either Rspo1 or Wnt4 in XX gonads promotes: (1) ectopic steroidogenic precursors, endothelial cell migration and the formation of a coelomic vessel (Chassot et al., 2008b; Jeays-Ward et al., 2003); and (2) sex reversal of the supporting cell lineages with expression of the Sertoli cell markers, SOX9 or Dhh, and the development of ovoestes around birth (Chassot et al., 2008b; Tomizuka et al., 2008; Vainio et al., 1999). WNTs and R-spondins act synergistically by interaction of their respective receptors LRPR5/6 and LGR4/5 (Carmon et al., 2011; de Lau et al., 2011; Glinka et al., 2011). R-spondin binding activates WNT/CTNNB1 signalling and can disrupt WNT/planar cell polarity signalling (Hao et al., 2012). How RSP01 and WNT4 interact in the gonad remains to be elucidated; however, in absence of Rspo1 and its effector CTNNB1, Wnt4 upregulation is impaired, indicating that Rspo1 is required for Wnt4 upregulation in the ovary after 11.5 dpc (Chassot et al., 2008b; Liu et al., 2009; Manuylov et al., 2008; Tomizuka et al., 2008). WNT/CTNNB1 signalling is required for Foxl2 upregulation (Manuylov et al., 2008), which in turn promotes follicular differentiation (Ottolenghi et al., 2005; Schmidt et al., 2004) and homeostasis in the ovaries (Uhlenhaut et al., 2009).

In addition to its role in ovarian development, Wnt4 is also involved in testis differentiation. Indeed, in XY gonads, loss of function of Wnt4 induces a delay in sex cord formation that is compensated at birth (Jeays-Ward et al., 2004). By contrast, Rspo1–/– males are normally fertile and do not exhibit gross gonadal abnormalities (Chassot et al., 2008a).

Here, we show that Rspo1 is not only required for ovarian differentiation, but also for testis differentiation. The XY Wnt4–/–; Rspo1 –/– double knockouts exhibit hypoplastictic testes, resulting from a dramatically reduced number of seminiferous tubules. Cell proliferation in the coelomic region is significantly impaired in XX and more severely in XY Rspo1 Wnt4 knockout mutants, compared with control gonads. Hence, our findings support a synergetic role for Rspo1 and Wnt4 in cell proliferation in the early gonad and, as a consequence, this pathway regulates the number of differentiating Sertoli cells and in turn testicular development.

MATERIALS AND METHODS

Mouse strains and genotyping

The experiments described here were carried out in compliance with the relevant institutional and French animal welfare laws; guidelines and policies and were approved by the French ethics committee Comité Institutionnel d’Éthique Pour l’Animal de Laboratoire (number: NCE/2011-12). All mouse lines were kept on a mixed 129/C57BL6/J background. Rspo1–/– and Axin2fl/fl transgenic mice have been previously described (Chassot et al., 2008b; Lustig et al., 2002). Wnt4–/– mice (Vainio et al., 1999) were mated with Rspo1–/– mice and recombination events between both genes was selected by backcross. To obtain Wnt4–/–; Rspo1–/– embryos, we next mated Wnt4–/–; Rspo1–/– mice together. Embryonic samples were collected from timed matings (day of vaginal plug = E0.5). Genotyping was performed as previously described (Chassot et al., 2008b; Hogan et al., 1994; Stark et al., 1994). Litter mates were used for all comparisons, except those between Wnt4–/– and Wnt4–/–; Rspo1–/– embryos, as litters were obtained containing both of these genotypes. This is because Wnt4 and Rspo1 are relatively close on the same chromosome making this recombination a rare event.

Histological analysis

Urogenital organs were dissected, fixed in Bouin’s solution overnight and processed to obtain 5 μm paraffin sections. For each genotype, five sections of three different embryos were processed for Haematoxylin and Eosin staining, and quiescent germ cells were analysed with a light microscope, using a 100× objective. The quiescent state was identified by a uniform size of the gonocytes and the absence of any heterochromatin in the nuclei, whereas the proliferative state was characterized by the variation in nuclear size, perinuclear heterochromatin (late S phase and G2 phase), and appearance of chromosome condensation and chromosomal threads (mitosis). Pictures were taken with an Axioimager Mrm camera (Zeiss) and processed with Adobe Photoshop.

