

—Review—

The roles of kisspeptin revisited: inside and outside the hypothalamus

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Abstract. Kisspeptin, encoded by *KISS1/Kiss1* gene, is now considered a master regulator of reproductive functions in mammals owing to its involvement in the direct activation of gonadotropin-releasing hormone (GnRH) neurons after binding to its cognate receptor, GPR54. Ever since the discovery of kisspeptin, intensive studies on hypothalamic expression of *KISS1/Kiss1* and on physiological roles of hypothalamic kisspeptin neurons have provided clues as to how the brain controls sexual maturation at the onset of puberty and subsequent reproductive performance in mammals. Additionally, emerging evidence indicates the potential involvement of extra-hypothalamic kisspeptin in reproductive functions. Here, we summarize data regarding kisspeptin inside and outside the hypothalamus and revisit the physiological roles of central and peripheral kisspeptins in the reproductive functions of mammals.

Key words: Follicle-stimulating hormone, Gonadotropin-releasing hormone, Kisspeptin, Luteinizing hormone, Puberty
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Introduction

In the late 1940s, Harris [1] predicted the presence of hypothalamic releasing hormones, which are conveyed from the median eminence to the pituitary gland through the hypophyseal portal circulation to control the synthesis and secretion of pituitary hormones such as gonadotropins. This opened the door to the discovery of the hypothalamic releasing hormones. After intensive studies on the predicted hormones, two independent groups led by Schally [2] and Guillemin [3], the 1977 Nobel laureates, isolated luteinizing hormone-releasing hormone (LHRH), a ten-amino-acid neuropeptide, from the hypothalamus of pigs and sheep. This decapeptide stimulates both follicle-stimulating hormone (FSH) and luteinizing hormone (LH) secretion in several mammals [4] and, therefore, has been termed as the ‘gonadotropin-releasing hormone’ (GnRH).

The importance of GnRH secretion in mammalian reproduction was demonstrated by the pioneer experiments of Knobil and his colleagues in the late 1970s and early 1980s. They had established a GnRH replacement regimen to deliver GnRH in a pulsatile manner at a rate equivalent to the physiological frequency of LH pulses [5, 6], which was observed in ovariectomized rhesus monkeys using radioimmunoassays [7]. This regimen successfully recovered both FSH and LH levels in female monkeys bearing hypothalamic lesions that abolished gonadotropin secretion [5]. In addition, the regimen successfully induced regular menstrual cycles and the withdrawal

of GnRH reverted prepubertal female monkeys to an immature state [8]. The necessity of the pulsatile nature of tonic GnRH secretion can be understood in light of the regulation of GnRH receptors by GnRH itself in gonadotrophs of the anterior pituitary, because the continuous infusion of GnRH secretion abolished gonadotropin secretion in female monkeys [5]. Tonic FSH and LH secretion is found to be pulsatile in males and in most phases of estrous or menstrual cycles in females [9–12]. A positive relationship between GnRH and LH has been clearly demonstrated in sheep where each GnRH pulse in the hypophyseal portal blood corresponds to each LH pulse in peripheral circulation [13]. The tonic gonadotropin secretion is fine-tuned by negative feedback action of circulating estrogen derived from the ovarian follicles [14]. The mechanism of the feedback action, however, is largely unknown.

Besides the pulse mode of GnRH/gonadotropin secretion, the surge mode of GnRH release is characterized by a large amount of GnRH/gonadotropin secretion in females. The GnRH surge-induced LH surge is required to induce ovulation, a critical event in female reproduction [15–17]. As ovarian follicles grow larger and become mature, high levels of circulating estrogen exert their positive impact on GnRH neurons to induce a GnRH surge and hence the LH surge in female mammals. The GnRH surge in the hypophyseal portal circulation has clearly been demonstrated to correspond to the LH surge in peripheral circulation in sheep [17–19]. Administration of high doses of estrogen reproduces GnRH/LH surges in gonadectomized females in diverse mammalian species [16, 17, 20]. On the other hand, the response to high doses of estrogen in castrated males varies from species to species. Administration of high doses of estrogen induces surge-like LH secretion in male primates [21–24] and goats [25, 26], but not in sheep [27] and rodents [28–30]. Thus, the brain mechanism generating GnRH/LH surges (also known as the mechanism underlying the positive feedback action of estrogen) is likely conserved in the males of primates and goats, whereas it

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appears sexually differentiated in sheep and rodents.

The molecular and cellular mechanism underlying the negative and positive feedback actions of estrogen has been a big concern in reproductive physiology for years. This is primarily because GnRH neurons do not express estrogen receptor α (ER α) [31], which is considered to mediate both types of estrogen feedback actions. The most plausible explanation was that other ER α -expressing neurons receive and transmit estrogen signals to the GnRH neurons and hence properly control GnRH neuronal activities during the estrous cycle in females [14, 32, 33]. In recent years, the two populations of hypothalamic kisspeptin neurons are found to be the targets of estrogen negative/positive feedback actions in order to control two modes (pulses and surges) of GnRH/gonadotropin secretion in mammals. In addition, emerging evidence indicates the potential physiological roles of extra-hypothalamic kisspeptin, produced in gonads, uteri, and placenta, on reproductive performance in mammals. The present review thus focuses on the roles of kisspeptin inside and outside the hypothalamus. A brief review of the discovery of kisspeptin is followed by a discussion of the physiological roles of kisspeptin in controlling gonadal functions in mammals.

Discovery of Kisspeptin and Its Cognate Receptors

KISS1 gene [34] and its translation product [35] was first identified as a gene and protein responsible for metastasis suppression in humans. *KISS1* was isolated from human nonmetastatic melanoma cells in 1996 [34]. The processed 54-amino-acid peptide *KISS1* translation product was identified in human placenta as an endogenous ligand of GPR54, a galanin receptor-like orphan G-protein coupled receptor, in 2001 [35]. The peptide exhibited the ability to suppress tumor metastasis and was therefore designated as metastin [35]. A high level of *KISS1* expression was found in healthy and tumorous human tissues [35]. Concurrently, *KISS1* translation products were found in human placenta as endogenous ligands of GPR54 and designated as kisspeptides [36]. To date, the term kisspeptin has been preferably used in the field of reproductive biology after discussion at the First World Conference of Kisspeptin Signaling in the Brain, in Cordoba in 2008.

The amino acid sequence of processed kisspeptin deduced from cloned cDNA consists of 52 to 54 amino acids and is well conserved in most mammals examined to date [35–41]. In particular, the C-terminal-amidated 10-amino acid sequence, which is considered to bind to GPR54 [35], is identical among mammalian species, except for tyrosine at the C-terminal being changed to phenylalanine in primates. Primate kisspeptin contains the RF-amide motif at the C-terminal, and thus kisspeptin is classified as a member of the RF-amide peptide family [42]. Ours and other previous studies showed that human kisspeptin activated intracellular signaling by exhibiting potent binding affinity to GPR74 and GPR147, that are known receptors for neuropeptide FF and RF-amide-related peptide [43, 44], which are other members of the RF-amide peptide family. The physiological significance of kisspeptin-GPR74/147 signaling in reproductive biology, if any, remains to be determined. In light of this promiscuous relationship between peptides and receptors, the term *GPR54/Gpr54* is used in this review instead of *KISS1R/Kiss1r*, the official gene symbol of the kisspeptin receptor.

Kisspeptin as a Gatekeeper of Puberty Onset in Mammals

The first evidence for the physiological significance of kisspeptin-GPR54 signaling in the onset of puberty dates back to two independent findings of loss-of-function mutations of *GPR54* in humans with hypogonadotropic hypogonadism, a pubertal failure with impaired secretion of gonadotropins [45, 46]. One of these research groups generated *Gpr54* knockout mice and showed the *Gpr54* knockout mice successfully reproduced the phenotype of human *GPR54* mutations [46]. These findings strongly suggest that GPR54 and its endogenous ligand kisspeptin play a key role as gatekeepers of sexual maturation at the onset of puberty. To date, the phenotype of *GPR54* mutations in humans was recapitulated in loss-of-function mutations of *KISS1* in humans [47] and in several animal models carrying targeted mutations in *Kiss1* or *Gpr54* loci [48–54].

Further analysis of the first *Gpr54* knockout mouse line, which was generated by *LacZ* insertion in *Gpr54* locus, revealed β -galactosidase activity representing GPR54 expression in normally migrated GnRH neurons [49]. Kisspeptin, therefore, is a key molecule that directly controls GnRH neurons, as opposed to contributing to the migration of GnRH neurons from the nasal placode in mammals. Indeed, kisspeptin or its C-terminal amidated decapeptide (also known as Kp-10) profoundly stimulates gonadotropin secretion via GnRH secretion [55–57]. These findings suggest that kisspeptin is a potent stimulator of GnRH secretion via GPR54 expressed in GnRH neurons. Recently, we generated *Kiss1* knockout rats to evaluate the hormonal profiles in *Kiss1* knockout animal models in more detail [54]. The *Kiss1* knockout rats exhibited a lack of both pulse and surge modes of gonadotropin (both LH and FSH) secretion and failure of puberty onset, indicating that kisspeptin plays an indispensable role in generating tonic and cyclic GnRH secretion to regulate puberty onset and normal reproductive performance. It should be noted that the *Kiss1* knockout male rats exhibit no male sexual behaviors, but showed female-like lordosis reflex, suggesting that kisspeptin is also indispensable for the defeminization and masculinization of the brain mechanism controlling sexual behaviors in male rats [58].

