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REVIEW ARTICLE

Peripheral and Central Mechanisms Involved in the Hormonal Control of Male and Female Reproduction

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Reproduction involves the integration of hormonal signals acting across multiple systems to generate a synchronised physiological output. A critical component of reproduction is the luteinising hormone (LH) surge, which is mediated by oestradiol (E_2) and neuroprogesterone interacting to stimulate kisspeptin release in the rostral periventricular nucleus of the third ventricle in rats. Recent evidence indicates the involvement of both classical and membrane E_2 and progesterone signalling in this pathway. A metabolite of gonadotrophin-releasing hormone (GnRH), GnRH-(1-5), has been shown to stimulate GnRH expression and secretion, and has a role in the regulation of lordosis. Additionally, gonadotrophin release-inhibitory hormone (GnIH) projects to and influences the activity of GnRH neurones in birds. Stress-induced changes in GnIH have been shown to alter breeding behaviour in birds, demonstrating another mechanism for the molecular control of reproduction. Peripherally, paracrine and autocrine actions within the gonad have been suggested as therapeutic targets for infertility in both males and females. Dysfunction of testicular prostaglandin synthesis is a possible cause of idiopathic male infertility. Indeed, local production of melatonin and corticotrophin-releasing hormone could influence spermatogenesis via immune pathways in the gonad. In females, vascular endothelial growth factor A has been implicated in an angiogenic process that mediates development of the corpus luteum and thus fertility via the Notch signalling pathway. Age-induced decreases in fertility involve ovarian kisspeptin and its regulation of ovarian sympathetic innervation. Finally, morphological changes in the arcuate nucleus of the hypothalamus influence female sexual receptivity in rats. The processes mediating these morphological changes have been shown to involve the rapid effects of E_2 controlling synaptogenesis in this hypothalamic nucleus. In summary, this review highlights new research in these areas, focusing on recent findings concerning the molecular mechanisms involved in the central and peripheral hormonal control of reproduction.

Key words: progesterone, oestrogens, androgens, paracrine, autocrine

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Introduction

Reproduction is tightly regulated by the actions of hormones, both central and peripheral in origin. The 'classical' mechanisms of steroidal control of reproduction have been studied for decades, yet questions remain about how these hormones interact within the nervous system to elicit a coordinated response leading to ovulation and fertilisation. The common final pathway to the regulation of reproductive function is dependent on the appropriate functioning of the hypothalamic-pituitary-gonadal (HPG) axis. The proper coordination of the HPG axis relies largely on the inputs that regulate gonadotrophin-releasing hormone (GnRH) release from hypothalamic neurones. In recent years, numerous nonclassical mechanisms have been uncovered, including newly understood membrane, autocrine and paracrine actions of steroid hormones. In addition, novel neuropeptides have been added to the list of

neuroendocrine mediators such as the truncated GnRH [GnRH-(1-5)], as well as the inhibitory gonadotrophin release-inhibitory hormone (GnIH). Together, these recently appreciated events have changed our understanding of the interaction of the HPG axis and the relationship between the periphery and the central nervous system in the regulation of reproduction.

Control of the LH surge

Central nervous system (CNS) regulation of the LH surge

As reviewed previously, oestradiol membrane signalling, comprising oestradiol (E_2) signalling that is initiated at the cell membrane, plays an important role in the CNS synthesis of progesterone (neuroP) needed for oestrogen positive-feedback of the LH surge (1). Although the preovulatory rise in circulating E_2 is essential for stimulating gonadotrophin release (2–4), progesterone is also necessary for the LH surge (5–9). In ovariectomised rats and mice, E_2 induces an LH release (10) and LH levels are augmented by additional application of progesterone (11,12). Blocking progesterone receptor (PR) or progesterone synthesis prevents the E_2-induced GnRH and LH surges in ovariectomised rats (5,13) and arrests the oestrous cycle in intact female rats (14). Most critically for this discussion, ablation of PR in kisspeptin (KP)-expressing neurones abrogates oestrogen positive-feedback (15), indicating that that both E_2 and progesterone are necessary for surge release of LH.

Where does neuroP act to influence the LH surge? It is well established that GnRH neurones themselves do not express the requisite steroid hormone receptors, oestrogen receptor (ER)α and PR (16,17). There is now solid evidence that the LH surge 'pattern generator', which integrates steroid hormone information and regulates oestrogen positive-feedback is a population of KP-expressing neurones of the rostral periventricular nucleus of the third ventricle (RP3V), an area that includes the anterior periventricular nucleus and the anteroventral periventricular nucleus (18–25). Kiss1 neurones in the RP3V are critical for GnRH secretion because KP released from Kiss1 neurones activates GnRH neurones via GPR54, a G-protein coupled receptor that binds KP (26–28). Although much of the work on steroid regulation of KP and its gene, *Kiss1*, has focused on E_2 (29,30), it is now evident that E_2 and neuroP function together to regulate KP. First, both ERα and PR are needed for positive-feedback of the LH surge (31,32), and both have been localised in KP neurones, although neither are found in GnRH neurones (20,33). Consistent with the need for E_2-induced PRs for the LH surge, a substantial number of KP neurones in RP3V and the arcuate nucleus of the hypothalamus (ARH) express PR after E_2 treatment (25,30,33,34). Coincident with this, rising E_2 levels during pro-oestrus induce neuroP synthesis (14,35).