X-gal staining and immunological analyses

Samples were fixed with 4% paraformaldehyde overnight or 2 hours and then processed for paraffin embedding or equilibrated in sucrose and embedded in Cryomount (Histolab) for cryosection. Samples for X-Gal staining were processed as described previously (Moore et al., 1998). For each genotype, five cryostat or microtome sections of 8 μm thickness of two different embryos were processed for X-Gal staining and immunostaining. The following dilutions of primary antibodies were used: DDX4/MVH (catalogue code 13840, Abcam), 1:200; SOX9 (kindly provided by Michael Wegner, Institute für Biochemie, Erlangen, Germany), 1:150; AMH/MIS (C-20, catalogue code sc6886, Santa Cruz), 1:200; FOXL2 (kindly provided by Eric Pailhoux, INRA Jouy-en-Josas, France), 1:250; PECAM1 (H300, catalogue code sc8306, Santa Cruz), 1:200; K67 (clone SP6, catalogue code 9106, Thermo-Scientific), 1:200; laminin (catalogue code L9393, Sigma), 1:150; phospho-histone H3 (catalogue code ab14955, Abcam), 1:100; SF1 (kindly provided by Ken Morohashi, Kyushu University, Japan), 1:1500, FGFR2 (Bek C17 catalogue code sc122, Santa Cruz) 1:100, SRY (kindly provided by Dagmar Wilhelm (Bradford et al., 2007), 1:50.

DAPI (blue) was used to detect nuclei. For histology, 5 μm sections of three embryos of each genotype were stained with Hematoxylin and Eosin. Fluorescent studies were performed with a motorized Axio ImagerZ1 microscope (Zeiss) or a Zeiss LSM-510 confocal microscope, and pictures were taken with an Axiocamer Mrm camera (Zeiss) and processed with Axiosvision LE or LSM Image Browser for confocal pictures.

After immunostaining, SRY-positive cells and total cells (DAPI-positive cells) of the embryos were manually quantified on eight sections from three embryos of each genotype (XY control and XY Wnt4–/–; Rspo1–/–), and the percentage of SRY-positive versus total cells was plotted on a graph.

In situ hybridization

In situ hybridization was carried out essentially as described previously (Wilkinson, 1992). Sox9 riboprobes were synthesized according to Morais da Silva et al. (Morais da Silva et al., 1996), and reverse transcribed using the RNA RT-PCR kit (Stratagene). Primers and probes were designed by the Roche Assay Design Center (https://www.rocheappliedscience.com/sis/tpcr/ul/adc.jsp). Hprt1, 5′-tcctctcaagacaccttt-3′ and 5′-cgcgtctgtcatgcatc-3′ (probe 95); Sry, 5′-agctgcacaggaggtct-3′ and 5′-agcaagcgacaggttaa-3′ (probe 82); Wt1, 5′-caccagacagacagacagt-3′ and 5′-tcaccaccttcactgt-3′ (+KTS isofrom) or 5′-gcgcttccttcaggtgag-3′ (+KTS isoform) (probe 47); Cdh2/2A33, 5′-gagcgcagagacaagac-3′ and 5′-attgcagtcgcctagtc-3′ (probe 88); fgf11, 5′-gagattctttcacaatcact-3′ and 5′-actcctgtgacctgttctc-3′ (probe 104); Sfl, 5′-ccgtctgcaagaggaagagag-3′ and 5′-aagggcagaaaag-3′ (probe 10); Gata4, 5′-actagtgccgcaagacaagcctgctctc-3′ and 5′-ggagcaagcttcacagagc-3′ (probe 58); Fos2, 5′-gcgaagctctgcttgaggcttc-3′ and 5′-gctggctctgcttgagggttctc-3′ (probe 92); Cited2, 5′-agtcgaagcagagaggg-3′ and 5′-gctcgctgcttgatgcgc-3′ (probe 77); Sox9, 5′-cagagagcttcgagaagagagcagag-3′ and 5′-acacagagctgcgctggcttc-3′ (probe 60); Atrx, 5′-ccagagcttcacagagcagag-3′ and 5′-ggagcaagcttcacagagc-3′ (probe 50).