Hypothalamic Kisspeptin Neurons Control GnRH Secretion

Two populations of hypothalamic kisspeptin neurons

KISS1/Kiss1 expression and its localization in the brain were extensively examined in several mammalian species. Localization of hypothalamic kisspeptin neurons is largely similar in all mammalian species examined [24, 26, 39, 40, 59–63]. Hypothalamic kisspeptin neurons are mainly localized in two regions: the anterior region of the hypothalamus called the anteroventral periventricular nucleus (AVPV) in rodents, or the preoptic area (POA) in other species, and the posterior region of the hypothalamus called the arcuate nucleus (ARC). As shown below, kisspeptin neurons localized in the AVPV of rodents are possibly equivalent to those in the POA of goats and monkeys. In addition to the two major populations, there are a few additional small populations of kisspeptin neurons in the hypothalamus, such as ventromedial hypothalamus and paraventricular nucleus [64, 65]. Xu *et al.* [64] suggested a potential role of those

kisspeptin neurons in reproductive behavior. This supposition is consistent with our recent study showing that *Kiss1* knockout rats exhibit abnormal sexual behavior [58].

The two major populations of kisspeptin neurons localized in the POA/AVPV and ARC are considered to have separate roles in female reproduction, because earlier studies in rodents demonstrated a different pattern of *Kiss1* expression in these two hypothalamic regions. Briefly, AVPV *Kiss1* expression is highest in the afternoon of proestrus and is positively regulated by estrogen, whereas ARC *Kiss1* expression is negatively regulated by estrogen treatment in rodents [60, 62, 66, 67]. It is, therefore, likely that the AVPV kisspeptin neurons are a target of estrogen positive feedback action and hence generate the GnRH surge and that the ARC kisspeptin neurons are a target of estrogen negative feedback action and are involved in GnRH pulse generation. The bidirectional regulation of *Kiss1* expression by estrogen might be mediated by ER α , because estrogen changes AVPV or ARC *Kiss1* expression in ovariectomized ER β knockout mice, but not in ER α knockout mice [60]. Recent advances in epigenetic research for the regulation of *Kiss1* expression [68, 69] provide a clue as to how estrogen regulates *Kiss1* expression in these two hypothalamic regions in a different manner. In the AVPV, estrogen-ER α complexes, which are highly recruited at the *Kiss1* promoter, are likely involved in the histone acetylation of the *Kiss1* promoter and the subsequent *Kiss1* expression by a chromatin loop formation between the *Kiss1* promoter and the 3'-downstream enhancer region [68]. In the ARC, histone acetylation of the *Kiss1* promoter and a chromatin loop formation between the *Kiss1* promoter and the 5'-upstream enhancer region seems to be involved in *Kiss1* expression in the absence of estrogen [68, 69]. Taken together, histone acetylation of the *Kiss1* promoter is positively correlated with *Kiss1* expression in both hypothalamic nuclei, and region-specific enhancers serve as switches for the bidirectional regulation of *Kiss1* expression (Fig. 1). Further studies are warranted to elucidate how the histone acetylation of the *Kiss1* promoter region is bidirectionally regulated by estrogen in the AVPV and ARC kisspeptin neurons.

Functions of the POA/AVPV kisspeptin neurons

It is well accepted that the POA/AVPV kisspeptin neurons play a key role as a surge generator, mediating the positive feedback action of estrogen to trigger the preovulatory GnRH/LH surge in female mammals (Fig. 2). The AVPV has been considered to be a site of positive feedback action of estrogen in rats for years, because estrogen microimplants in this region successfully evoked, but electrical lesion of this region abolished the LH surge in rats [20, 70]. Besides previous studies, the POA/AVPV kisspeptin neurons are well accepted to be equipped with a GnRH surge-generating mechanism. The POA/AVPV kisspeptin neurons express ER α [40, 60, 62, 67] and their *KISS1/Kiss1* expression is induced by estrogen in a variety of mammals [24, 26, 39, 40, 60, 62, 71]. The physiological roles of kisspeptin in the induction of LH surge were demonstrated by a blockade of preovulatory or estradiol-induced LH surges with a microinjection of anti-kisspeptin antibody into the POA in rats [62, 66], or with a central injection of a kisspeptin antagonist in sheep and rats [72, 73].

In rodents, the distribution of AVPV kisspeptin neurons is sexually differentiated: Female rodents exhibit a large number of kisspeptin

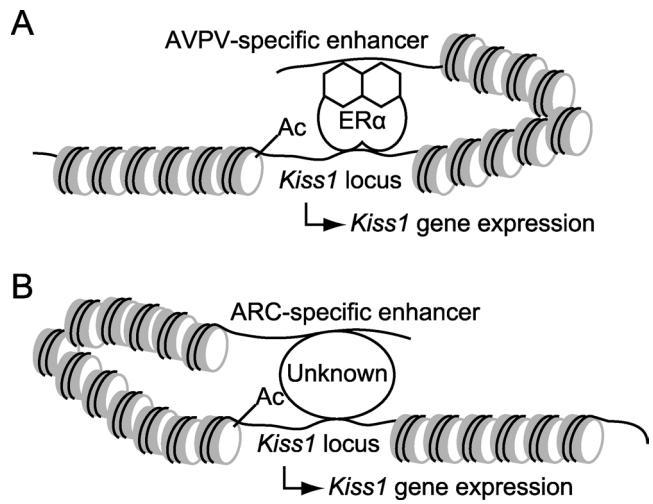


Fig. 1. Schematic illustration of the molecular and epigenetic mechanism underlying hypothalamic *Kiss1* expression. (A) In the anteroventral periventricular nucleus (AVPV), estrogen-estrogen receptor α (ER α) complex induces *Kiss1* expression via histone acetylation of the *Kiss1* promoter and chromatin loop formation between the *Kiss1* promoter region and the 3'-downstream region. (B) In the arcuate nucleus (ARC), histone acetylation of the *Kiss1* promoter and chromatin loop formation between the *Kiss1* promoter region and the 5'-upstream region via unknown transcriptional factor(s) seems to be involved in *Kiss1* expression. Ac, histone acetylation.

neurons along the ventricle of the AVPV, whereas males show only a few scattered kisspeptin neurons in this nucleus [61, 62, 74]. The sexual dimorphism of AVPV kisspeptin neurons is caused by an organizational effect of steroids secreted by perinatal testes, because neonatal castration in male rats allows estrogen-induced AVPV *Kiss1* expression in genetically male rats [29]. On the other hand, female rats with neonatal androgen/estrogen treatment display a male-like pattern of AVPV *Kiss1* expression at adulthood [29, 74]. Thus, it is plausible that estrogen converted from perinatal testicular androgen causes defeminization of the AVPV kisspeptin system in rodents.

The sexual dimorphism in AVPV kisspeptin neurons is likely responsible for the sexually differentiated mechanism underlying LH surge generation in rodents: Orchidectomized male rodents did not show a LH surge even if they received preovulatory levels of estrogen [28–30]. There are species differences in the sexual dimorphism of the LH surge generating system, because the estrogen-induced LH surge is evident in castrated male primates [22, 24] and goats [25, 26] as described earlier in this review. Recent studies [24, 26] demonstrated preovulatory levels of estrogen-induced POA *KISS1* expression and/or c-Fos expression detected in the kisspeptin neurons in males of these species. Thus, unlike rodents, the inherent LH surge generating system seems to be conserved in male monkeys and goats at adulthood. The responsiveness to estrogen in the POA kisspeptin neurons in monkeys and goats is likely to be lower in males than females: The numbers of the POA kisspeptin neurons in male monkeys and c-Fos expressing kisspeptin neurons in male goats are fewer than those in females in the presence of preovulatory levels of estrogen [24, 26]. Thus, the POA kisspeptin neurons in

