The role of WNT signaling in adult ovarian folliculogenesis

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Abstract

Wingless-type mouse mammary tumor virus integration site (WNT) signaling molecules are locally secreted glycoproteins that play an important role in regulation of ovarian follicle maturation and steroid production. Components of the WNT signaling pathway have been demonstrated to impact reproductive functions, including embryonic development of the sex organs and regulation of follicle maturation controlling steroidogenesis in the postnatal ovary. Emerging evidence underscores the complexity of WNT signaling molecules in regulation of dynamic changes that occur in the ovary during the reproductive cycle. While disruption in the WNT signaling cascade has been recognized to have deleterious consequences to normal sexual development, more recent studies are beginning to highlight the importance of these molecules in adult ovarian function related to follicle development, corpus luteum formation, steroid production, and fertility. Hormonal regulation of WNT genes and expression of members of the WNT signaling network, including WNT ligands, frizzled receptors, and downstream signaling components that are expressed in the postnatal ovary at distinct stages of the estrous cycle suggest a crucial role in normal ovarian function. Similarly, FSH stimulation of T-cell factor-dependent gene expression requires input from β-catenin, a lynchpin molecule in canonical WNT signaling, further indicating β-catenin participation in regulation of follicle maturation. This review will focus on the multiple functions of WNT signaling in folliculogenesis in the adult ovary.


Introduction

The adult ovary is a dynamic organ undergoing constant changes throughout the estrous cycle as follicles progress from immature preantral follicles to more developed preovulatory follicles and eventually formation of the corpus luteum following ovulation. The multifaceted process of folliculogenesis relies on synchronized input of hormones exchanged between the hypothalamus, the pituitary, and the gonads. While the initial stages of follicle development occur largely in the absence of gonadotropin input, the transition from preantral to a preovulatory follicle occurs as a result of increased follicle-stimulating hormone (FSH) and luteinizing hormone (LH) responsiveness (Richards 1980) along with involvement of numerous other local hormones and growth factors (Findlay 1993, Monget & Bondy 2000).

The actions of the gonadotropins are also dependent on other signaling pathways and a diverse set of intraovarian factors expressed in a cell-specific manner at defined stages of follicular growth (Richards et al. 2002a). One more recently identified regulator of ovarian function is the wingless-type mouse mammary tumor integration site family (WNT) of signaling molecules. WNTs are highly conserved signaling molecules that act through β-catenin dependent and β-catenin independent pathways to regulate important processes of cellular growth and differentiation including cell proliferation, cell fate specifications, embryonic induction, and the generation of cell polarity (Cadigan & Nusse 1997, Miller et al. 1999, Komiya & Habas 2008). Misregulation of WNT signal transduction can lead to a variety of pathologies, including the development of carcinomas of the breast, colon, skin, and ovary (Polakis 2000, Giles et al. 2003, Logan & Nusse 2004, Boerboom et al. 2005). The foundational study establishing a requirement of WNT signaling molecules in the female ovary was performed by Vainio et al. (1999). This group utilized mice null for Wnt4 to demonstrate a role for this molecule in early ovarian development and suppression of the male reproductive tract. Wnt4 null females have sex-reversed ovaries that express genes associated with testicular development, along with a reduced number of oocytes at birth. Evaluation of Wnt4 in the postnatal ovary using this mouse model was not possible, as the homozygous mutation results in death shortly after birth due to renal failure. Subsequent work aimed at elucidating the importance of WNT signaling in the postnatal ovary has identified multiple Wnt/WNT family member transcripts expressed at specific stages of follicle...
A  
No WNT signal  
Canonical WNT signaling pathway  
WNT signal  

Frizzled  
LRP  
AXIN  
GSK3  
CK1  
APC  
DVL  
Proteasome  
Groucho  
TCF  

B  
No WNT signal  
Emerging WNT signaling pathway model  
WNT signal  

Frizzled  
LRP  
AXIN  
GSK3  
CK1  
APC  
DVL  
Proteasome  
Groucho  
TCF  
β-catenin  
β-TrCP  

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development within the adult ovary of mice, rats, humans, and cattle (Hsieh et al. 2002, Ricken et al. 2002, Wang et al. 2009, Gupta et al. 2014). In addition, functional studies in the adult ovary have shown a fundamental requirement of WNT signaling for normal ovarian function and fertility. Though our understanding of contributions of WNT signaling to the regulation of folliculogenesis has grown tremendously in recent years, much still remains unknown about the broader physiological involvement of WNT signaling in the adult ovary. This review will focus on the role of WNT ligands, downstream signaling molecules, and their interaction with various hormones in the maturation of the ovarian follicle.