All real-time PCR assays were carried out using the LC-Faststart DNA Master kit Roche. QPCR was performed on cDNA from one gonad and
compared with a standard curve. QPCR were repeated in at least two independent runs. Relative expression levels of each sample were determined in the same run and normalized by measuring the amount of Hprt1 (total gonadal cells) cDNA. For each genotype, n=12 gonads (six pairs of gonads).

Statistical analysis
QPCR experiments
For each sample, relative expression levels were quantified and normalized. For each genotype (n=12), the mean of these 12 absolute expression levels (i.e. normalized) was calculated and then divided by the mean of the 12 absolute expression levels of the XX samples considered as the reference (=1 when divided by itself), leading to the fold of change. Graphs of QPCR results show fold of change +1 s.e.m.

Proliferation experiments
For each of the four genotypes, four sagittal sections of three embryos were processed for confocal experiments. Immunostaining experiment followed by confocal analysis was performed four times (16 pictures per genotype).

RESULTS
WNT/CTNNB1 signalling is activated in the coelomic region of the gonad at E11.5
As expected for a gene involved in ovarian differentiation, Rspo1 is robustly expressed in embryonic ovaries. However, in situ hybridization analysis has shown that Rspo1 is also strongly expressed in the coelomic region of XY gonads at E12.5 (Parma et al., 2006). This prompted us to study the role of Rspo1 during testis development in more detail. To characterize proliferation in the early gonad, we have used whole-mount in situ hybridization in embryos at 15 ts (E11.25). Rspo1 and Wnt4 were expressed in both XX and XY gonads at this stage (Fig. 1A). These results are consistent with previous studies reporting that Wnt4 is initially expressed in both sexes (Vainio et al., 1999).

As Rspo1 and Wnt4 are WNT/CTNNB1 activators during gonadal development (Chassot et al., 2008b; Maatouk et al., 2008), we next tested whether CTNNB1 signalling is activated at an early stage of development. As a readout, we have made use of the Axin2::lacZ line that is considered to be a universal reporter of nuclear CTNNB1 activity (Lustig et al., 2002). Whole-mount X-Gal staining in embryos at E10.5 did not show a strong expression of the Axin2::lacZ reporter, suggesting that the Axin2::lacZ reporter is not yet upregulated or the canonical β-catenin signalling pathway is not activated at this stage. At E11.5, X-Gal staining revealed blue cells in the coelomic region of XX and XY gonads (Fig. 1B), and staining was confirmed in cells of the coelomic region on gonadal sections. Thus, CTNNB1 activation occurs in the coelomic region of the early gonad in both XX and XY gonads. At this stage, XY gonads exhibited high levels of cell proliferation within the coelomic epithelium, which appeared as multiple cell layers. By contrast, the coelomic epithelium of XX gonads was markedly thinner (Schmahl et al., 2000). The stronger blue staining (Axin2::lacZ) in XY gonads when compared with XX gonads may reflect the difference in thickness of the coelomic epithelium at this stage of development. These results show that Rspo1 is expressed in the XY gonad and that the WNT/CTNNB1 signalling pathway is activated in both sexes during early gonadogenesis.

XY Wnt4+/-; Rspo1+/- mice exhibit impaired testis development
It has been shown that XY Wnt4+/- gonads exhibit a delay in Sertoli cell differentiation and sex cord formation that is compensated at birth (Jeays-Ward et al., 2004). As Rspo1 is an activator of the WNT/CTNNB1 signalling pathway (Binnerts et al., 2007; Carmon et al., 2011; de Lau et al., 2011; Glinka et al., 2011), and Rspo1 and Wnt4 are expressed in the early developing gonad, we asked whether Rspo1 activates WNT4 signalling to promote testis development. At E18.5, the XY Wnt4+/-; Rspo1+/- mice exhibited descended hydroplastic testes in comparison with XY controls (Fig. 2A). Macroscopic analysis of XY control, Wnt4+/-; Rspo1-/- and Wnt4+/-; Rspo1-/- gonads at birth showed that XY Wnt4+/-; Rspo1-/- foetuses exhibit smaller gonads than the single mutants or controls (Fig. 2B), suggesting that Rspo1 and Wnt4 act synergically during testicular development. The size reduction of XY Wnt4+/-; Rspo1-/- gonads was variable (see Fig. 5), probably owing to the mixed genetic background.