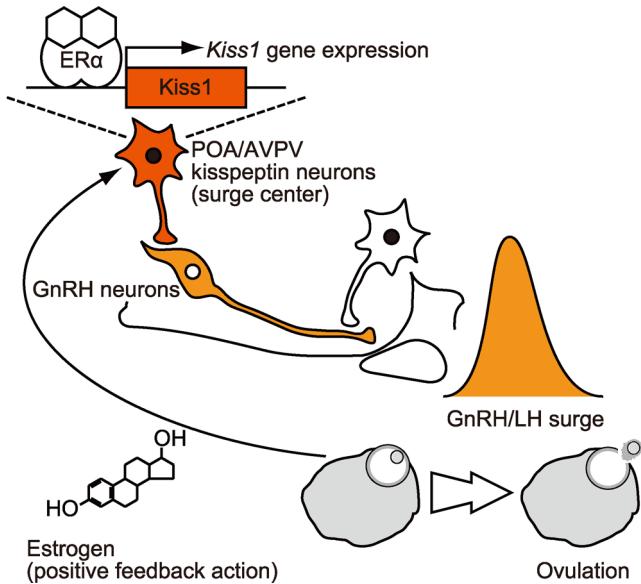


Fig. 2. Schematic illustration of the brain mechanism controlling the preovulatory gonadotropin-releasing hormone (GnRH)/luteinizing hormone (LH) surge in mammals. Estrogen derived from the mature follicles exerts a positive feedback action on *Kiss1* expression in the preoptic area (POA)/AVPV. Kisspeptin appears to act on GnRH neuronal cell bodies and triggers GnRH/LH surge and subsequent ovulation in females.

monkeys and goats are sensitive to testicular androgen during the developmental period as suggested in rodents and are partly defeminized by estrogen during the period. It might be dependent on species differences in the timing of androgen secretion from the fetal testes and the critical period window of brain organization and differentiation. Indeed, gestational androgen exposure induces polycystic ovary syndrome in rhesus monkeys [75], suggesting a dysfunction of the LH surge generating system. It should be noted that estrogen failed to induce the LH surge in intact male monkeys [16], probably because of the inert mechanism generating the LH surge in the presence of androgen.

The involvement of the POA kisspeptin neurons in inducing LH surge is still open to dispute in sheep. Conflicting evidence exists regarding estrogen-induced POA *KISS1* expression in ewes [63, 71]. Estrogen did not always exert a stimulatory influence on *KISS1* expression in this nucleus. Ewes exhibit higher *KISS1* expression in both the POA and ARC at the late follicular phase compared to the luteal phase [63]. Hoffman *et al.* [76] showed the activation of POA but not ARC kisspeptin neurons at the timing of LH surge in ewes. Further studies are required to evaluate the role of POA kisspeptin neurons in the induction of LH surge in ewes. The involvement of ARC kisspeptin neurons in GnRH/LH surge generation will be discussed in the next section of this review.

Functions of the ARC kisspeptin neurons

The ARC kisspeptin neurons are considered a part of the GnRH pulse generator. A method for detecting the ARC multiple unit activity (MUA) volleys has been introduced to rhesus monkeys in 1980s

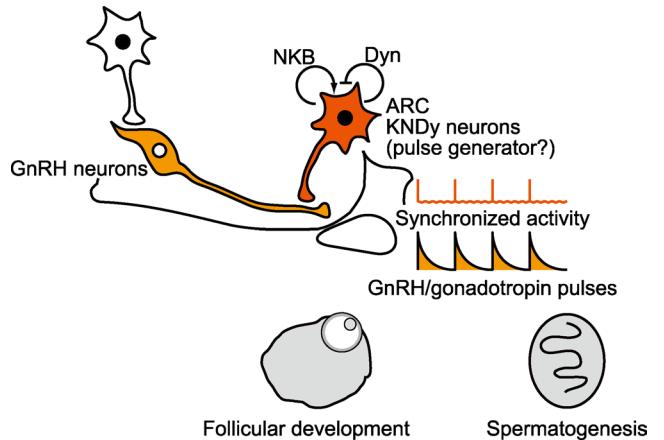


Fig. 3. Schematic illustration of the brain mechanism generating GnRH pulses in mammals. The most plausible explanation is that, in the ARC, KNDy neurons are an intrinsic source of GnRH pulses; under this condition, neurokinin B (NKB) stimulates, while dynorphin A (Dyn) inhibits, synchronized neuronal activity among KNDy neurons. The interaction of these peptides probably generates pulsatile kisspeptin secretion. Kisspeptin appears to act on the GnRH neuronal terminals and generates pulsatile secretion of GnRH and hence gonadotropin, which regulates ovarian follicular development and testicular spermatogenesis.

[77], then to rats [78], and finally goats [79]. The ARC MUA volleys correspond to LH pulses and therefore are considered to represent the activity of the GnRH pulse generator. The ARC kisspeptin neurons would be the source of the periodic MUA volleys, because MUA volleys are successfully monitored only when the recording electrodes are placed in close proximity to the kisspeptin neurons in the goat ARC [38]. The ARC kisspeptin neurons project their fibers to the median eminence, where kisspeptin fibers are closely associated with GnRH fibers in rats and goats [80, 81]. This suggests that GnRH neuronal terminals in the median eminence are one of the action sites of kisspeptin for stimulating GnRH secretion [80, 81]. In this context, Keen *et al.* [82] showed pulsatile kisspeptin secretions at the median eminence and most of the secretions were correlated with GnRH pulses in rhesus monkeys.

The morphological characteristics of the ARC kisspeptin neurons bring us a better understanding of the GnRH pulse generator. In 2007, Goodman *et al.* [83] discovered that two neuropeptides, neurokinin B and dynorphin A, are colocalized in the ARC kisspeptin neurons in sheep. Since then, the ARC kisspeptin neurons are referred to as KNDy (kisspeptin/neurokinin B/dynorphin A) neurons [84]. The colocalization of the three neuropeptides in the ARC was then confirmed in other mammals, such as mice and goats [85, 86]. Wakabayashi *et al.* [86] demonstrated that neurokinin B facilitated, and dynorphin A inhibited, the frequency of MUA volleys in goats. The effects of neurokinin B and dynorphin A on LH pulses were then confirmed in sheep [87]. These findings suggest that the KNDy neuron is an intrinsic source of the GnRH pulse generator, in which the two neuropeptides may function in an autocrine and/or paracrine manner (Fig. 3). Indeed, most KNDy neurons express tachykinin receptor 3 (NK3R), a receptor for neurokinin B, in sheep [88]

and mice [85]. Thus, it is likely that neurokinin B is involved in the generation of intermittent bursts of KNDy neurons via NK3R activation and that kisspeptin transmits the pulse generator activity toward the GnRH neurons [86, 87, 89]. On the other hand, dynorphin A has been suggested to terminate the burst activity of the GnRH pulse generator via an unknown mechanism(s), because only a small number of KNDy neurons express κ-opioid receptors, which are receptors for dynorphin A [85, 90]. The transmitter phenotypes of neurons expressing κ-opioid receptors, which are involved in GnRH pulse generation, remain an open question.

Interestingly, the ARC kisspeptin neurons might also be involved in GnRH/LH surge generation as well. In sheep, the number of ARC *KISS1*-expressing cells increased in the late follicular phase [63, 91]. Merkley *et al.* [92] suggested that an activation of the ARC kisspeptin neurons as well as their POA population determines the timing of LH surge in sheep. Similarly, the activation of kisspeptin neurons located in the ARC and AVPV of rats at the proestrous stage was found in an earlier study [66]. Recently, O'Byrne and colleagues [93] showed that the reduction of ARC kisspeptin expression by virus-induced *Kiss1*-antisense expression resulted in a decrease in the amplitude but not in the incidence of LH surge in rats. Thus, the ARC kisspeptin neurons may play some roles in the generation and/or amplification of GnRH/LH surges in rats.

Extra-hypothalamic Kisspeptins

Emerging evidence indicates the potential involvement of extra-hypothalamic kisspeptin in reproductive functions. Table 1 summarizes the localization and potential roles of kisspeptin located outside the hypothalamus.

Kisspeptin neurons in the limbic system and hippocampus

Kisspeptin neurons have been found in the medial amygdala and the bed nucleus of stria terminalis, a limbic system [59, 64, 94]. In addition, *Kiss1* expression was also found in the rat hippocampus at lower levels than in the two major hypothalamic populations or in the amygdala [95]. Limbic and hippocampal *Kiss1* expression seems to be controlled by sex steroids: Estrogen increases *Kiss1* expression in the limbic system in rats and mice of both sexes [64, 94], whereas androgen decreases *Kiss1* expression in male rat hippocampus [96]. In the medial amygdala, *Kiss1* expression shows sexual dimorphism with males having more kisspeptin neurons than females [94]. Compared to the hypothalamic kisspeptin neurons, little is known about the physiological role of kisspeptin neurons in the limbic system and hippocampus. Recently, Pineda *et al.* [97] showed reciprocal connectivity between the accessory olfactory bulb and the amygdala kisspeptin neurons, suggesting the role of amygdala kisspeptin neurons as putative mediators of olfactory control of the reproductive function in rodents. Indeed, Comninou *et al.* [98] and Gresham *et al.* [99] showed that injection of kisspeptin into the amygdala enhanced LH secretion in rats, suggesting that kisspeptin-GPR54 signaling in the amygdala may have a physiological role in stimulating LH secretion in rats.