A combination of *in vitro* and *in vivo* experiments have demonstrated that neuroP acts on KP neurones to mediate oestrogen positive-feedback (Fig. 1). Integrated steroid signalling was studied in a cell line (mHypoA51s) that approximates 'sexually mature' female hypothalamic neurones. These immortalised neurones have the characteristics of post-pubertal RP3V KP neurones because they express ERα, PR and KP (36). As with KP neurones *in vivo*, E_2 and the ERα agonist, PPT, induced KP and PR in mHypoA51s. Significantly, E_2-induced PR up-regulation was dependent on an intracellular ER, whereas KP expression was stimulated by membrane-impermeable E_2 (E_2 coupled to bovine serum albumin; E-6-BSA). These data suggest that anterior hypothalamic KP neurones utilise both membrane-initiated and classical nuclear oestrogen signalling to up-regulate KP and PR, which are essential for the LH surge.

The nature of progesterone signalling in KP neurones remains to be clarified. In addition to classical nuclear PR, there are intriguing suggestions that KP neurones *in vitro* and *in vivo* have membrane progesterone receptors, especially mPRβ (37). The mPRs are seven-transmembrane proteins that activate G proteins that belong to the progestin and adipoQ receptor (PAQR) family not the classic G protein-coupled receptor (GPCR) family (38–40). PAQRs can signal through mitogen-activated protein kinase activation and increasing $[Ca^{2+}]_i$ (41–47); but see also (48). Studies in mHypoA51s indicate that classical PR is responsible for progesterone-induced signalling events. Treatment of E_2-primed mHypoA51s with progesterone induces a rapid increase in free cytoplasmic calcium ($[Ca^{2+}]_i$), which appears to be responsible for the release of KP induced by progesterone, whereas inhibition with RU486 prevents the $[Ca^{2+}]_i$ increase (36).

In vivo, preliminary experiments have demonstrated that exogenous progesterone rescued the LH surge in females whose hypothalamic steroidogenesis was blocked with the CYP11A1 inhibitor aminoglutethimide (AGT) (49). In AGT-treated animals, infusions of progesterone or KP into the diagonal band of Broca induced an LH surge, confirming that KP operates downstream of neuroP. Finally, KP knockdown in the RP3V prevented the E_2-induced LH surge (49). Most importantly, the ablation of PR in KP neurones in ovariectomised mice abrogates E_2 positive-feedback (15) demonstrating that that both E_2 and neuroP are necessary for the surge release of LH.

Molecular mechanisms of GnRH-(1-5) action

The decapeptide GnRH (pGlu-His-Trp-Ser-Tyr-Gly-Leu-Arg-Pro-Gly-NH2) is highly conserved across species, suggesting its functional importance throughout evolution (50). GnRH is primarily known for its role in regulating reproductive function and behaviour via interaction with KP and its cognate receptor, GPR54, in the hypothalamus (51–57). Within each oestrous cycle, a rapid increase in GnRH secretion culminates in an LH surge, which precedes the onset of sexual receptivity and ovulation. In addition to its effects on the secretion of LH, GnRH can autoregulate its own biosynthesis and secretion via an ultrashort-loop feedback mechanism (58–62).

GnRH not only functions in its full form, but also can signal via its metabolite, GnRH-(1-5). GnRH-(1-5) is produced by the cleavage of GnRH by the zinc metalloendopeptidase EC3.4.24.15 (EP24.15) at the covalent bond linking the fifth and sixth amino acids (63–65) (Fig. 2). Localisation of EP24.15 supports the involvement of EP24.15 in the modulation of hypothalamic GnRH neuronal function (63,66). EP24.15 immunoreactivity is sensitive to hormonal fluctuations: increasing on pro-oestrous day of the rat oestrous cycle within the median eminence, with a peak expression coinciding with the LH surge (63). Unlike GnRH, GnRH-(1-5) robustly