To address whether ablation of both Wnt4 and Rspo1 leads to a general developmental defect, we compared the body size of littermates at birth. Wnt4+/-; Rspo1-/- double mutants and control littermates were similar in size (Fig. 2C), indicating that the gonadal hypoplasia observed in XY Wnt4+/-; Rspo1-/- foetuses is organ specific.

Given that in ovarian differentiation, upregulation of Wnt4 is initially promoted by Rspo1 expression (Tomizuka et al., 2008), XX Wnt4+/-; Rspo1-/- gonads may not exhibit more dramatic phenotypes than the single mutant gonads. As expected, XX Wnt4+/-; Rspo1-/- gonads were grossly similar to the XX Rspo1-/- gonads (data not shown), confirming that Rspo1 and Wnt4 act along the same pathway.

Proliferation of the coelomic epithelium is impaired in Wnt4+/-; Rspo1+/- gonads
Given that Rspo1 can stimulate proliferation (Chassot et al., 2011; Kim et al., 2005) and that proliferation of the coelomic epithelium is crucial for gonadal development (Schmahl and Capel, 2003; Schmahl et al., 2000), we hypothesised that Rspo1 and Wnt4 are involved in gonadal cell proliferation. To address whether cell proliferation in the coelomic epithelium is affected by Rspo1 and Wnt4 ablation in the gonads, we have performed immunostaining experiments followed by statistical analyses at 12-14 ts and 16-17 ts in three different embryos of the different genotypes: XY and XX Wnt4+/-; Rspo1-/-, and controls. At this stage, the Sf1-positive cells of the coelomic epithelium are actively proliferating and will become Sertoli cells (Schmahl et al., 2000). To quantify proliferation within the coelomic epithelium, we have used antibodies against either Ki67 (Fig. 3A,B) or phosphorylated histone H3 (data not shown), as a marker of proliferation, and laminin to delimit the basal membrane of the coelomic epithelium (Fig. 3B). At 12-14 ts (E10.5), the coelomic epithelium is made of...
a single cell layer. Proliferation in this cell layer was reduced in both XX and XY Wnt4–/–; Rspo1–/– gonads (15 and 11% of proliferating cells, respectively) when compared with XY and XX control gonads (Fig. 3A) (29 and 26%, respectively). At 16-17 ts (E11.25), proliferation in the coelomic epithelium was dramatically and highly significantly reduced in XY Wnt4–/–; Rspo1–/– gonads, and only 42% of cells were positive for proliferation markers compared with 79% in XY controls. This percentage of proliferating cells was even lower than in XX control gonads (62%) (Fig. 3B). Proliferation in the coelomic epithelium of XX Wnt4–/–; Rspo1–/– gonads was also significantly decreased, i.e. 53% of proliferative cells compared with 62% in XX controls. However, this reduction was less severe than in XY gonads. Although the proliferative activity stays constant in XX gonads (Schmahl et al., 2000), it is amplified as early as 14-15 ts in XY gonads by the action of FGF9, a growth factor secreted by the first differentiated Sertoli cells (Schmahl et al., 2004). This suggests that the greater disparity in proliferation between XY Wnt4–/–; Rspo1–/– and control gonads compared with that of the XX gonads is due to an impairment of the male-specific FGF9 effect. Indeed, the level of expression of Fgf9 was significantly reduced in XY Wnt4–/–; Rspo1–/– gonads (Fig. 4C), indicating that the decrease in Fgf9 expression amplified the defects in proliferation in XY mutant gonads relative to XY controls.

Number of SRY-positive cells number is reduced in XY Wnt4–/–; Rspo1–/– gonads

Sry is expressed within pre-Sertoli cells that are derived from the coelomic epithelium (Sekido et al., 2004; Wilhelm et al., 2005). Consequently, the proliferation of the coelomic epithelium is crucial for the production of sufficient pre-Sertoli (SRY-positive cells) and Sertoli cells (SOX9-positive cells). To investigate whether SRY expression was modified in the XY Wnt4–/–; Rspo1–/– gonads, we performed immunostaining followed by quantification of the SRY-expressing cells in XY double mutant and control gonads at E11.25 (16±1 ts). Statistical analysis revealed that the number of SRY-expressing cells was significantly decreased to half of the number of SRY-positive cells in the control gonad (Fig. 4A) by quantitative PCR was significantly reduced to around half of the level measured in the XY control gonads (Fig. 4C). To verify whether SRY expression is delayed in the mutant gonad, we next analysed SRY expression at E12.5 (Fig. 4A). Whereas only a few cells still expressed SRY in the control gonad, SRY expression was maintained in the mutant gonad, but the number of SRY-expressing cells never reached the number observed earlier in the control gonads. This suggests that, in addition to the proliferation defects, the gonadal development is partly delayed in XY Wnt4–/–; Rspo1–/– embryos.