Ovarian kisspeptin

Kisspeptin expression has been found in the ovary of rats [100,

101], but the results are inconsistent between these studies. Castellano *et al.* [100] showed kisspeptin-immunoreactivities in the theca layers of growing follicles, the corpora lutea, and the interstitial tissue of the rat ovary. In contrast, Laoharatchathanin *et al.* [101] showed *Kiss1* mRNA almost solely in the follicles of rat ovary using the laser-capture microdissection technique. Both studies showed a transient increase in *Kiss1* mRNA at the proestrus or after human chorionic gonadotropin (hCG) stimulation. Ovarian *Kiss1* expression seems to be controlled by preovulatory LH surge [100] and a kisspeptin antagonist exerts a negative influence on the shape of the corpus luteum *in vivo* and progesterone production from granulosa cells *in vitro* [101]. These suggest that ovarian kisspeptin may serve as a local regulator of luteinization. On the other hand, Ricu *et al.* [102] suggested that ovarian kisspeptin acts as a local regulator of follicular development, because local administration of the same kisspeptin antagonist at a higher dose exerts a negative influence on puberty onset and estrous cyclicity without changes in plasma LH levels in rats. Recently, two groups showed that ovarian *Kiss1* expression is higher in aged rats and mice than in young ones and suggested a possible role of ovarian kisspeptin in reproductive senescence, in particular ovarian aging [103, 104].

Recently, forced ovulation in *Kiss1* or *Gpr54* knockout mice was reportedly achieved by a combination of estradiol priming and a standard superovulation protocol using equine CG and hCG [105]. In addition, the oocytes collected from *Kiss1* knockout mice were successfully fertilized with wildtype mouse sperm and developed to the blastocyst stage *in vivo*. This suggests that ovarian kisspeptin is dispensable for oocyte maturation. Further studies are warranted to clarify the role(s) of local kisspeptin in oocyte fertilizability and developmental ability.

Testicular kisspeptin

There are conflicting results on the *Kiss1*/kisspeptin expression in the testis. Mei *et al.* [106] found *Kiss1* or *Gpr54* promoter-driven β-galactosidase activity in the testis as well as in the hypothalamus of knock-in mice carrying targeted mutations in *Kiss1* or *Gpr54* loci with a *LacZ* insertion. More specifically, the β-galactosidase activity was almost solely found in haploid spermatids. The same study failed to detect any kisspeptin-immunoreactivities in spermatids, suggesting that the *Kiss1* mRNA may be translationally repressed in mice.

Pinto *et al.* [107] reported that kisspeptin- and GPR54-immunoreactivities were found in mature human spermatozoa and suggested that kisspeptin-GPR54 signaling may control sperm motility and hyperactivation. So far, there is little physiological evidence regarding the function of the sperm, such as motility and fertility. The functions of the sperm should be analyzed in *Kiss1* or *Gpr54* knockout animal models to resolve this conflict.

Placental and uterine kisspeptin: an implication to implantation

Kisspeptin was first identified in human placenta [35, 36], because it is highly expressed in the syncytiotrophoblast cells of the placenta [108, 109] and its concentrations in the maternal blood markedly increased throughout the period of pregnancy [108, 110]. In rat placenta, kisspeptin expression is found in the trophoblast giant cells and transiently increases at embryonic day 12 when the embryo

Table 1. Localization and potential roles of extra-hypothalamic kisspeptin

Brain area/Organ	Species	Potential roles of kisspeptin
Limbic system	Rats [64, 94] and mice [59, 94]	Mediator of olfactory function [97] Control of LH secretion [98, 99]
Hippocampus	Rats [95, 96]	Cognition and epilepsy [96]
Ovary	Rats [100–103] and mice [104]	Corpus luteum formation and progesterone production [101] Follicular development [102] Ovarian aging [103, 104]
Testis	Mice [106] and humans [107]	Sperm motility and hyperactivation [107]
Uteri	Mice [111]	Implantation [105]
Placenta	Rats [37] and humans [35, 36, 108, 109]	Implantation [37]

Reference numbers are shown in square brackets.

exhibits the implantation [37]. This suggests that kisspeptin may be involved in the implantation in rodents, though the physiological role(s) of large amounts of placental kisspeptin is presently unknown even in humans.

Kiss1 and *Gpr54* expression is also found in uteri in mice. Zhang *et al.* [111] showed that both *Kiss1* and *Gpr54* expression increases with the initiation of implantation and the progression of uterine decidualization. Calder *et al.* [105] showed that *Kiss1* heterozygous embryos failed to implant in superovulated *Kiss1* knockout mice. Thus, uterine kisspeptin is likely involved in the implantation process. In addition, Calder *et al.* [105] showed insufficient expression of leukemia inhibitory factor, a cytokine absolutely required for implantation in mice [112], and the administration of leukemia inhibitory factor to superovulated *Kiss1* knockout females was sufficient to partially rescue the implantation of *Kiss1* heterozygous embryos. These studies may indicate a novel role of uterine kisspeptin in embryonic implantation.

Conclusion and Unanswered Questions

Ever since the discovery of kisspeptin in 2001, intensive studies on hypothalamic expression of *KISS1/Kiss1* and on physiological roles of hypothalamic kisspeptin neurons have provided a clue as to how the brain controls sexual maturation at the onset of puberty and subsequent reproductive performance in mammals. As described in this review, the two major populations of hypothalamic kisspeptin neurons are considered centers generating GnRH pulses and surges. There are still some important unanswered questions on hypothalamic kisspeptin neurons. First, it remains unclear how the ARC kisspeptin neurons are synchronized to each other in order to generate the pulsatile kisspeptin and hence GnRH secretion. Morphologically, the fibers of the kisspeptin neurons extend over the whole ARC, indicating a neuronal connection among kisspeptin neurons. Second, afferent inputs to the ARC kisspeptin neurons remain unsettled. In particular, inhibitory inputs to the ARC kisspeptin neurons responsible for physiological restriction of GnRH/gonadotropin secretion during the prepubertal and lactation periods are still poorly understood. Our recent study demonstrates that kisspeptin neurons integrate the stimulatory inputs of glutamatergic and noradrenergic neurons to stimulate GnRH secretion in rats [54]. Thus, such stimulatory inputs may be suppressed or inhibited during the prepubertal and lactation periods, and besides, particular inhibitory inputs to kisspeptin neurons, if any,

may mediate GnRH/gonadotropin suppression under the adversity.

In contrast to the intra-hypothalamic roles of kisspeptin, little is known about the physiological significance of kisspeptin produced in the extra-hypothalamic tissues as mentioned in the last part of the present review. So far, the results obtained from the *Kiss1* or *Gpr54* knockout animal models demonstrated that a central defect of *Kiss1* expression accounts for a large portion of the hypogonadotropic hypogonadism. These results, however, cannot eliminate the possibility that extra-hypothalamic kisspeptin serves as an autocrine/paracrine factor in order to exert its physiological role in the peripheral tissues. Further investigation is needed in order to uncover the peripheral mechanisms controlling reproduction in mammals, in which kisspeptin plays a role.

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References

1. Harris GW. Neural control of the pituitary gland. *Physiol Rev* 1948; **28**: 139–179. [\[Medline\]](#)
2. Schally AV, Arimura A, Kastin AJ, Matsuo H, Baba Y, Redding TW, Nair RM, Debeljuk L, White WF. Gonadotropin-releasing hormone: one polypeptide regulates secretion of luteinizing and follicle-stimulating hormones. *Science* 1971; **173**: 1036–1038. [\[Medline\]](#) [\[CrossRef\]](#)
3. Amoss M, Burgus R, Blackwell R, Vale W, Fellows R, Guillemin R. Purification, amino acid composition and N-terminus of the hypothalamic luteinizing hormone releasing factor (LRF) of ovine origin. *Biochem Biophys Res Commun* 1971; **44**: 205–210. [\[Medline\]](#) [\[CrossRef\]](#)
4. Schally AV. Aspects of hypothalamic regulation of the pituitary gland. *Science* 1978; **202**: 18–28. [\[Medline\]](#) [\[CrossRef\]](#)
5. Belchetz PE, Plant TM, Nakai Y, Keogh EJ, Knobil E. Hypophysial responses to continuous and intermittent delivery of hypothalamic gonadotropin-releasing hormone. *Science* 1978; **202**: 631–633. [\[Medline\]](#) [\[CrossRef\]](#)
6. Knobil E, Plant TM, Wildt L, Belchetz PE, Marshall G. Control of the rhesus monkey menstrual cycle: permissive role of hypothalamic gonadotropin-releasing hormone. *Science* 1980; **207**: 1371–1373. [\[Medline\]](#) [\[CrossRef\]](#)
7. Dierschke DJ, Bhattacharya AN, Atkinson LE, Knobil E. Circhoral oscillations of plasma LH levels in the ovariectomized rhesus monkey. *Endocrinology* 1970; **87**:

- 850–853. [Medline] [CrossRef]
8. Wildt L, Marshall G, Knobil E. Experimental induction of puberty in the infantile female rhesus monkey. *Science* 1980; **207**: 1373–1375. [Medline] [CrossRef]
 9. Naftolin F, Yen SS, Tsai CC. Rapid cycling of plasma gonadotrophins in normal men as demonstrated by frequent sampling. *Nat New Biol* 1972; **236**: 92–93. [Medline] [CrossRef]
 10. Nankin HR, Troen P. Repetitive luteinizing hormone elevations in serum of normal men. *J Clin Endocrinol Metab* 1971; **33**: 558–560. [Medline] [CrossRef]
 11. Yen SS, Tsai CC, Naftolin F, Vandenberg G, Ajabor L. Pulsatile patterns of gonadotropin release in subjects with and without ovarian function. *J Clin Endocrinol Metab* 1972; **34**: 671–675. [Medline] [CrossRef]
 12. Naftolin F, Judd HL, Yen SS. Pulsatile patterns of gonadotropins and testosterone in man: the effects of clomiphene, with and without testosterone added. *J Clin Endocrinol Metab* 1973; **36**: 285–288. [Medline] [CrossRef]
 13. Moenter SM, Brand RM, Midgley AR, Karsch FJ. Dynamics of gonadotropin-releasing hormone release during a pulse. *Endocrinology* 1992; **130**: 503–510. [Medline]
 14. Herbison AE. Multimodal influence of estrogen upon gonadotropin-releasing hormone neurons. *Endocr Rev* 1998; **19**: 302–330. [Medline] [CrossRef]
 15. Monroe SE, Atkinson LE, Knobil E. Patterns of circulating luteinizing hormone and their relation to plasma progesterone levels during the menstrual cycle of the Rhesus monkey. *Endocrinology* 1970; **87**: 453–455. [Medline] [CrossRef]
 16. Yamaji T, Dierschke DJ, Hotchkiss J, Bhattacharya AN, Surve AH, Knobil E. Estrogen induction of LH release in the rhesus monkey. *Endocrinology* 1971; **89**: 1034–1041. [Medline] [CrossRef]
 17. Moenter SM, Caraty A, Locatelli A, Karsch FJ. Pattern of gonadotropin-releasing hormone (GnRH) secretion leading up to ovulation in the ewe: existence of a preovulatory GnRH surge. *Endocrinology* 1991; **129**: 1175–1182. [Medline] [CrossRef]
 18. Moenter SM, Caraty A, Karsch FJ. The estradiol-induced surge of gonadotropin-releasing hormone in the ewe. *Endocrinology* 1990; **127**: 1375–1384. [Medline] [CrossRef]
 19. Moenter SM, Brand RC, Karsch FJ. Dynamics of gonadotropin-releasing hormone (GnRH) secretion during the GnRH surge: insights into the mechanism of GnRH surge induction. *Endocrinology* 1992; **130**: 2978–2984. [Medline]
 20. Goodman RL. The site of the positive feedback action of estradiol in the rat. *Endocrinology* 1978; **102**: 151–159. [Medline] [CrossRef]
 21. Stearns EL, Winter JS, Faiman C. Positive feedback effect of progestin upon serum gonadotropins in estrogen-primed castrate men. *J Clin Endocrinol Metab* 1973; **37**: 635–638. [Medline] [CrossRef]
 22. Karsch FJ, Dierschke DJ, Knobil E. Sexual differentiation of pituitary function: apparent difference between primates and rodents. *Science* 1973; **179**: 484–486. [Medline] [CrossRef]
 23. Hodges JK, Hearn JP. A positive feedback effect of oestradiol on LH release in the male marmoset monkey, *Callithrix jacchus*. *J Reprod Fertil* 1978; **52**: 83–86. [Medline] [CrossRef]
 24. Watanabe Y, Uenoyama Y, Suzuki J, Takase K, Suetomi Y, Ohkura S, Inoue N, Maeda KI, Tsukamura H. Oestrogen-induced activation of preoptic kisspeptin neurones may be involved in the luteinising hormone surge in male and female Japanese monkeys. *J Neuroendocrinol* 2014; **26**: 909–917. [Medline] [CrossRef]
 25. Dial GD, Wiseman BS, Ott RS, Smith AL, Hixon JE. Absence of sexual dimorphism in the goat: Induction of luteinizing hormone discharge in the castrated male and female and in the intersex with estradiol benzoate. *Theriogenology* 1985; **23**: 351–360. [Medline] [CrossRef]
 26. Matsuda F, Nakatsukasa K, Suetomi Y, Naniwa Y, Ito D, Inoue N, Wakabayashi Y, Okamura H, Maeda KI, Uenoyama Y, Tsukamura H, Ohkura S. The luteinising hormone surge-generating system is functional in male goats as in females: involvement of kisspeptin neurones in the medial preoptic area. *J Neuroendocrinol* 2014; **27**: 57–65. [Medline] [CrossRef]
 27. Karsch FJ, Foster DL. Sexual differentiation of the mechanism controlling the preovulatory discharge of luteinizing hormone in sheep. *Endocrinology* 1975; **97**: 373–379. [Medline] [CrossRef]
 28. Brown-Grant K. Steroid hormone administration and gonadotrophin secretion in the gonadectomized rat. *J Endocrinol* 1974; **62**: 319–332. [Medline] [CrossRef]
 29. Homma T, Sakakibara M, Yamada S, Kinoshita M, Iwata K, Tomikawa J, Kanazawa T, Matsui H, Takatsu Y, Ohtaki T, Matsumoto H, Uenoyama Y, Maeda K, Tsukamura H. Significance of neonatal testicular sex steroids to feminize anteroventral periventricular kisspeptin neurons and the GnRH/LH surge system in male rats. *Biol Reprod* 2009; **81**: 1216–1225. [Medline] [CrossRef]
 30. Sakakibara M, Deura C, Minabe S, Iwata Y, Uenoyama Y, Maeda KI, Tsukamura H. Different critical perinatal periods and hypothalamic sites of oestradiol action in the defeminisation of luteinising hormone surge and lordosis capacity in the rat t. *J Neuroendocrinol* 2013; **25**: 251–259. [Medline] [CrossRef]
 31. Herbison AE, Pape JR. New evidence for estrogen receptors in gonadotropin-releasing hormone neurons. *Front Neuroendocrinol* 2001; **22**: 292–308. [Medline] [CrossRef]
 32. Terasawa E. Control of luteinizing hormone-releasing hormone pulse generation in nonhuman primates. *Cell Mol Neurobiol* 1995; **15**: 141–164. [Medline] [CrossRef]
 33. Petersen SL, Ottem EN, Carpenter CD. Direct and indirect regulation of gonadotropin-releasing hormone neurons by estradiol. *Biol Reprod* 2003; **69**: 1771–1778. [Medline] [CrossRef]
 34. Lee JH, Miele ME, Hicks DJ, Phillips KK, Trent JM, Weissman BE, Welch DR. KiSS-1, a novel human malignant melanoma metastasis-suppressor gene. *J Natl Cancer Inst* 1996; **88**: 1731–1737. [Medline] [CrossRef]
 35. Ohtaki T, Shintani Y, Honda S, Matsumoto H, Hori A, Kanehashi K, Terao Y, Kumano S, Takatsu Y, Masuda Y, Ishibashi Y, Watanabe T, Asada M, Yamada T, Suenaga M, Kitada C, Usuki S, Kurokawa T, Onda H, Nishimura O, Fujino M. Metastasis suppressor gene KiSS-1 encodes peptide ligand of a G-protein-coupled receptor. *Nature* 2001; **411**: 613–617. [Medline] [CrossRef]
 36. Kotani M, Dethieux M, Vandenbogaerde A, Communi D, Vanderwinden JM, Le Poule E, Brézillon S, Tyldesley R, Suarez-Huerta N, Vandeput F, Blanpain C, Schiffmann SN, Vassart G, Parmentier M. The metastasis suppressor gene KiSS-1 encodes kisspeptides, the natural ligands of the orphan G protein-coupled receptor GPR54. *J Biol Chem* 2001; **276**: 34631–34636. [Medline] [CrossRef]
 37. Terao Y, Kumano S, Takatsu Y, Hattori M, Nishimura A, Ohtaki T, Shintani Y. Expression of KiSS-1, a metastasis suppressor gene, in trophoblast giant cells of the rat placenta. *Biochim Biophys Acta* 2004; **1678**: 102–110. [Medline] [CrossRef]
 38. Ohkura S, Takase K, Matsuyama S, Mogi K, Ichimaru T, Wakabayashi Y, Uenoyama Y, Mori Y, Steiner RA, Tsukamura H, Maeda KI, Okamura H. Gonadotrophin-releasing hormone pulse generator activity in the hypothalamus of the goat. *J Neuroendocrinol* 2009; **21**: 813–821. [Medline] [CrossRef]
 39. Tomikawa J, Homma T, Tajima S, Shibata T, Inamoto Y, Takase K, Inoue N, Ohkura S, Uenoyama Y, Maeda K, Tsukamura H. Molecular characterization and estrogen regulation of hypothalamic *KISS1* gene in the pig. *Biol Reprod* 2010; **82**: 313–319. [Medline] [CrossRef]
 40. Inoue N, Sasagawa K, Ikai K, Sasaki Y, Tomikawa J, Oishi S, Fujii N, Uenoyama Y, Ohmori Y, Yamamoto N, Hondo E, Maeda K, Tsukamura H. Kisspeptin neurons mediate reflex ovulation in the musk shrew (*Suncus murinus*). *Proc Natl Acad Sci USA* 2011; **108**: 17527–17532. [Medline] [CrossRef]
 41. Naniwa Y, Nakatsukasa K, Setsuda S, Oishi S, Fujii N, Matsuda F, Uenoyama Y, Tsukamura H, Maeda K, Ohkura S. Effects of full-length kisspeptin administration on follicular development in Japanese Black beef cows. *J Reprod Dev* 2013; **59**: 588–594. [Medline] [CrossRef]
 42. Tsutsui K, Bentley GE, Kriegsfeld LJ, Osugi T, Seong JY, Vaudry H. Discovery and evolutionary history of gonadotrophin-inhibitory hormone and kisspeptin: new key neuropeptides controlling reproduction. *J Neuroendocrinol* 2010; **22**: 716–727. [Medline]
 43. Oishi S, Misu R, Tomita K, Setsuda S, Masuda R, Ohno H, Naniwa Y, Ieda N, Inoue N, Ohkura S, Uenoyama Y, Tsukamura H, Maeda K, Hirayama A, Tsujimoto G, Fujii N. Activation of neuropeptide FF receptor by kisspeptin receptor ligands. *ACS Med Chem Lett* 2011; **2**: 53–57. [Medline] [CrossRef]
 44. Lyubimov Y, Engstrom M, Wurster S, Savola JM, Korpi ER, Panula P. Human kisspeptins activate neuropeptide FF2 receptor. *Neuroscience* 2010; **170**: 117–122. [Medline] [CrossRef]
 45. de Roux N, Genin E, Carel JC, Matsuda F, Chaussain JL, Milgrom E. Hypogonadotropic hypogonadism due to loss of function of the KiSS1-derived peptide receptor GPR54. *Proc Natl Acad Sci USA* 2003; **100**: 10972–10976. [Medline] [CrossRef]
 46. Seminara SB, Messager S, Chatzidakis EE, Thresher RR, Acienro JS Jr, Shagoury JK, Bo-Abbas Y, Kuohung W, Schwinof KM, Hendrick AG, Zahn D, Dixon J, Kaiser UB, Slaugenhoupt SA, Gusella JF, O’Rahilly S, Carlton MB, Crowley WF Jr, Aparicio SA, Colledge WH. The GPR54 gene as a regulator of puberty. *N Engl J Med* 2003; **349**: 1614–1627. [Medline] [CrossRef]
 47. Topaloglu AK, Tello JA, Kotan LD, Ozbek MN, Yilmaz MB, Erdogan S, Gurbuz F, Temiz F, Millar RP, Yuksel B. Inactivating *KISS1* mutation and hypogonadotropic hypogonadism. *N Engl J Med* 2012; **366**: 629–635. [Medline] [CrossRef]
 48. Funes S, Hedrick JA, Vassileva G, Markowitz L, Abbondanzo S, Golovko A, Yang S, Monsma FJ, Gustafson EL. The KiSS-1 receptor GPR54 is essential for the development of the murine reproductive system. *Biochem Biophys Res Commun* 2003; **312**: 1357–1363. [Medline] [CrossRef]
 49. Messager S, Chatzidakis EE, Ma D, Hendrick AG, Zahn D, Dixon J, Thresher RR, Malinge I, Lomet D, Carlton MB, Colledge WH, Caraty A, Aparicio SA. Kisspeptin directly stimulates gonadotropin-releasing hormone release via G protein-coupled receptor 54. *Proc Natl Acad Sci USA* 2005; **102**: 1761–1766. [Medline] [CrossRef]
 50. d’Anglemont de Tassigny X, Fagg LA, Dixon JP, Day K, Leitch HG, Hendrick AG, Zahn D, Franceschini I, Caraty A, Carlton MB, Aparicio SA, Colledge WH. Hypogonadotropic hypogonadism in mice lacking a functional Kiss1 gene. *Proc Natl Acad Sci USA* 2007; **104**: 10714–10719. [Medline] [CrossRef]
 51. Dungan HM, Gottsch ML, Zeng H, Gragerov A, Bergmann JE, Vassilatis DK, Clifton DK, Steiner RA. The role of kisspeptin-GPR54 signaling in the tonic regulation and surge