WNT signaling

The WNT signaling pathway is a conserved pathway among many species that controls numerous developmental processes as well as disease states. WNTs can initiate three separate signal transduction cascades through interaction of the ligand with their cognate frizzled (FZ) receptor. Most mammalian genomes are comprised of 19 structurally related Wnt genes (Logan & Nusse 2004) that encode secreted glycoproteins, which interact with a large extracellular cysteine-rich domain (CRD) on FZ seven-transmembrane receptors (Bhanot et al. 1996, Dann et al. 2001). In general, WNT proteins range in length from 350 to 400 amino acids, and are ~40 kDa in size (Cadigan & Nusse 1997, Clevers & Nusse 2012). WNTs contain 20–85% identity among species and are defined by their nearly identical primary sequence that contains 23–24 specifically spaced cysteine residues (Cadigan & Nusse 1997, Miller 2002). While WNTs have been classified as morphogens capable of specifying cell fate in a concentration-dependent manner, in most contexts they are short-range molecules acting predominately on cells that are close to each other (Christian 2000, Sato et al. 2011, Strand & Micchelli 2011). The paracrine or autocrine quality of WNTs is likely reflective of the low (~200 ng/ml) expression levels of these proteins (Willert et al. 2003).

The activity of WNT signaling is dependent on the cellular context and the particular combination in which the more than 15 receptors and co-receptors are expressed (reviewed in Niehrs (2012)). The ten FZ proteins are membrane-bound receptors belonging to the G-protein coupled receptor family (Slusarski et al. 1997, Liu et al. 2001, Foord et al. 2005, Bjarnadottir et al. 2006) and are thought to bind to WNT proteins promiscuously. FZ proteins contain a conserved 120-amino acid CRD that mediates the binding of WNT ligands (MacDonald & He 2012) with nanomolar affinity ($K_d$ of 1–10 nM) (Hsieh et al. 1999, Rulifson et al. 2000, Wu & Nusse 2002). Differences in affinity of specific WNTs with different FZ may determine which signaling branch is activated (He et al. 1997). Transduction of a WNT signal involves an interaction between WNT and FZ as well as cooperation with single-pass co-receptors, LDL receptor-related protein 5 or 6 (LRP5/6) or receptor tyrosine kinase-like orphan receptor 1 or 2, to direct β-catenin-dependent or β-catenin-independent pathways respectively. The main WNT signaling pathways include the canonical WNT/β-catenin (β-catenin-dependent) and non-canonical (β-catenin-independent) planar cell polarity, and WNT/Ca$^{2+}$ pathways. Upon binding of WNT to the FZ/co-receptor complex, the signal is relayed to the downstream cytoplasmic phosphoprotein dishevelled (DVL) that is pivotal in all three pathways (Boutros & Mlodzik 1999, Sheldahl et al. 2003).

The most extensively dissected and therefore the best understood WNT pathway is the canonical WNT signaling cascade that signals through the transcriptional co-factor, β-catenin to regulate gene expression. In addition to the WNT/FZ complex, the canonical WNT/β-catenin pathway also requires the presence of a single-span transmembrane molecule identified in vertebrates as LRP5/6 (Pinson et al. 2000) to relay a signal. The prevailing view regarding the mechanism regulating cytoplasmic β-catenin has been that in the absence of WNT ligand, constitutively active casein kinase 1 (CK1) and glycogen synthase kinase 3 beta (GSK3β) phosphorylate β-catenin, captured by the degradation complex, at four specific serine and threonine residues (Axin1/APC complex. In the presence of a WNT signal, β-catenin accumulates in the cytoplasm and translocates to the nucleus where it acts as a coactivator of TCF/LEF to restore transcriptional activity of genes normally bound by repressor complexes. (B) An emerging view of canonical WNT signaling relies on an intact degradation complex to regulate β-catenin. In the absence of a WNT signal, the degradation complex binds β-catenin, and subsequent phosphorylation, ubiquitination, and proteosomal degradation occur within the AXIN1/GSK3β/APC complex. In the presence of a WNT signal, activation of the FZ/LRP co-receptors promotes association of the intact AXIN1 degradation complex with the phosphorylated tail of LRP and the dissociation of β-TrCP. The degradation complex still binds and phosphorylates β-catenin, but ubiquitination by β-TrCP fails to occur. Phosphorylated β-catenin saturates the complex, effectively inactivating the complex and allowing newly synthesized β-catenin to initiate gene transcription. Figure modified from Clevers & Nusse (2012), for details see Li et al. (2012).
The role of WNT in follicle development