Moreover, the level of Axin2 expression in XY Wnt4–/–; Rspo1–/– gonads collected at E11.5 (18±1 ts) measured by quantitative PCR was significantly reduced (Fig. 4B), compared with the XY gonad, suggesting that Wnt4 and Rspo1 act through the canonical β-catenin signalling pathway during early gonadogenesis. These results imply that Rspo1 and Wnt4 together, possibly through canonical β-catenin signalling, stimulate proliferation in the bi-
potential gonad and are directly or indirectly involved in Sry expression. This shows that these two genes – previously described as ‘female genes’ – are unexpectedly participating in regulating the development of the male gonad.

We next asked whether RSPO1, together with WNT4, can regulate the expression of genes involved in Sry expression. Several genetic interactions implicated in Sry transcriptional or post-transcriptional regulation have been identified, including Wt1 (–KTS and +KTS isoforms), CBX/M33 (Cbx1 and Cbx2 – Mouse Genome Informatics), Igf1r, Gata4, Fog2 (Zfpm – Mouse Genome Informatics), Sf1 and Cited2 (Barbaux et al., 1997; Buaas et al., 2009; Hammes et al., 2001; Katoh-Fukui et al., 1998; Neff et al., 2003; Tevosian et al., 2002). In XY Wnt4−/+; Rspo1−/+ gonads collected at E11.5 (18±1 ts), Wt1+KTS, Wt1-KTS, CBX/M33 and Igf1r exhibited significantly reduced levels of expression when measured by quantitative PCR, whereas Gata4, Fog2 and Sf1 showed a tendency to reduced levels of expression in the XY Wnt4−/+; Rspo1−/+ gonads relative to XY controls (Fig. 4C). This general reduction of gene expression suggests that the number of pre-Sertoli cells expressing Sry is reduced in the XY Wnt4−/+; Rspo1−/+ gonads, which is consistent with a defect in proliferation in the coelomic epithelium.

**SOX9 expression is downregulated in the XY Wnt4−/+; Rspo1−/+ gonads**

In XY gonads, SRY upregulates Sox9 that in turn induces Sertoli cell differentiation and male development (Sekido and Lovell-Badge, 2008; Vidal et al., 2001). In mice, Sox9 is upregulated in XY gonads at E11.5 (Kent et al., 1996; Morais da Silva et al., 1996) and initiates the expression of a genetic network, including the genes Amh, Fgf9 and L-Pdgs that are required for sex cord formation (Arango et al., 1999; De Santa Barbara et al., 1998; Kim et al., 2006; Malki et al., 2005; Moniot et al., 2009). Sox9 expression is therefore an important feature of testis differentiation, prompting us to analyze Sox9 expression in XY Wnt4−/+; Rspo1−/+ and Wnt4−/+; Rspo1−/+ gonads at different developmental stages.

No gonadal phenotype has been observed in XY Rspo1−/+ adult mice and these mice are normally fertile (Chassot et al., 2008b). However, we cannot exclude that a delayed testicular development
is compensated at birth, as described in the XY Wnt4+/− embryos (Jeays-Ward et al., 2004). Sox9 expression was downregulated in the XY Wnt4+/− gonad at E11.5 (Jeays-Ward et al., 2004) (Fig. 5A), but returned to normal levels between E14.5 and E18.5. To determine whether a similar delay occurs in the XY Rspo1−/− embryos, we analysed Sox9 expression at E11.5, E12.5 and E14.5 (Fig. 5), these stages corresponded to the most obvious defects in the Wnt4 mutant (Jeays-Ward et al., 2004). However, analysis of Sox9 expression in XY Rspo1−/− gonads did not reveal any differences compared with XY controls at E11.5, nor any defect in gonadogenesis and sex cord formation at E12.5 and E14.5. This suggests that ablation of Rspo1 alone does not trigger a developmental delay in sex cord formation.