- release of gonadotropin-releasing hormone/luteinizing hormone. *J Neurosci* 2007; **27**: 12088–12095. [Medline] [CrossRef]
52. Lapatto R, Pallas JC, Zhang D, Chan YM, Mahan A, Cerrato F, Le WW, Hoffman GE, Seminara SB. *Kiss1*^{-/-} mice exhibit more variable hypogonadism than *Gpr54*^{-/-} mice. *Endocrinology* 2007; **148**: 4927–4936. [Medline] [CrossRef]
 53. Chan YM, Broder-Fingert S, Wong KM, Seminara SB. Kisspeptin/Gpr54-independent gonadotrophin-releasing hormone activity in *Kiss1* and *Gpr54* mutant mice. *J Neuroendocrinol* 2009; **21**: 1015–1023. [Medline] [CrossRef]
 54. Uenoyama Y, Nakamura S, Hayakawa Y, Ikegami K, Watanabe Y, Deura C, Minabe S, Tomikawa J, Goto T, Ieda N, Inoue N, Sanbo M, Tamura C, Hirabayashi M, Maeda KI, Tsukamura H. Lack of pulse and surge modes and glutamatergic stimulation of luteinizing hormone release in *Kiss1* knockout rats. *J Neuroendocrinol* 2015; **27**: 187–197. [Medline] [CrossRef]
 55. Irwig MS, Fraley GS, Smith JT, Acohido BV, Popa SM, Cunningham MJ, Gottsch ML, Clifton DK, Steiner RA. Kisspeptin activation of gonadotropin releasing hormone neurons and regulation of KiSS-1 mRNA in the male rat. *Neuroendocrinology* 2004; **80**: 264–272. [Medline] [CrossRef]
 56. Matsui H, Takatsu Y, Kumano S, Matsumoto H, Ohtaki T. Peripheral administration of metasin induces marked gonadotropin release and ovulation in the rat. *Biochem Biophys Res Commun* 2004; **320**: 383–388. [Medline] [CrossRef]
 57. Shahab M, Mastronardi C, Seminara SB, Crowley WF, Ojeda SR, Plant TM. Increased hypothalamic GPR54 signaling: a potential mechanism for initiation of puberty in primates. *Proc Natl Acad Sci USA* 2005; **102**: 2129–2134. [Medline] [CrossRef]
 58. Nakamura S, Uenoyama Y, Ikegami K, Dai M, Watanabe Y, Takahashi C, Hirabayashi M, Tsukamura H, Maeda K-I. Neonatal kisspeptin is steroid-independently required for defeminization and peripubertal kisspeptin-induced testosterone is required for masculinisation of the brain: a behavioural study using *Kiss1* KO rats. *J Neuroendocrinol* 2016. (in press) [Medline] [CrossRef]
 59. Gottsch ML, Cunningham MJ, Smith JT, Popa SM, Acohido BV, Crowley WF, Seminara SB, Clifton DK, Steiner RA. A role for kisspeptins in the regulation of gonadotropin secretion in the mouse. *Endocrinology* 2004; **145**: 4073–4077. [Medline] [CrossRef]
 60. Smith JT, Cunningham MJ, Rissman EF, Clifton DK, Steiner RA. Regulation of *Kiss1* gene expression in the brain of the female mouse. *Endocrinology* 2005; **146**: 3686–3692. [Medline] [CrossRef]
 61. Clarkson J, Herbison AE. Postnatal development of kisspeptin neurons in mouse hypothalamus: sexual dimorphism and projections to gonadotropin-releasing hormone neurons. *Endocrinology* 2006; **147**: 5817–5825. [Medline] [CrossRef]
 62. Adachi S, Yamada S, Takatsu Y, Matsui H, Kinoshita M, Takase K, Sugiura H, Ohtaki T, Matsumoto H, Uenoyama Y, Tsukamura H, Inoue K, Maeda K. Involvement of anteroventral periventricular metasin/kisspeptin neurons in estrogen positive feedback action on luteinizing hormone release in female rats. *J Reprod Dev* 2007; **53**: 367–378. [Medline] [CrossRef]
 63. Smith JT, Li Q, Pereira A, Clarke IJ. Kisspeptin neurons in the ovine arcuate nucleus and preoptic area are involved in the preovulatory luteinizing hormone surge. *Endocrinology* 2009; **150**: 5530–5538. [Medline] [CrossRef]
 64. Xu Z, Kaga S, Mochiduki A, Tsubomizu J, Adachi S, Sakai T, Inoue K, Adachi AA. Immunocytochemical localization of kisspeptin neurons in the rat forebrain with special reference to sexual dimorphism and interaction with GnRH neurons. *Endocr J* 2012; **59**: 161–171. [Medline] [CrossRef]
 65. Lehman MN, Merkley CM, Coolen LM, Goodman RL. Anatomy of the kisspeptin neural network in mammals. *Brain Res* 2010; **1364**: 90–102. [Medline] [CrossRef]
 66. Kinoshita M, Tsukamura H, Adachi S, Matsui H, Uenoyama Y, Iwata K, Yamada S, Inoue K, Ohtaki T, Matsumoto H, Maeda K. Involvement of central metasin in the regulation of preovulatory luteinizing hormone surge and estrous cyclicity in female rats. *Endocrinology* 2005; **146**: 4431–4436. [Medline] [CrossRef]
 67. Smith JT, Popa SM, Clifton DK, Hoffman GE, Steiner RA. Kiss1 neurons in the forebrain as central processors for generating the preovulatory luteinizing hormone surge. *J Neurosci* 2006; **26**: 6687–6694. [Medline] [CrossRef]
 68. Tomikawa J, Uenoyama Y, Ozawa M, Fukanuma T, Takase K, Goto T, Abe H, Ieda N, Minabe S, Deura C, Inoue N, Sanbo M, Tomita K, Hirabayashi M, Tanaka S, Imamura T, Okamura H, Maeda K, Tsukamura H. Epigenetic regulation of *Kiss1* gene expression mediating estrogen-positive feedback action in the mouse brain. *Proc Natl Acad Sci USA* 2012; **109**: E1294–E1301. [Medline] [CrossRef]
 69. Goto T, Tomikawa J, Ikegami K, Minabe S, Abe H, Fukanuma T, Imamura T, Takase K, Sanbo M, Tomita K, Hirabayashi M, Maeda K, Tsukamura H, Uenoyama Y. Identification of hypothalamic arcuate nucleus-specific enhancer region of *Kiss1* gene in mice. *Mol Endocrinol* 2015; **29**: 121–129. [Medline] [CrossRef]
 70. Wiegand SJ, Terasawa E. Discrete lesions reveal functional heterogeneity of suprachiasmatic structures in regulation of gonadotropin secretion in the female rat. *Neuroendocrinology* 1982; **34**: 395–404. [Medline] [CrossRef]