The presence and activity of WNT signaling components in the ovary is not unexpected given the variety of physiological processes known to be regulated by the WNT family of proteins. Members of the WNT family are divided into two functional groups, with the canonical WNTs (Wnt1, Wnt2, Wnt3A, and Wnt8) classified by their ability to induce secondary dorsal–ventral axis in Xenopus embryos and to transform mammary epithelial cell lines (Wong et al. 1994, Shimizu et al. 1997). Canonical WNT signaling is governed by the interaction of β-catenin with other molecules to regulate cellular decisions related to proliferation, differentiation, and morphogenesis (Willert & Jones 2006, Komiya & Habas 2008, Angers & Moon 2009). A series of studies have identified the expression and regulation of WNT ligands and downstream WNT signaling components in the developing follicle and corpus luteum of rats, mice, humans, and cattle (Hsieh et al. 2002, Ricken et al. 2002, Harwood et al. 2008, Wang et al. 2009, Castanon et al. 2012, Gupta et al. 2014; Table 1). However, characterization of specific WNT molecules during folliculogenesis has been focused primarily on Wnt2/ WNT2 and Wnt4/WNT4 in mice, rats, and humans, although recent studies have unveiled contributions of FZ receptor agonist, WNT3A in follicular development and steroid production of mice and rats (Li et al. 2014, Stapp et al. 2014).

Wnt2 expression is detected in granulosa cells of immature rat ovaries at all stages of follicle development (Ricken et al. 2002) with the greatest WNT2 immuno-reactivity in mouse cumulus and mural granulosa cells and in large, healthy preantral and antral follicles (Wang et al. 2010). Supporting a role of WNT2 during these distinct stages of follicle growth is the demonstrated increased expression of WNT2 mRNA in response to FSH-treatment in cultured bovine granulosa cells (Castanon et al. 2012) and WNT2 in human cumulus cells collected after gonadotropin stimulation (Wang et al. 2009). Likewise, RNAi-mediated knockdown of Wnt2 inhibits granulosa cell proliferation that inversely increased the proportion of Edu-positive granulosa cells with a WNT2 encoding retrovirus (Wang et al. 2010). Overexpression of WNT2 via transduction of granulosa cells with a WNT2 encoding retrovirus conversely increased the proportion of Edu-positive cells and abundance of PCNA, events that are expected to promote cell proliferation (Wang et al. 2010). Additionally, WNT2/Wnt2 overexpression increases cytoplasmic and nuclear accumulation of β-catenin in mouse granulosa cells (Wang et al. 2010) and in a rat granulosa cell line (DC3) that displays characteristics of early-stage follicle development (Finnson et al. 2012). The mechanism by which WNT2 controls β-catenin is seemingly by regulating cytoplasmic accumulation of...
### Table 1 Expression of WNT ligand and FZ receptor in adult mammalian ovaries.