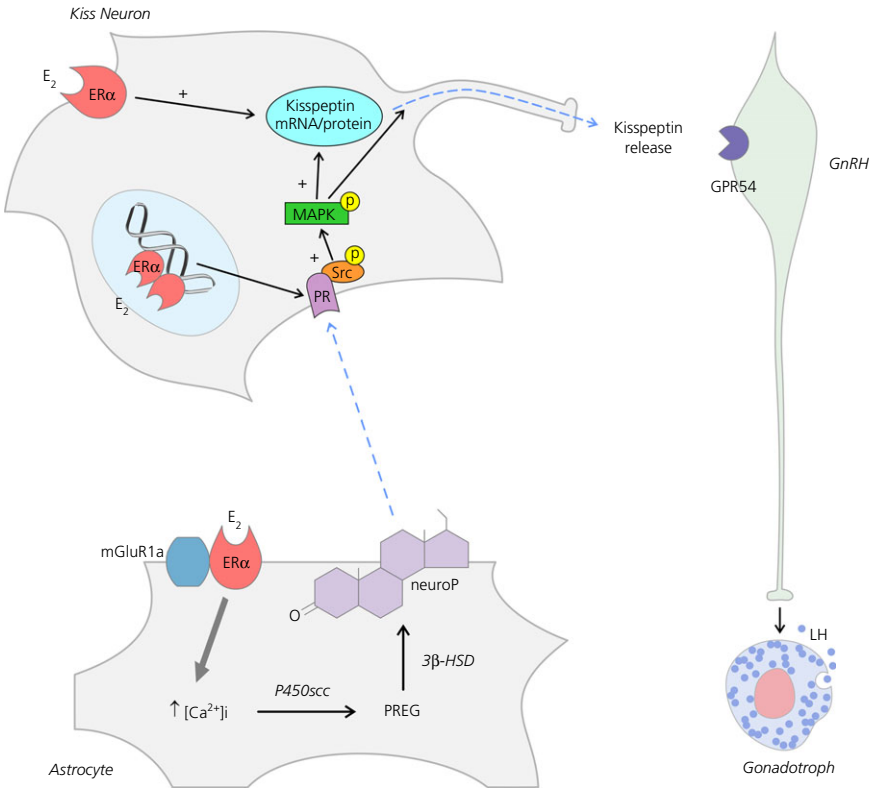

Fig. 1. A model showing proposed actions of oestradiol (E_2) on hypothalamic cells. In kisspeptin (Kiss1) neurones, E_2 acts at both membrane and nuclear oestrogen receptors. During di-oestrus, classical nuclear E_2 signalling induces progesterone receptor (PR) expression in Kiss1 neurones in the rostral periventricular nucleus of the third ventricle (RP3V). On pro-oestrus, rising E_2 leads to transactivation of mGluR1a in astrocytes, which increases $[Ca^{2+}]_i$, leading to the conversion of cholesterol to pregnenolone (PREG) by the P450scc enzyme and the conversion of PREG to progesterone (neuroP) by 3β-hydroxysteroid dehydrogenase (HSD). Simultaneously, E_2 activates an oestrogen receptor (ER)α-mGluR1a complex in neurones leading to the expression of Kiss1. Newly synthesised neuroP diffuses out of the astrocytes and activates E_2-induced PR, which has been trafficked to the Kiss1 neuronal membrane. This leads to a series of events culminating in Kiss1 secretion onto GPR54 expressing gonadotrophin-releasing hormone (GnRH) neurones. Signalling through PR in Kiss1 neurones induces Kiss1 release, activating GnRH neurones and triggering the E_2-induced luteinising hormone (LH) surge from anterior pituitary gonadotrophs. MAPK, mitogen-activated protein kinase.

stimulates GnRH gene expression (67) and stimulates GnRH secretion (68). Moreover, the GnRH facilitation of lordosis behaviour is actually mediated by its metabolism to GnRH-(1-5) (69).

Interestingly, studies show that GnRH-(1-5) does not bind to the GnRH receptor (51) but binds to two orphan GPCRs: GPR101 (70) and GPR173 (71,72) (Fig. 2). Both GPR101 and GPR173 are members of the Rhodopsin class of receptors. The Rhodopsin family is the largest of the five groups of orphan receptors with 672 members of which 63 have no known ligands. Both GnRH-(1-5)-binding GPCRs are highly conserved and are highly expressed in the hypothalamus (Allen Brain Bank) (73,74). In several species, the coding sequence for GPR101 is located on the X chromosome in a band that is syntenic between species (75). In mouse, GPR101 mRNA is 2186 bases, encoding a seven-transmembrane receptor that is approximately 51 kDa (76). The sequenced GPR173 mRNA is 1122 bases, which translates to a 42-kDa seven-transmembrane receptor (73). Functional studies suggest that GnRH-(1-5) retards the cellular migration of neural cells via GPR173 (71–73). By contrast, GnRH-(1-5) may stimulate cellular migration and invasion of the extracellular matrix in endometrial cells via GPR101 (70,77).