In XY Wnt4+/−; Rspo1−/− gonads collected at E11.5 (18±1 ts), Sox9 expression level was reduced to around one third of the level found in normal XY gonads when measured by quantitative PCR (Fig. 4C). Moreover, in situ hybridization experiments revealed that at E11.5 (19-21 ts) in XY Wnt4+/−; Rspo1−/− gonads, Sox9 expression was dramatically decreased in comparison with XY controls (Fig. 5A). At E12.5, when sex cords are forming, XY Wnt4+/−; Rspo1−/− gonads were thinner than XY controls and fewer SOX9-expressing cells could be detected in XY Wnt4+/−; Rspo1−/− gonads relative to XY controls (Fig. 5B). In the XY mutant gonads at E14.5, sex cords were less abundant relative to XY gonads, as evidenced by whole-mount in situ hybridization for Sox9 (Fig. 5C). Although there was some variability between individuals, fewer sex cords were always observed in XY Wnt4+/−; Rspo1−/− gonads compared with XY controls, leading in some cases to the development of very small testes (Fig. 5C). In addition, histology and immunochemistry using the Sertoli cell markers FGFR2, SDMG1 (TMEM184A – Mouse Genome Informatics) and AMH (supplementary material Fig. S1; Fig. 7B) showed that fewer sex cords are formed in XY Wnt4+/−; Rspo1−/− gonads, when compared with XY gonads, at E14.5 and E18.5. This indicates that the
developmental defects observed in XY Wnt4−/−; Rspo1−/− gonads are not compensated for at birth.

The establishment of an XY specific vasculature with the formation of the coelomic vessel is one of the first cellular events observed during testis differentiation (Brennan et al., 2002; Coveney et al., 2008). This process seems to be disturbed in XY Wnt4−/−; Rspo1−/− gonads, as highlighted by PECAM1 immunostaining at E12.5 (Fig. 5B). Such alteration was not observed in the single Wnt4−/− and Rspo1−/− XY gonads. It has been shown that endothelial cells migration is required in male-specific proliferation (Cool et al., 2011). However, the defects/delays in coelomic vessel formation in XY Wnt4−/−; Rspo1−/− gonads at E12.5 are therefore likely to result from the early proliferation defects. This suggests that the male-specific proliferation and vascularisation of the gonad are two interdependent processes.

Taken together, these data indicate that the proliferation defect in the coelomic epithelium in absence of RSPO1 and WNT4 leads to a reduction in Sertoli cell numbers, evidenced by reduced expression of a range of Sertoli cell-specific genes, as well as a defect/delay in vascularisation of the gonad and a deficit in testis cord formation.

No sex reversal in the XY Wnt4−/−; Rspo1−/− gonads

Subsequently, we investigated the identity of the different cell lineages forming the XY Wnt4−/−; Rspo1−/− gonads. To verify whether or not the somatic cells of the XY Wnt4−/−; Rspo1−/− gonads have adopted a female cellular fate, we analyzed the expression of the ovarian markers FOXL2 at E12.5 (Fig. 6B). Such alteration was not observed in the single Wnt4−/− and Rspo1−/− XY gonads. It has been shown that endothelial cells migration is required in male-specific proliferation (Cool et al., 2011). However, the defects/delays in coelomic vessel formation in XY Wnt4−/−; Rspo1−/− gonads at E12.5 are therefore likely to result from the early proliferation defects. This suggests that the male-specific proliferation and vascularisation of the gonad are two interdependent processes.

Taken together, these data indicate that the proliferation defect in the coelomic epithelium in absence of RSPO1 and WNT4 leads to a reduction in Sertoli cell numbers, evidenced by reduced expression of a range of Sertoli cell-specific genes, as well as a defect/delay in vascularisation of the gonad and a deficit in testis cord formation.
reminiscent of an ovotestis (Fig. 7A). Given that testis development requires not only the expression of male-specific genes such as Sry/Sox9, but also the repression of female-specific genes, such as Wnt4 (Jameson et al., 2012a), ablation of Wnt4 prevents both Sox9 expression and male-to-female sex reversal in XY Wnt4–/–; Rspo1–/– gonads.