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<th>Descriptions of location</th>
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<td>Luteinized granulosa cells from healthy and endometrial afflicted ovaries</td>
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<td>Luteinized granulosa cells from healthy and endometrial afflicted ovaries</td>
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<td>Granulosa and luteal cells from hormone stimulated ovaries</td>
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<td>Wnt6</td>
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<td>Wnt7a/WNT7A</td>
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<td>Luteal cells</td>
<td>Mouse, Harwood et al. (2008)</td>
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<td>Wnt7b</td>
<td>Whole ovary on days 6–12 postpartum</td>
<td>Porcine, Kiewisz et al. (2011)</td>
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<td>Wnt8</td>
<td>Whole ovary following PMSG/hCG stimulation</td>
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<td>Wnt8B</td>
<td>Whole ovary following PMSG/hCG stimulation</td>
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<td>Wnt9b</td>
<td>Whole ovary on days 0–21 postpartum</td>
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<td>Wnt10a</td>
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<td>Wnt10b</td>
<td>Whole ovary on days 0–21 postpartum</td>
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<td>Wnt11/WNT11</td>
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<td>Mouse, Abedini et al. (2015)</td>
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<td>Granulosa cells from dominant follicles</td>
<td>Mouse, Harwood et al. (2008)</td>
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<td>Wnt16/WNT16</td>
<td>Whole ovary on days 0–21 postpartum</td>
<td>Mouse, Abedini et al. (2015)</td>
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<td>Fzd1</td>
<td>Whole ovary on days 0–21 postpartum</td>
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<td>Cumulus cell–oocyte complex</td>
<td>Mouse, Abedini et al. (2015)</td>
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<td>Granulosa cells of pre-ovulatory follicles from ovaries following PMSG/hCG</td>
<td>Mouse, Hernandez-Gonzalez et al. (2006)</td>
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<td>Fzd2</td>
<td>Whole ovary on days 0–21 postpartum</td>
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<td>Cumulus cell–oocyte complex</td>
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<td>Fzd3</td>
<td>Whole ovary following PMSG/hCG stimulation</td>
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<td>Fzd4</td>
<td>Whole ovary on days 0–21 postpartum</td>
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<td>PMSG/hCG stimulated, pregnant and postpartum ovaries as well as CL</td>
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<td>Fzd5</td>
<td>Whole ovary on days 0–21 postpartum</td>
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<td>Fzd6/FZD6</td>
<td>Whole ovary on days 0–21 postpartum</td>
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<td>Granulosa cells from follicles at the emergence, predeviation, onset of deviation, and early dominance stage</td>
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<td>Fzd7</td>
<td>Whole ovary following PMSG/hCG stimulation</td>
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<td>Whole ovary on days 0–21 postpartum</td>
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<td>Fzd9</td>
<td>Whole ovary on days 0–21 postpartum</td>
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<td>Fzd10</td>
<td>Whole ovary on days 0–21 postpartum</td>
<td>Mouse, Harwood et al. (2008)</td>
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GSK3β as WNT2 knockdown granulosa cells have increased cytoplasmic GSK3β that results in reduced β-catenin. Moreover, siRNA knockdown of β-catenin reduced granulosa cell expression of PCNA and prevents WNT2 overexpression to enhance DNA synthesis of mouse granulosa cells (Wang et al. 2010). These data indicate that regulation of granulosa cell proliferation relies on intact WNT2/β-catenin signaling.

Additional recent data also indicate that in mouse granulosa cells WNT2 can regulate gap junction signaling pathways important for ovarian folliculogenesis (Wang et al. 2013). In WNT2 siRNA treated mouse granulosa cells, connexin 43, a gap junction protein required for follicular development beyond the early preantral stages, and gap junctional intercellular communication between cells was reduced (Wang et al. 2013). While WNT2 appears to be important for follicle maturation and granulosa cell proliferation, female mice null for Wnt2 are reported to be fertile (Monkley et al. 1996), suggesting compensatory activity of other molecules, possibly other WNTs. Though defects in placental vascularization are observed in Wnt2-null females, no data specifically related to ovarian function have been reported (Monkley et al. 1996). Together these data suggest that Wnt2 expression is regulated by FSH and contributes to preantral to antral maturation of the follicle through granulosa cell proliferation mediated by β-catenin.

Wnt4 expression is found in rat and murine granulosa cells throughout follicle development (Hsieh et al. 2002) and in mouse cumulus–oocyte complexes (Hernandez-Gonzalez et al. 2006). Conversely, WNT4 is not detected in human cumulus granulosa cells obtained from oocytes prior to IVF (Wang et al. 2009). In adult rodent granulosa cells Wnt4 is elevated in response to human chorionic gonadotropin (hCG) stimulation and remains elevated in the corpora lutea (Hsieh et al. 2002). Likewise, estrus synchronization of gilts utilizing PGF2α/pregnant mares serum gonadotropin (PMSG)/hCG increased expression of WNT4 in luteal tissue compared to control females (Kiewisz et al. 2011). Targeted deletion of Wnt4 in mouse granulosa cells resulted in subfertile females with smaller ovaries and fewer healthy antral follicles at 42 days of age compared with control mice (Boyer et al. 2010). These results suggest that WNT4 originating from the granulosa cells is necessary for follicle maturation. Adenoviral overexpression of WNT4 in cultured granulosa cells from equine CG (eCG)-treated mice results in increased expression of ovarian β-catenin target genes, Cyp11a1, Cyp19a1, and StAR (Boyer et al. 2010). Furthermore, WNT4 was shown to regulate the expression of steroidogenic genes in vivo as granulosa cells isolated from Wnt4-null mice treated for 48 h with eCG, followed by an ovulatory dose of hCG had lower expression of Cyp11a1, Cyp19a1, and StAR, compared to controls (Boyer et al. 2010). Similarly, eCG-treated Wnt4-null mice had lower serum progesterone at 0, 12, and 24 h after hCG compared to controls. Further evidence of WNT4 signaling via β-catenin is found in the fetal mouse ovary where constitutively active β-catenin is able to prevent germ cell loss in Wnt4 KO ovaries (Liu et al. 2010). Data suggests that β-catenin can mediate the events of WNT4 that are important in regulation of antral follicle maturation and steroidogenesis.