These studies support the idea that GnRH-(1-5) represents another layer of regulatory complexity in tissues where GnRH is also produced. The identification of an endogenous ligand to an orphan GPCR is important because these receptors may have therapeutic potential (74). Furthermore, the identification of a GPCR that binds GnRH-(1-5) may help resolve some of the current quandaries regarding the actions of GnRH (agonist/antagonist) and enhance our understanding in the evolution of peptide metabolism and processing.

Role of GnIH in avian reproductive system; regulation of GnIH by photoperiod and stress and the effects of these changes on reproductive behaviours

Although GnRH and its metabolite, GnRH-(1-5), are known for promoting reproduction-related functions in the HPG axis, a more recently discovered hormone has been implicated as a potential brake on the HPG system. GnIH has received attention because of its role in the inhibition of activity of components of the HPG axis, including a reduction of sexual behaviour (78–86). Despite a great deal of investigation into its specific functions and the factors that

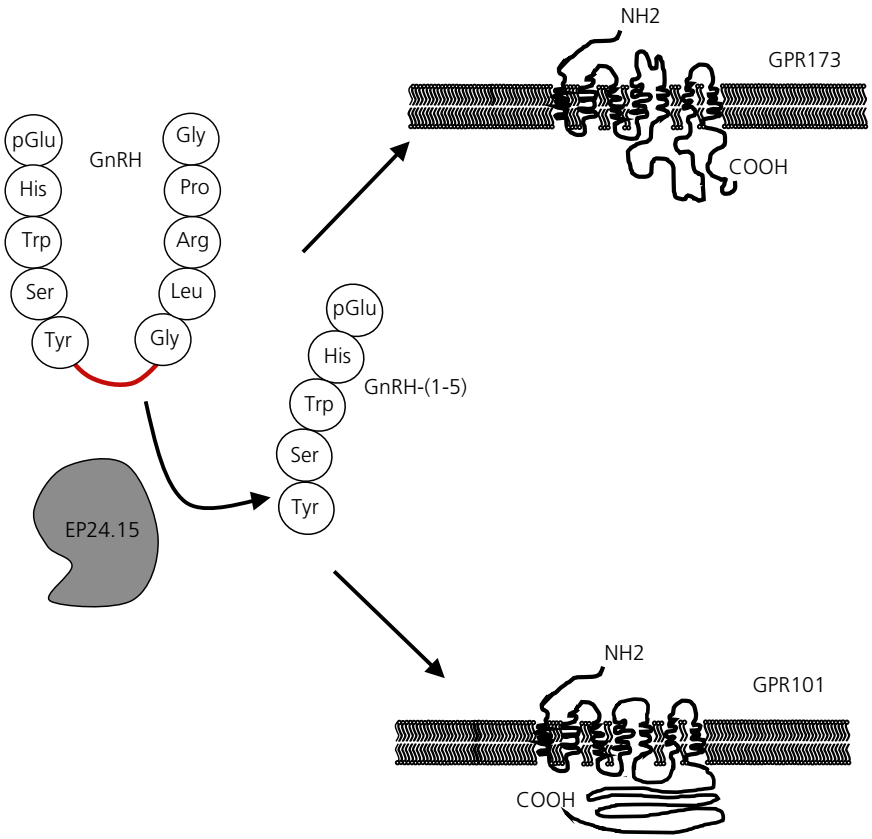

Fig. 2. Gonadotropin-Releasing Hormone (GnRH) peptide processing and action. The decapeptide, GnRH, is processed extracellularly to form the metabolite, GnRH-(1-5) by the zinc metalloendopeptidase, EC3.4.24.15 (EP24.15; 66, 73). The metabolite, GnRH-(1-5), exerts is biological activities via 2 putative receptors, the G-protein coupled receptors (GPR) GPR101 and GPR173 (70, 71).

regulate GnIH, the full range of actions of GnIH within the central nervous system remain unknown. At present, we know that, in birds, GnIH projects to GnIH receptor-expressing GnRH-I and -II neurones in addition to the median eminence (84,87). In several species of mammals, GnIH projects to and also influences the activity of GnRH neurones (85,88), as well as the external layer of the median eminence (88–92), although this latter finding remains disputed (85,93). There are GnIH projections to multiple other brain areas (e.g. brainstem) and possibly to the spinal cord (84,93), although the function of GnIH in these extra-hypothalamic areas remains obscure. The GnIH content of the brain is influenced by changes in day length and the associated changing melatonin signal in seasonal breeders (84,94–99). In birds, despite the influence of GnIH on GnRH neurones, it appears that GnIH does not influence the termination of reproduction at the end of the breeding season. Rather, it is more likely that GnIH plays a role in temporary reproductive suppression within the breeding season in response to different physiological stimuli, such as stress (84,100–102).