 71. Smith JT, Coolen LM, Kriegsfeld LJ, Sari IP, Jaafarzadehshirazi MR, Maltby M, Bateman K, Goodman RL, Tilbrook AJ, Ubuka T, Bentley GE, Clarke IJ, Lehman MN. Variation in kisspeptin and RFamide-related peptide (RFRP) expression and terminal connections to gonadotropin-releasing hormone neurons in the brain: a novel medium for seasonal breeding in the sheep. *Endocrinology* 2008; **149**: 5770–5782. [Medline] [CrossRef]
 72. Pineda R, Garcia-Galiano D, Roseweir A, Romero M, Sanchez-Garrido MA, Ruiz-Pino F, Morgan K, Pinilla L, Millar RP, Tena-Sempere M. Critical roles of kisspeptins in female puberty and preovulatory gonadotropin surges as revealed by a novel antagonist. *Endocrinology* 2010; **151**: 722–730. [Medline] [CrossRef]
 73. Smith JT, Li Q, Yap KS, Shahab M, Roseweir AK, Millar RP, Clarke IJ. Kisspeptin is essential for the full preovulatory LH surge and stimulates GnRH release from the isolated ovine median eminence. *Endocrinology* 2011; **152**: 1001–1012. [Medline] [CrossRef]
 74. Kauffman AS, Gottsch ML, Roa J, Byquist AC, Crown A, Clifton DK, Hoffman GE, Steiner RA, Tena-Sempere M. Sexual differentiation of *Kiss1* gene expression in the brain of the rat. *Endocrinology* 2007; **148**: 1774–1783. [Medline] [CrossRef]
 75. Abbott AD, Colman RJ, Tiefenthaler R, Dumesic DA, Abbott DH. Early-to-mid gestation fetal testosterone increases right hand 2D:4D finger length ratio in polycystic ovary syndrome-like monkeys. *PLoS ONE* 2012; **7**: e42372. [Medline] [CrossRef]
 76. Hoffman GE, Le WW, Franceschini I, Caraty A, Advis JP. Expression of fos and in vivo median eminence release of LHRH identifies an active role for preoptic area kisspeptin neurons in synchronized surges of LH and LHRH in the ewe. *Endocrinology* 2011; **152**: 214–222. [Medline] [CrossRef]
 77. Knobil E. Patterns of hypophysiotropic signals and gonadotropin secretion in the rhesus monkey. *Biol Reprod* 1981; **24**: 44–49. [Medline] [CrossRef]
 78. Kawakami M, Uemura T, Hayashi R. Electrophysiological correlates of pulsatile gonadotropin release in rats. *Neuroendocrinology* 1982; **35**: 63–67. [Medline] [CrossRef]
 79. Mori Y, Nishihara M, Tanaka T, Shimizu T, Yamaguchi M, Takeuchi Y, Hoshino K. Chronic recording of electrophysiological manifestation of the hypothalamic gonadotropin-releasing hormone pulse generator activity in the goat. *Neuroendocrinology* 1991; **53**: 392–395. [Medline] [CrossRef]
 80. Uenoyama Y, Inoue N, Pheng V, Homma T, Takase K, Yamada S, Ajiki K, Ichikawa M, Okamura H, Maeda KI, Tsukamura H. Ultrastructural evidence of kisspeptin-gonadotropin-releasing hormone (GnRH) interaction in the median eminence of female rats: implication of axo-axonal regulation of GnRH release. *J Neuroendocrinol* 2011; **23**: 863–870. [Medline] [CrossRef]
 81. Matsuyama S, Ohkura S, Mogi K, Wakabayashi Y, Mori Y, Tsukamura H, Maeda K, Ichikawa M, Okamura H. Morphological evidence for direct interaction between kisspeptin and gonadotropin-releasing hormone neurons at the median eminence of the male goat: an immunoelectron microscopic study. *Neuroendocrinology* 2011; **94**: 323–332. [Medline] [CrossRef]
 82. Keen KL, Wegner FH, Bloom SR, Ghatei MA, Terasawa E. An increase in kisspeptin-54 release occurs with the pubertal increase in luteinizing hormone-releasing hormone-1 release in the stalk-median eminence of female rhesus monkeys in vivo. *Endocrinology* 2008; **149**: 4151–4157. [Medline] [CrossRef]
 83. Goodman RL, Lehman MN, Smith JT, Coolen LM, de Oliveira CV, Jafarzadehshirazi MR, Pereira A, Iqbal J, Caraty A, Ciofi P, Clarke IJ. Kisspeptin neurons in the arcuate nucleus of the ewe express both dynorphin A and neurokinin B. *Endocrinology* 2007; **148**: 5752–5760. [Medline] [CrossRef]
 84. Lehman MN, Coolen LM, Goodman RL. Minireview: kisspeptin/neurokinin B/dynorphin (KNDy) cells of the arcuate nucleus: a central node in the control of gonadotropin-releasing hormone secretion. *Endocrinology* 2010; **151**: 3479–3489. [Medline] [CrossRef]
 85. Navarro VM, Gottsch ML, Chavkin C, Okamura H, Clifton DK, Steiner RA. Regulation of gonadotropin-releasing hormone secretion by kisspeptin/dynorphin/neurokinin B neurons in the arcuate nucleus of the mouse. *J Neurosci* 2009; **29**: 11859–11866. [Medline] [CrossRef]
 86. Wakabayashi Y, Nakada T, Murata K, Ohkura S, Mogi K, Navarro VM, Clifton DK, Mori Y, Tsukamura H, Maeda K, Steiner RA, Okamura H. Neurokinin B and dynorphin A in kisspeptin neurons of the arcuate nucleus participate in generation of periodic oscillation of neural activity driving pulsatile gonadotropin-releasing hormone secretion in the goat. *J Neurosci* 2010; **30**: 3124–3132. [Medline] [CrossRef]
 87. Goodman RL, Hileman SM, Nestor CC, Porter KL, Connors JM, Hardy SL, Millar RP, Cernea M, Coolen LM, Lehman MN. Kisspeptin, neurokinin B, and dynorphin act in the arcuate nucleus to control activity of the GnRH pulse generator in ewes. *Endocrinology* 2013; **154**: 4259–4269. [Medline] [CrossRef]
 88. Amstalden M, Coolen LM, Hemmerle AM, Billings HJ, Connors JM, Goodman RL, Lehman MN. Neurokinin 3 receptor immunoreactivity in the septal region, preoptic area and hypothalamus of the female sheep: colocalisation in neurokinin B cells of the arcuate nucleus but not in gonadotropin-releasing hormone neurones. *J Neuroendocrinol* 2010; **22**: 1–12. [Medline] [CrossRef]
 89. Goodman RL, Coolen LM, Lehman MN. A role for neurokinin B in pulsatile GnRH secretion in the ewe. *Neuroendocrinology* 2014; **99**: 18–32. [Medline] [CrossRef]
 90. Navarro VM, Gottsch ML, Wu M, García-Galiano D, Hobbs SJ, Bosch MA, Pinilla L, Clifton DK, Dearth A, Ronnekleiv OK, Braun RE, Palmeter RD, Tena-Sempere