Similar to WNT ligands, FZ receptors have been shown to be expressed at specific stages during ovarian follicular maturation, ovulation, and luteinization (Table 1). A number of FZ receptors have been detected in granulosa cells; however, little is known about the physiological relevance of FZ in adult folliculogenesis. In the mouse ovary, Fz1 expression is selectively and transiently induced in large ovulatory follicles by an ovulatory dose of hCG (Hsieh et al. 2002). Evaluation of Fz1 expression in progesterone receptor (PR) knockout mice, which fail to ovulate when hormonally stimulated, show an altered expression of Fz1 compared with PR heterozygotes. In this model, the initial increase of Fz1 expression is comparable in ovaries of PR knockout and PR heterozygotes, however, by 12 h after LH-stimulation (a time point just prior to ovulation), the expression of Fz1 was reduced in PR knock out ovaries compared to PR heterozygotes (Hsieh et al. 2002). While these data indicate that LH-mediated induction of Fz1 appears to depend on PR, Fz1-deficient mice are fertile (Yu et al. 2010) with only marginal differences in litter size reported (Lapointe et al. 2012). Therefore, Fz1 does not appear to be necessary in processes related to rupture. In contrast to Fz1, Fz4 displays distinct expression in the adult rodent corpus luteum of gonadotropin-treated and pregnant mice and is required for fertility. Mice lacking Fz4 receptor demonstrate follicle development that is responsive to hormone stimulation, and results in the expected genes expression profiles involved in early follicle development (Hsieh et al. 2005). Furthermore, adult female Fz4-null mice exhibit normal ovulation and ability to produce fertilized oocytes but are sterile as a consequence of failure of embryo implantation. This inability to establish a successful implantation is due to the impaired formation of the corpora lutea and the associated reduction of luteal-specific gene expression and progesterone production (Hsieh et al. 2005).

Of note, Lrp4, a member of the LDL receptor family implicated in a number of diverse biological functions has been detected in follicular cells of the adult mouse ovary (Yamaguchi et al. 2006). While the ligand for LRP4 remains unknown, it is closely related to the WNT co-receptors LRP5/6 (Zong et al. 2012). Expression of Lrp4 specific to the migratory primordial germ cells and adult gonad but not in embryo or germ cell-derived stem cells suggest Lrp4 may be a marker distinguishing germ cells from embryo-derived pluripotent stem cells (Yamaguchi et al. 2006).
Gonadotropin regulation of WNT gene expression