The action of GnIH is not restricted to the brain and the anterior pituitary gland. GnIH and its receptor (GPR147) are synthesised in the gonads of both sexes of all vertebrates studied to date (103–108). Furthermore, in birds, GnIH-producing neurones in the brain project to the pars nervosa, suggesting that GnIH is released directly into the bloodstream (G. Bentley, unpublished observations). If confirmed, then not only can locally produced GnIH act within the gonads, but also neurally produced GnIH could be released to the general circulation and act upon peripheral targets.

It is possible that GnIH-producing neurones can be subdivided into heterogenous subpopulations that respond to unique environmental and physiological cues. For example, GnIH neurones express melatonin receptor (MelR) and glucocorticoid receptor (GR) mRNA. However, not all of the GnIH neurones express MelR or GR (98,109) and it is not known whether single GnIH neurones can express both MelR and GR, suggesting that there could be MelR- and GR-specific subpopulations of GnIH neurones, each with potentially distinct functions. Thus, it remains to be determined whether or how melatonin and glucocorticoids interact to influence GnIH action within the brain.

In birds and mammals, melatonin and corticosterone can act on the gonadal GnIH system. This suggests the possibility that the neural and gonadal GnIH systems could differentially respond to hormones and, together, could coordinate a response to circulating hormones (perhaps via direct innervation of the gonad). Unfortunately, only *in vitro* preparations can be used to answer this question. Without separating the gonads from the blood circulation and from potential neural input, it is impossible to determine gonadal responses to a changing hormonal environment, especially if GnIH is present in circulating blood. However, *in vivo* studies in this area

could also be very informative, especially if localised blockade of GnIH receptor could be induced in the gonads.

GnIH responses to chronic stress have been documented in male and female rats, with a significant impact on reproduction (109–111). To date, there has been only one study on chronic stress effects upon GnIH in birds with sex-specific effects of treatment. Female European starlings (*Sturnus vulgaris*) exhibited increased ovarian GnIH expression compared to their nonstressed counterparts and were also reported not to ovulate, whereas nonstressed animals did (111). Acute stressors can certainly influence the avian GnIH system, although these effects appear to depend on the species, the time of year, the sex of the bird and the stressor (112–114). In addition, some stressors influence the gonads directly rather than via neural GnIH (112). The same is true for chronic housing stress in European starlings, as noted above (111). Thus, it is clear that neural and GnIH systems can respond differently to any particular stressor, regardless of whether it is acute or chronic. Further studies in this area should determine the response of gonadal and neural GnIH systems to stressors and hormones, and should also assess communication between these GnIH systems in a variety of species.

Local regulation of gonadal function

Autocrine and paracrine regulation of testicular function: molecular pathways involved in testis pathophysiology leading to infertility

Gonadotrophins are key regulators of male gonadal function. LH and follicle-stimulating hormone (FSH) released from the pituitary reach the testis and exert their effects through receptors located in the plasma membrane of Leydig and Sertoli cells, respectively (115,116). In addition, local factors and hormones influence testicular function via paracrine and autocrine mechanisms. Several molecules that reach the testis and/or are locally produced in the gonad regulate the activity of different cell types (e.g. Leydig cells, Sertoli cells, mast cells, macrophages, myofibroblasts), include peptides (117), neurotransmitters (118), neurohormones (119), cytokines (120) and prostaglandins (PGs) (121).

In this context, the neurohormones serotonin (122), melatonin (123) and corticotrophin-releasing hormone (CRH) (124) act in the testes as important negative regulators of cAMP and androgen production. Serotonin, melatonin and CRH can be produced within the CNS and secreted into peripheral circulation, or locally synthesised in the testes (125,126). Melatonin and also serotonin inhibit steroidogenesis via their 5-HT_2 receptor- and Mel1a receptor-mediated signalling pathways, which influence CRH centrally (125,127) and in the testes (127,128). This CRH-mediated inhibition of steroid production occurs through the activation of tyrosine phosphatases, which reduces the phosphorylation of extracellular regulated kinase (ERK) and c-Jun N-terminal kinase, and subsequently down-regulates c-jun, c-fos and steroid acute regulatory protein (StAR), thereby inhibiting testosterone production (128).

Melatonin has been postulated to have a physiological role as a paracrine signalling molecule, directly regulating the production of factors (e.g. immune, interleukin-2) in its immediate vicinity (129). Recent observations show that melatonin modulates local cellular activity in testicular immune cells, inducing the expression of antioxidant enzymes and reducing the generation of reactive oxygen species in mast cells. In testicular macrophages, melatonin inhibits cell proliferation, the expression of proinflammatory cytokines, interleukin-1β and tumour necrosis factor α, and PG production (130). PGs are derived from arachidonic acid by the action of inducible isoenzyme cyclooxygenase (COX). In testicular biopsies of men with impaired spermatogenesis, COX-2 is expressed in immune cells, highlighting their relevance in testicular inflammation associated with idiopathic infertility (131). Furthermore, Leydig and Sertoli cells also produce PGs and express several prostanoid receptors (132,133), suggesting autocrine/paracrine action in testicular somatic cells.