- M, Alreja M, Steiner RA. Regulation of NKB pathways and their roles in the control of Kiss1 neurons in the arcuate nucleus of the male mouse. *Endocrinology* 2011; **152**: 4265–4275. [Medline] [CrossRef]
91. Estrada KM, Clay CM, Pompolo S, Smith JT, Clarke IJ. Elevated KiSS-1 expression in the arcuate nucleus prior to the cyclic preovulatory gonadotrophin-releasing hormone/lutenising hormone surge in the ewe suggests a stimulatory role for kisspeptin in oestrogen-positive feedback. *J Neuroendocrinol* 2006; **18**: 806–809. [Medline] [CrossRef]
92. Merkley CM, Porter KL, Coolen LM, Hileman SM, Billings HJ, Drews S, Goodman RL, Lehman MN. KNDy (kisspeptin/neurokinin B/dynorphin) neurons are activated during both pulsatile and surge secretion of LH in the ewe. *Endocrinology* 2012; **153**: 5406–5414. [Medline] [CrossRef]
93. Hu MH, Li XF, McCausland B, Li SY, Gresham R, Kinsey-Jones JS, Gardiner JV, Sam AH, Bloom SR, Poston L, Lightman SL, Murphy KG, O'Byrne KT. Relative Importance of the Arcuate and Anteroventral Periventricular Kisspeptin Neurons in Control of Puberty and Reproductive Function in Female Rats. *Endocrinology* 2015; **156**: 2619–2631. [Medline] [CrossRef]
94. Kim J, Semaan SJ, Clifton DK, Steiner RA, Dhamija S, Kauffman AS. Regulation of Kiss1 expression by sex steroids in the amygdala of the rat and mouse. *Endocrinology* 2011; **152**: 2020–2030. [Medline] [CrossRef]
95. Arai AC, Xia YF, Suzuki E, Kessler M, Civelli O, Nothacker HP. Cancer metastasis-suppressing peptide metastin upregulates excitatory synaptic transmission in hippocampal dentate granule cells. *J Neurophysiol* 2005; **94**: 3648–3652. [Medline] [CrossRef]
96. Arai AC. The role of kisspeptin and GPR54 in the hippocampus. *Peptides* 2009; **30**: 16–25. [Medline] [CrossRef]
97. Pineda R, Plaisier F, Millar RP, Ludwig M. Amygdala Kisspeptin Neurons: Putative Mediators of Olfactory Control of the Gonadotropic Axis. *Neuroendocrinology* 2016. (in press) [Medline] [CrossRef]
98. Comninou AN, Anastasova J, Sahuri-Arisoylu M, Li X, Li S, Hu M, Jayasena CN, Ghatei MA, Bloom SR, Matthews PM, O'Byrne KT, Bell JD, Dhillo WS. Kisspeptin signaling in the amygdala modulates reproductive hormone secretion. *Brain Struct Funct* 2016; **221**: 2035–2047. [Medline] [CrossRef]
99. Gresham R, Li S, Adekunbi DA, Hu M, Li XF, O'Byrne KT. Kisspeptin in the medial amygdala and sexual behavior in male rats. *Neurosci Lett* 2016; **627**: 13–17. [Medline] [CrossRef]
100. Castellano JM, Gaytan M, Roa J, Vigo E, Navarro VM, Bellido C, Dieguez C, Aguilar E, Sánchez-Criado JE, Pellicer A, Pinilla L, Gaytan F, Tena-Sempere M. Expression of KiSS-1 in rat ovary: putative local regulator of ovulation? *Endocrinology* 2006; **147**: 4852–4862. [Medline] [CrossRef]
101. Laocharatathanin T, Terashima R, Yonezawa T, Kurusu S, Kawaminami M. Augmentation of Metastin/Kisspeptin mRNA Expression by the Proestrous Luteinizing Hormone Surge in Granulosa Cells of Rats: Implications for Luteinization. *Biol Reprod* 2015; **93**: 15. [Medline] [CrossRef]
102. Ricu MA, Ramirez VD, Paredes AH, Lara HE. Evidence for a celiac ganglion-ovarian kisspeptin neural network in the rat: intraovarian anti-kisspeptin delays vaginal opening and alters estrous cyclicity. *Endocrinology* 2012; **153**: 4966–4977. [Medline] [CrossRef]
103. Fernandes D, Na E, Cuevas F, Cruz G, Lara HE, Paredes AH. Kisspeptin is involved in ovarian follicular development during aging in rats. *J Endocrinol* 2016; **228**: 161–170. [Medline] [CrossRef]
104. Merhi Z, Thornton K, Bonney E, Cipolla MJ, Charron MJ, Buyuk E. Ovarian kisspeptin expression is related to age and to monocyte chemoattractant protein-1. *J Assist Reprod Genet* 2016; **33**: 535–543. [Medline] [CrossRef]
105. Calder M, Chan YM, Raj R, Pampillo M, Elbert A, Noonan M, Gillio-Meina C, Caligioni C, Bérubé NG, Bhattacharya M, Watson AJ, Seminara SB, Babwah AV. Implantation failure in female Kiss1^{-/-} mice is independent of their hypogonadic state and can be partially rescued by leukemia inhibitory factor. *Endocrinology* 2014; **155**: 3065–3078. [Medline] [CrossRef]
106. Mei H, Doran J, Kyle V, Yeo SH, Colledge WH. Does Kisspeptin Signaling have a Role in the Testes? *Front Endocrinol (Lausanne)* 2013; **4**: 198. [Medline]
107. Pinto FM, Cejudo-Román A, Ravina CG, Fernández-Sánchez M, Martín-Lozano D, Illanes M, Tena-Sempere M, Cadenas ML. Characterization of the kisspeptin system in human spermatozoa. *Int J Androl* 2012; **35**: 63–73. [Medline] [CrossRef]
108. Horikoshi Y, Matsumoto H, Takatsu Y, Ohtaki T, Kitada C, Usuki S, Fujino M. Dramatic elevation of plasma metastin concentrations in human pregnancy: metastin as a novel placenta-derived hormone in humans. *J Clin Endocrinol Metab* 2003; **88**: 914–919. [Medline] [CrossRef]
109. Bilban M, Ghaffari-Tabrizi N, Hintermann E, Bauer S, Molzer S, Zoratti C, Malli R, Sharabi A, Hiden U, Graier W, Knöfler M, Andreea F, Wagner O, Quaranta V, Desoye G. Kisspeptin-10, a KiSS-1/metastin-derived decapeptide, is a physiological invasion inhibitor of primary human trophoblasts. *J Cell Sci* 2004; **117**: 1319–1328. [Medline] [CrossRef]
110. Dhillo WS, Savage P, Murphy KG, Chaudhri OB, Patterson M, Nijher GM, Foggo VM, Dancey GS, Mitchell H, Seckl MJ, Ghatei MA, Bloom SR. Plasma kisspeptin is raised in patients with gestational trophoblastic neoplasia and falls during treatment. *Am J Physiol Endocrinol Metab* 2006; **291**: E878–E884. [Medline] [CrossRef]
111. Zhang P, Tang M, Zhong T, Lin Y, Zong T, Zhong C, Zhang B, Ren M, Kuang H. Expression and function of kisspeptin during mouse decidualization. *PLoS ONE* 2014; **9**: e97647. [Medline] [CrossRef]
112. Stewart CL, Kaspar P, Brunet LJ, Bhatt H, Gadi I, Köntgen F, Abbondanzo SJ. Blastocyst implantation depends on maternal expression of leukaemia inhibitory factor. *Nature* 1992; **359**: 76–79. [Medline] [CrossRef]