There is also evidence that select Wnt family gene expression is hormonally regulated in rodent ovaries. For example, Wnt4 expression is elevated in rat granulosa cells following hCG stimulation, and high expression of Wnt4 is detected in terminally differentiated luteal cells (Hsieh et al. 2002). Additionally, genetically modified mice that hypersecrete LH (Tg[(Gsa-LHB/CGB)94Jhn]) also develop granulosa cell tumors that display alterations in members of the WNT signaling pathway (Owens et al. 2002). Specifically, Wnt4 and secreted frizzled related protein 4 (SFRP4), a proposed inhibitor of the WNT pathway, are dramatically decreased in granulosa cell tumors, while a WNT receptor, Fz10, was increased in these same granulosa cell tumors. However, it was the work of Parakh et al. (2006) that provided the first direct indication that β-catenin was required for FSH/cAMP-induction of Cyp19a1 expression in a human granulosa tumor cell line (KGN), and in primary cultures of rat granulosa cells. This increased expression of Cyp19a1 in response to FSH was determined in KGN cells to be mediated by functional interactions of β-catenin with steroidogenic factor 1 (NR5A1). In subsequent studies, conditional deletion of β-catenin in primary cultures of mouse granulosa cells similarly resulted in a compromised ability of FSH to stimulate Cyp19a1 expression as well as consequent estradiol (E2) production, reinforcing a role for β-catenin in steroid production from the ovary (Hernandez Gifford et al. 2009). A requirement for β-catenin in FSH regulation of steroid production has more recently been identified in granulosa cells of large bovine antral follicles, as high estrogen-producing follicles demonstrate an increase in β-catenin protein accumulation compared to follicles with low intrafollicular E2 concentrations (Castanon et al. 2012). Consistent with β-catenin’s role in regulation of steroidogenesis is the demonstrated ability of FSH to directly increase β-catenin protein accumulation (Castanon et al. 2012, Stapp et al. 2014) and β-catenin/TCF dependent transcriptional activity in granulosa cells (Fan et al. 2010, Stapp et al. 2014). In addition, Law et al. (2013) showed that FSH via PKA stimulates phosphorylation of β-catenin on Ser552 and Ser675, leading to its activation. FSH stimulation of transcriptionally active β-catenin promotes NR5A1 and TCF-regulated gene expression, including Lhcgr (Law et al. 2013). Together these data confirm that activation of β-catenin facilitates FSH-mediated actions in ovarian follicular cells.

β-catenin’s participation in the regulation of steroidogenesis has also been linked to LH-mediated production of progesterone from bovine corpora lutea. In cultured bovine luteal cells, LH stimulation of cAMP/PKA results in phosphorylation of GSKβ allowing stabilization of β-catenin (Roy et al. 2009). Increased levels of transcriptionally active β-catenin interact with the proximal promoter of the STAR gene and successively increase STAR mRNA expression and progesterone synthesis. However, it appears that β-catenin alone is insufficient to modulate steroid pathways and that contributions of the gonadotropins are integral for β-catenin to maximally impact steroidogenesis in ovarian cells. Overexpression of adenoviral Δ90 β-catenin, a β-catenin mutant lacking N-terminal GSK3β phosphorylation sites involved in its targeted degradation, resulted in only modest regulation of Cyp19a1 and Cyp11a2 mRNA in granulosa cells (Parakh et al. 2006) and had no effect on progesterone concentrations in media from cultured luteal cells (Roy et al. 2009).

Negative feedback loops regulate WNT/β-catenin

Whereas previous studies utilizing overexpression systems indicate β-catenin participates in gonadotropin induction of steroidogenic enzyme expression and steroid output, a recent study from Stapp et al. (2014) revealed a previously unappreciated inhibition of steroidogenesis with concomitant stimulation of FSH and canonical WNT signaling pathways. Exposure of primary rat granulosa cells to recombinant WNT3A at a minimal effective dose of 50 ng/ml caused specific induction of canonical WNT signaling as determined by increased expression of the WNT target gene, Axin2 and stimulation of the β-catenin/TCF promoter reporter TOPFlash (Stapp et al. 2014). Unexpectedly, WNT3A induction of β-catenin resulted in downregulation of FSH-mediated expression of key steroidogenic enzymes (StAR, Cyp11a1, and Cyp19a1) and ovarian differentiation factors (Lhcgr and inhibin alpha). Co-incubation of FSH and WNT3A repressed FSH-induced steroidogenic enzyme expression that further translated to a reduction in E2 and progesterone production (Stapp et al. 2014). In agreement with these findings, WNT pathway agonist/GSK3β inhibitor, LiCl, and WNT3A significantly decreased E2 concentration in cultured mouse follicles, while treatment with a WNT inhibitor increased culture media concentrations of E2 (Li et al. 2014).

The noted upregulation of Axin2, a negative regulator of WNT signaling, in response to co-stimulation of granulosa cells with WNT3A and FSH allowed for detection of a negative feedback mechanism whereby FSH regulates canonical WNTs in an effort to control TCF responsive genes. These data provide valuable insight into the physiological functions of β-catenin in the adult ovary. The notion of creating a negative feedback loop to ensure β-catenin remains controlled is consistent with the detection of WNT/β-catenin signaling antagonists VNT inhibitory factor 1 (Wif1), naked cuticle homolog 1 (Nkd1), dickkopf 4 (Dkk4), and Axin2 in ovaries of mice that constitutively express β-catenin (Boerboom et al. 2006). Similarly,
overactivation of β-catenin has negative effects on LH-induced cumulus–oocyte complex expansion, ovulation, luteinization, and progesterone production (Fan et al. 2010). Granulosa cells from mice expressing dominant stable β-catenin have muted expression of StAR, Cyp11a1, and Lhcgr following forskolin and phorbol myristate acetate (PMA)-treatment that is meant to mimic the effects of LH in vitro (Fan et al. 2010).