PGD2 has a stimulatory effect on basal testosterone production in Leydig cells (134), whereas PGF2α exerts an inhibitory role in the expression of the StAR and 17β-hydroxysteroid dehydrogenase (HSD), as well as in the synthesis of testosterone induced by human chorionic gonadotrophin (hCG)/LH (133), demonstrating that the role of PGs on steroidogenesis, spermatogenesis and ultimately fertility depends on the specific PG in question.

Recent research indicates that multiple local signals influence testicular physiology and are involved in the pathogenesis or maintenance of human infertility. Notably, male infertility results from endocrine dysfunctions associated with the hypothalamic-pituitary-testicular axis only in a small number of cases (135), suggesting the source of infertility likely occurs within local, intra-testicular pathways. Thus, new insights about how cell–cell interactions within the testes affect testicular function and fertility will contribute to the understanding of male reproductive physiopathology, and future studies focusing on testicular paracrine and autocrine interactions may lead to new therapeutic approaches to idiopathic male infertility.

Follicular development, corpus luteum and progesterone regulation of ovarian vascularisation and molecular pathways involved

Similar to testicular functions including spermatogenesis and steroidogenesis, ovarian follicular development and regression is a continuous and cyclic process that depends on a number of endocrine, paracrine and autocrine signals. In healthy tissues, physiological angiogenesis is mainly limited to the reproductive system. The ovarian vasculature is closely associated with preovulatory follicle and corpus luteum during the ovarian cycle and is one of the few sites where nonpathological development and regression of blood vessels occurs in the adult. Recently, local factors such as vascular endothelial growth factor A (VEGF-A) and angiopoietins, which act specifically on vascular endothelial cells or pericytes and smooth muscle to control angiogenesis or angiolysis, were identified in the growing follicle and corpus luteum of several species, including humans (136).

VEGF-A is a key angiogenic factor involved in the formation of new blood vessels within many tissues. It is required to initiate the

formation of new immature vessels by promoting endothelial cell proliferation and vascular permeability. Inhibition of VEGF-A and angiopoietin 1 (ANGPT1) action in rat ovaries by intrabursal administration of VEGF-A-Trap or ANGPT1 antibodies, respectively, produces an imbalance in the ratio of anti-apoptotic : pro-apoptotic proteins leading to greater follicular atresia (137,138). In addition, VEGF-A prevents apoptosis and stimulates the proliferation of granulosa and theca cells of antral follicles through a direct interaction with its KDR receptor localised in granulosa cells, a pathway that involves phosphoinositide 3-kinase (PI3K)/AKT (139). Furthermore, *in vitro* studies performed in early antral follicles and granulosa cell cultures isolated from rat demonstrate that VEGF acts directly on follicular cells synergistically with FSH and E_2, preventing apoptosis and stimulating proliferation, thus promoting follicular development and the selection of the follicle to ovulate (140). Such work reported a direct role for VEGF in early antral follicles mediated by the PI3K/AKT and ERK1/2 pathways, besides the classical and well known proangiogenic function. Together, these data support the notion that angiogenic factors have an important role in controlling ovarian function.

In vitro studies have shown that Notch signalling is critical for the survival of luteal cells isolated from pregnant rats (141). Local Notch inhibition decreases progesterone levels and cell survival, confirming that Notch has a direct action on both steroidogenesis and luteal viability (141). The Notch signalling pathway is a cell–cell communication pathway that is evolutionarily conserved from *Drosophila* to humans. To date, four different Notch receptors (Notch1, 2, 3 and 4) and five different ligands (Jagged-1 and -2 and DLL-1 -3 and -4) have been identified in mammals. This Notch system regulates cell fate, proliferation and death. The Notch genes encode transmembrane receptors, which, upon binding their ligand, are cleaved, releasing the intracellular domain. The intracellular portion of the receptor translocates to the nucleus to act as a transcriptional coactivator, regulating cell fate genes (142).

Moreover, in the rat, there is an interaction between the Notch signalling pathway and progesterone that maintains the functionality of the corpus luteum (143). Notch signalling augments P450scc synthesis, leading to an increased synthesis of progesterone, which in turn regulates the activated intracellular Notch domain. Thus, Notch induces progesterone production *in vitro* through the activation of cytochrome P450 cholesterol side chain cleavage enzyme (P450scc) and decreases apoptosis-mediated cell death. This is the first evidence that there is cross-talk between the Notch signalling system and progesterone, which increases the survival of luteal cells. Also, the Notch/PI3K/AKT signalling pathway might be interacting with progesterone, intensifying the survival role of this hormone in luteal cells. Nevertheless, future studies are required to thoroughly investigate this newly discovered Notch-progesterone relationship and how it contributes to ovarian function and reproduction as a whole.