We next investigated whether Leydig cells, the steroidogenic cells of the testis (Yao et al., 2002), differentiate normally within the XY Wnt4–/–; Rspo1–/– gonads. Indeed, P450scc (a steroidogenic marker) was expressed in XY Wnt4–/–; Rspo1–/– gonads at E14.5 (Fig. 6B). Moreover, Leydig cells were visible in histological sections (Fig. 7A), suggesting that differentiation of the Leydig cells occurs. In the foetal gonad, the Leydig cell population is required to produce androgens that promote the development of the Wolffian duct into the epididymis, vas deferens and seminal vesicles. In Wnt4–/–; Rspo1–/– foetuses, the reproductive tracts were similar to those of XY controls and testes were descended (data not shown), indicating the presence of hormones synthesised by the Leydig cells during development. These results demonstrate that in the male gonad a Wnt4 and Rspo1 deficiency does not affect Leydig cell differentiation. Altogether, these results show that in XY gonads, ablation of Rspo1 and Wnt4 promotes hypoplastic testis formation and prevents male-to-female sex reversal from occurring.

Germ cells are committed to male differentiation as soon as they become enclosed by Sertoli cells in developing sex cords, suggesting that their sexual fate is determined by factors provided by their somatic environment (for a review, see Kocer et al., 2009). However, when sex cord development is prevented in vitro (Yao and Capel, 2002), XY germ cells can develop into male gonocytes outside of the sex cords. Histological analysis and immunostaining for MVH (germ cells) and AMH (Sertoli cells) showed that XY Wnt4–/–; Rspo1–/– gonads contain germ cells both within and outside of the sex cords (Fig. 7A). Similar to XY controls, the majority of germ cells were quiescent male gonocytes. FGF9 has been identified as a differentiation promoting factor for gonocytes (Bowles et al., 2010). Fgf9 is expressed in the XY Wnt4–/–; Rspo1–/– gonads (Fig. 4C) and thus may participate in the differentiation into gonocyte/pro spermatogonia. Surprisingly, of those germ cells outside the seminiferous cords only very few exhibited some pachytene-like structures of meiotic germ cells (data not shown). This shows that the close contact with testis cords is not absolutely required for male germ cell differentiation and germ cells can adopt a male fate and survive when localized outside of the sex cords [as shown in vivo here and elsewhere (Tanaka et al., 2000)].

DISCUSSION
One of the earliest morphological changes to occur during sex determination is a dramatic increase in size of the XY gonad coinciding with a peak of Sry expression at E11.5 (Brennan et al., 1998; Schmahl et al., 2000). This increase is due to male-specific cell proliferation beginning within the coelomic epithelial cell layer, and the subsequent entry of precursors of the supporting cells from this layer into the gonad (Karl and Capel, 1998). This rapid male proliferation is essential to allow the production of a crucial number of Sertoli cells.

In the undifferentiated gonads, there is a basal level of proliferation that stays constant in XX gonads. When entering the
XY gonads, some of the cells will express Sry/Sox9 and differentiate into Sertoli cells, synthesizing FGF9 that further stimulates proliferation and Sertoli cell differentiation (Fig. 8). In XY gonads, the coelomic epithelial cells next participate in the establishment of interstitial cell lineages before ceasing proliferation. Finally, proliferation is no longer located in the coelomic region, but occurs within the somatic cells (Karl and Capel, 1998; Schmahl and Capel, 2003; Schmahl et al., 2000). XY Wnt4–/– gonads show reduced Sox9 levels at E11.5 or E12.5 (Fig. 5) (Jeays-Ward et al., 2004), but the expression levels of Sry
at E11.5 appears to be unchanged in these mice (Jeays-Ward et al., 2004), indicating that the number of Sertoli cell precursors are not severely affected when deleting Wnt4 alone. Similarly, loss of Rspo1 alone does not significantly affect male development. However, ablation of both genes induces testicular hypoplasia characterized by a significant reduction of Sry levels and a dramatic drop in coelomic epithelium proliferation. We therefore conclude that Wnt4 and Rspo1 work in synergy to promote proliferation in the undifferentiated (E10.5-E11.25) gonad. In XY gonads, RSPO1/WNT4 signalling becomes downregulated when SRY/SOX9 expression occurs and Sertoli cells differentiate. Although the precise molecular mechanisms underlying this antagonism in the gonads remain to be elucidated, in vitro experiments suggest that SRY can repress CTNNB1 signalling (Bernard et al., 2008) and that FGF signalling represses, in vivo, the female-promoting gene Wnt4, thus allowing Sox9 expression to occur (Jameson et al., 2012a).