**Modulators of β-catenin suppression**

Negative feedback mechanisms that limit the duration of a signaling event following initial stimulus are present in most signal transduction pathways. The data mentioned above provide evidence that FSH via β-catenin/TCF pathway upregulates FSH target genes involved in granulosa cell maturation and differentiation. WNT ligands appear to be another FSH target that may function in a feedback manner by upregulating Axin2 mRNA expression. Axin1 is a known negative regulator of the canonical WNT signaling pathway; however, the significance of the Axin1 homologue Axin2 in granulosa cells remains to be characterized. AXIN2 is thought to act as a scaffold protein to facilitate phosphorylation of β-catenin by GSK3β resulting in its consequent degradation (Jho et al. 2002). Induction of Axin2, therefore, may exert an inhibitory effect on β-catenin to effectively shut down β-catenin/TCF gene transcription (Fig. 2).

Numerous FSH target genes in granulosa cells are TCF-responsive, including but not limited to Cyp19a1 and Lhcgr (Law et al. 2013).

Additional alternative scenarios for limiting a WNT signal exist including β-catenin’s interaction with a nuclear molecule that could prevent it from binding transcriptional targets. One such candidate is Chibby (CBY1), a conserved nuclear associated antagonist of the WNT pathway that associates with the C-terminal domain of β-catenin and blocks its interaction with TCF/LEF transcription factors (Takemaru et al. 2003). The expression of Cby1 has been detected in a variety of adult human tissues (Takemaru et al. 2003). In COS7 cells, the CBY1 protein is largely nuclear and its
localization is unaffected by expression of WNT1, WNT5a, or β-catenin (Takemaru et al. 2003). While characterization and gonadotropin control of CBY1 in the ovary remains to be demonstrated, a recent study Finson et al. (2012) identified the expression of CBY1 in a SV-40 transformed rat granulosa cell line (DC3). Overexpression of Wnt2 in DC3 cells led to β-catenin accumulation in the nucleus but failed to stimulate β-catenin/TCF-dependent transcription, likely as a consequence of CBY1 association and suppression of endogenous β-catenin (Finson et al. 2012).

Another molecule that may modulate follicular development is the Forkhead box O (FOXO) family of transcription factors that are recognized for their involvement in the regulation of apoptosis, proliferation, and cell cycle arrest (Burgering & Medema 2003). FOXOs are downstream targets of PI3K/AKT pathway, and direct phosphorylation by AKT inhibits transcriptional activation of FOXO by causing their exclusion from the nucleus into the cytoplasm and subsequent degradation. FOXO transcription factors are found in the rodent ovary and are regulated by gonadotropins. In granulosa cells, FSH enhances Foxo1 gene expression in granulosa cells of the preovulatory follicle, and is rapidly downregulated following hCG induced ovulation (Richards et al. 2002b, Fan et al. 2010) a pattern consistent with FOXO1 repression of granulosa cell proliferation and steroidogenesis (Park et al. 2005, Liu et al. 2009). Likewise, FOXO1 represses Lhcgr expression in granulosa cells and is present on the promoter of vehicle-treated cells, but is removed from the promoter after FSH stimulation (Law et al. 2013). A study by Hoogeboom et al. (2008) proposed β-catenin to be a link between the WNT signaling and FOXO pathways, given the ability of FOXO3A to inhibit TCF-transcription by binding to β-catenin. To elucidate the role of WNT/β-catenin in regulation of early follicle development, a recent study employed an in vitro follicle culture system utilizing isolated secondary follicles that were cultured in the presence or absence of WNT pathway activators and inhibitors (Li et al. 2014). In this study, WNT pathway activators, LiCl and WNT3A were found to decrease phosphorylation of FOXO3A while the WNT inhibitor, IWR-1, increased FOXO3A phosphorylation. In addition, FOXO3A targets, Bim, Puma, and p27 were increased by WNT3A and LiCl and decreased by WNT inhibition (Li et al. 2014). Furthermore, activation of WNT/β-catenin resulted in a large number of abnormal follicles, while suppression of this pathway promoted follicle growth (Li et al. 2014). Consistent with negative feedback results of WNT inhibiting FSH signaling responses, these data suggest that β-catenin signaling may be necessary for keeping follicle growth in check by negatively controlling early follicle development and that several different mechanisms may participate in this regulation.