Ovarian kisspeptin and its role in follicular development

Reproduction in females requires an LH surge, which is centrally regulated by KP. However, KP is found in many peripheral organs (144,145), in particular, the ovary, which expresses KP and its receptor, GPR54, suggesting a role for KP in the peripheral control of reproductive events. KP expression in the ovary fluctuates throughout the oestrous cycle, strongly suggesting that it may be involved locally in the ovulatory cycle and luteinisation (146–148); but see also (28). However, the mechanisms of action of KP in the ovary, such as paracrine or autocrine functions remain largely unknown.

A recent study demonstrated that intraovarian administration of a KP antagonist (p234) delays vaginal opening and alters the oestrous cycle in rats (147). Additionally, local administration of exogenous KP decreases antral follicle and corpora lutea number in fertile and subfertile rats, which was reversed by p234 treatment, suggesting that KP also participates in both follicular development and ovulation at the level of the ovary (149). Moreover, during ovulation in humans and nonhuman primates, ovarian KP and GPR54 mRNA increases with other ovulation-associated genes, such as COX-2 and progesterone receptor. The ovarian administration of the COX-2 inhibitor, indomethacin, disrupted the ovulatory process in rats, supporting the idea of a local role of KP and GRP54 in ovulation (150). It appears that KP regulates progesterone secretion from luteal cells as well. In isolated chicken granulosa cells, KP stimulates progesterone secretion, possibly by directly altering levels of steroidogenic enzymes, including StAR, P450scc, which converts cholesterol to pregnenolone, and 3β-HSD (151), which converts pregnenolone to progesterone. Similarly, in rat luteal cells, KP increased progesterone production via ERK1/2 signalling and increased the expression of StAR and CYP11A mRNA (152). Furthermore, administration of a GPR54 antagonist, p234, inhibited progesterone secretion in granulosa cell cultures treated with hCG, implicating KP in the luteinisation of granulosa cells (148). Together, these data suggest a potential role of KP in the local control of ovarian function, potentially via progesterone synthesis. These and future studies involving paracrine and autocrine actions of ovarian KP will clarify the molecular mechanisms involved in the regulation of follicular development and ovulation during reproductive life and ovarian ageing.

Although a decreased follicular pool indicates physiological ageing of the ovary (153), an increased rate of follicular loss is also a pathology that affects the follicular reserve pool, and thereby fertility, in humans and other mammals (154). Reproductive ageing in women begins with shortened menstrual cycles, smaller increases in FSH and decreased levels of inhibin (155), which results in accelerated follicular growth and premature exhaustion of the follicular pool. One of the mechanisms involved in ovarian ageing is increased sympathetic nerve activity. Ovaries of postmenopausal women (≥ 51 years old) have a higher density of innervation compared to age-matched controls (156,157). In the rat, reproductive ageing is associated with increased ovarian sympathetic activity, which is strongly correlated with the spontaneous appearance of follicular cysts and a loss of preantral follicles (158,159). Indeed, the highest sympathetic innervation is found in postmenopausal women, suggesting a correlation between ageing-induced infertility and sympathetic nerve activation. Recent findings indicate that sympathetic innervation may be controlling age-induced infertility

via regulation of KP because ovarian sympathectomy diminishes KP levels (A. Paredes, unpublished observations). Additionally, during reproductive ageing, KP expression in the ovary increases from the subfertile to infertile period and is directly correlated with the increase in ovarian norepinephrine observed with ageing (149,158), suggesting that KP may be directly controlled by sympathetic innervation of the ovary (147), as well as supporting the idea that KP is regulated by the adrenergic system and that both the adrenergic system and KP participate in the local regulation of follicle development and ovulation during reproductive ageing. Furthermore, KP is involved in follicular dynamics: intraovarian administration of KP produced an increase in the numbers of corpora lutea and type III follicles in fertile and subfertile periods, which was reversed by KP receptor antagonism. Future studies should address the potential autocrine and paracrine roles of KP in the ovary, specifically the interaction of KP, steroidogenic pathways and sympathetic innervation and how they relate to reproductive outcomes across the lifespan.