Whereas the XY Wnt4−/−; Rspo1−/− gonads exhibit a reduced number of Sertoli cells, the differentiation of the steroidogenic lineage is not affected. In addition, absence of gross abnormalities of the reproductive tract in these mutants suggests that the embryonic testes produced a sufficient level of androgens to allow male genitalia development. This is surprising, given that Leydig cells differentiation is dependent on Sertoli cell differentiation. However, Jeays-Ward et al. (Jeays-Ward et al., 2004) have shown that Wnt4 ablation promotes an increase of steroidogenic cells (Cyp11a1 positive) in the early developing gonads. This suggests that a potential deficit of Leydig cell differentiation in the XY double mutant gonads might be compensated for by an increase of steroidogenic cells that would normally be repressed by Wnt4 expression in the early gonad.

In the female, the early proliferation is followed by a proliferation block occurring from E12.5 (Bouma et al., 2010; Mork et al., 2012; Nef et al., 2005). Transcriptional studies reveal that cell cycle inhibitors such as p21kip1, p57kip1 and p27kip1 are specifically expressed in XX gonads at E11.5 and E12.5 (Cederroth et al., 2007), suggesting that female-specific genetic networks also regulate proliferation in developing ovaries. Thus, Rspo1 and Wnt4 stimulate cell proliferation during early ovarian differentiation, which may then be regulated by the expression of the cell cycle inhibitors. At this stage, Rspo1 and Wnt4 become involved in ovarian differentiation (Chassot et al., 2008b; Vainio et al., 1999). R-spondins are potent stem cell growth factors in the crypt of the intestine (Sato et al., 2011) but their mechanism of action appears to be complex. Indeed, R-spondins are activators of both WNT/CTNNB1 (Kazanskaya et al., 2004) and WNT/planar cell polarity (PCP) (Glinka et al., 2011; Ohkawara et al., 2011) signalling pathways. The expression of the R-spondins receptors/co-receptors complexes at the membrane of the cell at a given time may determine the signalling pathway they activate. Leucine-rich repeat-containing G protein-coupled receptor (LGR) 5 and LGR4 are essential for both Rspo1-induced β-catenin and PCP signalling (Carmon et al., 2011; de Lau et al., 2011; Glinka et al., 2011).

In the gonad, Lgr4 and Lgr5 are expressed during sex determination in a dynamic manner (Jameson et al., 2012b). Indeed, Lgr5 is expressed in male somatic cells at E11.5, and Lgr4 is expressed in female somatic cells at E12.5. At E13.5, no Lgr genes are detected in male somatic cells whereas both Lgr4 and
Lgr5 are expressed in female somatic cells. It is presently unclear whether LGR5 is the receptor transmitting the RSPO1 signal in the coelomic region of the XX and XY early gonads, and whether LGR4 is the RSPO1 receptor in the XX gonads after sex determination, when Rspo1 and Wnt4 become upregulated.

One of the remaining questions is whether CTNNB1 ablation would completely prevent early cell proliferation in the gonad. To answer this question, conditional ablation of CTNNB1 is required, as CTNNB1 knockout embryos die at E7.5 (Haegel et al., 1995). So far, however, no transgenic line with restricted expression of the CRE recombinase in the coelomic domain has been described.

In conclusion, our study demonstrates that the RSPO1/WNT4 genetic pathway involved in ovarian differentiation is indeed required for testicular development by stimulating proliferation of the coelomic epithelium of the undifferentiated gonad.

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Competing interests statement
The authors declare no competing financial interests.

Supplementary material
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References


**Fig. S1. FGFR2, AMH and SDMG1 immunostaining.** Upper panels: immunostaining for FGFR2 (Sertoli cells in red) and AMH (Sertoli cells in green) at E14.5 in XY, XX and XY $\text{Wnt4}^{-/-}; \text{Rspo1}^{-/-}$ gonads. DAPI (blue) indicates nuclei. Scale bar: 50 $\mu$m. Lower panel: immunostaining for SDMG1 (Sertoli cells in red) at E18.5 in XY, XX and XY $\text{Wnt4}^{-/-}; \text{Rspo1}^{-/-}$ gonads. DAPI (blue) indicates nuclei. Scale bar: 50 $\mu$m.