Future considerations

A large body of data definitively recognizes WNT signaling as an essential factor for proper development of the female mammalian gonad (Vainio et al. 1999, Heikkila et al. 2001, Biason-Lauber & Konrad 2008, Maatouk et al. 2008); however, the contribution of WNT family signaling components to ovarian folliculogenesis in the adult remains to be fully elucidated. It is suspected that the divergent roles or even opposing effects of WNT signaling is likely attributed to the different stages of follicle development and hormonal milieu present during the development of the ovarian follicle. It is clear that pituitary gonadotropins regulate ovarian events during the estrous cycle through the convergence of multiple signaling pathways. One newly recognized pathway is the canonical WNT signaling pathway that regulates levels of the downstream transcriptional co-factor, β-catenin shown to impact gonadotropin-responsive target gene expression and steroid production. Identification of WNT signaling in gonadotropin-mediated events in the adult ovary highlights the role of this pathway in regulation of normal follicle maturation, ovulation and corpus luteum formation and function, but many questions in this field remain to be explored.

Functional studies in granulosa cells have evaluated the influences of only a few WNTs, namely WNT2, WNT4, and more recently WNT3A. A need therefore remains to determine if other WNTs known to be present in the adult ovary are involved in ovarian function. Although the non-canonical WNTs have been less characterized than the canonical WNT/β-catenin pathway, it is possible that these WNTs contribute to folliculogenesis and ovarian steroidogenesis. This idea is emphasized by the apparent discordant data in the literature regarding the effect of co-stimulation of the extracellular WNT and FSH signaling pathways on steroidogenic enzyme expression in granulosa cells. This difference is conceivably due to the use of two different WNT ligands employed in each study. Indeed, WNT3A and WNT4 have differing biological activities and as such are classified into two separate functional groups that can trigger distinct developmental outcomes (Wong et al. 1994, Du et al. 1995). However, the lines between these prototypical classifications are becoming blurred as data now suggests that WNT signaling is not strictly regulated by the ligand itself but that the receptor context dictates the signal output (Mikels & Nusse 2006). Furthermore, a single WNT protein has been shown to simultaneously activate different branches of the WNT signaling pathway in the same cell dependent on WNT concentration (Nalesso et al. 2011). Together, these findings underscore the significance of evaluating the specific receptors present during the different stages of follicular development, along with defining which WNTs may be binding. Since WNT proteins have been
shown to activate different pathways with distinct and independent outcomes depending on the concentration of WNT (Nalesso et al. 2011), it will be interesting to evaluate dose-dependent treatment paradigms at different stages of follicle development such as in granulosa, granulosa–lutein, and differentiated luteal cells. Investigating changes that occur in the FZ and co-receptor complexes in follicular cells co-incubated with gonadotropin and WNT ligands has not been evaluated but would also be of value.

Follicles are exposed to various WNTs during follicle maturation that target β-catenin to the nucleus via the canonical WNT/β-catenin pathway to regulate target gene expression. Recent studies also identify a unique PKA-dependent regulation of β-catenin in response to FSH stimulation (Law et al. 2013) that regulates granulosa cell gene expression. It is interesting to consider whether PKA activated β-catenin regulates a similar set of genes as β-catenin that is regulated by GSK3β. Additionally, it remains to be determined if PKA-activation of β-catenin by both LH and FSH occurs in an equivalent fashion. Evaluation of WNT promoters for steroid response elements or other important regulatory regions may provide insight into the factors that may play a role in their function. In conclusion, the WNT signaling pathway encompasses multiple layers of complexity, and while our understanding of the role of WNTs in regulation of postnatal ovarian function and steroidogenesis continues to expand, there are many important questions that need to be answered in order to gain a complete understanding of the contribution of this large family of signaling molecules to folliculogenesis.

Declaration of interest

The author declares that there is no conflict of interest that could be perceived as prejudicing the impartiality of the review.

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