Morphological changes in ARH initiated by oestradiol membrane signalling that mediate lordosis behaviour

Another key component to reproduction in rodents is female sexual receptivity, which is mediated by E_2-dependent alterations in hypothalamic neuronal structure. Although the molecular bases of E_2-dependent facilitation of female sexual receptivity have more recently been described in detail, the understanding that steroid hormones exert behavioural effects via changes in neural morphology is a well established phenomenon. The most well known example of E_2-induced changes in dendritic structure regulating memory-related behaviour is from the hippocampus (160), whereas E_2-induced changes in dendrites in the hypothalamus have also been known for some time (161). Indeed, changes in dendritic morphology are critical for the lordosis-regulating circuit (162), which extends from the ARH to the medial preoptic nucleus (MPN), to the ventromedial nucleus of the hypothalamus (VMH). Recent studies have begun to clarify the molecular mechanisms by which morphological changes in the ARH-MPN-VMH circuit allow for expression of lordosis behaviour. The primary step of E_2 signalling in the ARH occurs via ERα transactivation of mGluR1a, which initiates morphological changes that are coincident with and required for the display of lordosis behaviour. Within 4 h after E_2 treatment, immature, filapodia-like dendritic spines are formed in the ARH (162). Twenty-four hours after E_2 treatment, there is a shift in the proportion of dendritic spines, with a decrease in filapodia and a concomitant increase in mature, mushroom-shaped spines (162). The formation of new spines is necessary for the E_2-induced lordosis because blocking spine formation significantly reduces the expression of sexual receptivity (162).

Although it appears that spinogenesis is initiated by the action of E_2 at membrane ERα, it is unclear what molecular mechanisms underlie spine maturation. Evidence from other circuits suggests a role for the G-protein coupled ER, GPR30, in spine maturation and stabilisation. GPR30 is localised in spine heads, associates with PSD-95, and is regulated by E_2 (163,164). In the dorsal hippocampus, the GPR30 agonist, G1, increases PSD-95 immunoreactivity, suggesting a role for GPR30 in spine maturation (164). Indeed, this receptor has been implicated in the initiation of lordosis behaviour on the basis that the partial GPR30 agonist but ERα antagonist, ICI 182,780, facilitates lordosis in E_2-primed nonreceptive rats (165). Other studies suggest there could be a role for the STX-activated G_q-coupled membrane ER in the ARH-MPN circuit mediating sexual receptivity. STX is a tamoxifen analogue that does not bind to classical ERα or GPR30 but is blocked by the ER antagonist ICI 182,780 and has pharmacological profile similar to those of the ERα-specific agonist, PPT (166–168). STX treatment induces μ-opioid receptor (MOR) internalisation in the MPN and facilitates lordosis behaviour (169). Alternatively, spine maturation could be mediated by extra-neuronal mechanisms, such as astrocytic contact with neurones, which alters dendritic spine formation and stabilisation (170).

Additionally, it is unclear whether E_2 induces spinogenesis in the same population of neurones in the ARH that express ERα, the neuropeptide Y (NPY) neurones, which are the initial site of the action of E_2 in the ARH-MPN-VMH circuit, or whether E_2 is acting transsynaptically to induce spines on pro-opiomelanocortin (POMC) neurones, which release β-endorphin onto MORs in the MPN. Recent data suggest that the NPY neurones and not POMC neurones undergo spinogenesis, suggesting that spine formation occurs directly within the neurones where initial E_2 activation of ERα occurs (171). Regardless of the site of spinogenesis within the ARH, it is clear that spine maturation in this nucleus is coincident with lordosis behaviour, and also that blocking spinogenesis here reduces female sexual receptivity. To a first approximation, the timeline from E_2 treatment to the presence of mature dendritic spines is known. However, the time when fully functional synapses appear remains to be determined. Within 1 h of E_2 treatment, cofilin is deactivated via phosphorylation, which permits spinogenesis (162), and, in the MPN, MOR is activated/internalised, indicating that the ARH to MPN part of the circuit is functional (172). At 4 h post-E_2 treatment, filapodial spines are present, although these thin, labile spines are not considered to mediate functional synapses (173). At 20 h after E_2 treatment, the first time point when lordosis behaviour can be elicited with supplemental hormone treatment, there is an increase in the proportion of mushroom spines that are generally assumed to be indicative of functional synapses (162) and that contain the machinery required for synaptic transmission (e.g. PSD-95). Future studies should address the time course of this E_2-dependent spine maturation and the potential involvement of non-traditional ER in this process.

Conclusions

Taken together, these recent findings highlight both the redundancy and complexity of the hormonal control of reproduction: what was once considered to be a simple, direct circuit with a handful of steroid hormones and cognate receptors is continually updated with novel hormone regulators and mechanisms of hormone synthesis and action. However, the classical aspects of gonadal hormone control of reproduction remain intact, demonstrating that there are

multiple levels of control of the HPG axis, both centrally and peripherally. Future studies will likely only add to this increasingly complex circuit that regulates reproduction.

Disclaimer

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