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Preventing preterm birth: the past limitations and new potential of animal models

Christine K. Ratajczak¹, Justin C. Fay² and Louis J. Muglia³,*

The high rate of preterm birth in the USA and many other countries is a potential target for improving children's immediate health and reducing the medical problems they face as adults. The acute complications for infants born prematurely often require intensive care management and are followed by long-lasting cognitive, sensory, motor, and cardiovascular deficits that substantially limit adult capabilities and survival. The inability to effectively reduce preterm birth stems from the failure to understand normal mechanisms of parturition in humans. Although studies from several model organisms help define the physiology of maintenance and termination of pregnancy, there are fundamental differences between species. For example, species regulate their production of progesterone, the crucial hormone in sustaining pregnancy, differently. This limits the extent to which models can provide meaningful information about the physiological mechanisms of human gestation. The growing wealth of sequenced mammalian genomes, computational comparative genomic tools and systems biology approaches provides new potential to utilize the divergence of DNA sequences and physiology between species to understand the genetic underpinnings of preterm birth.

Preterm birth: an increasing public health concern

Three million infants die before their first birthday as the result of being born prematurely (Ahman and Zupan, 2007). According to global statistics, the greatest cause of infant mortality in the USA is preterm birth, which is the birth of a child after less than 37 weeks of completed gestation, rather than the typical 40 weeks. In 2007, 12.7% of all births in the USA were preterm, an increase of approximately 20% since 1990 (Heron et al., 2010). The rate of preterm birth in black women in the USA remains nearly twofold greater than for white women with otherwise-similar demographic characteristics (Martin et al., 2009). This difference represents one of the largest racial disparities in national health. Preterm birth is a complex multifactorial process associated with diverse pathogenetic mechanisms including infection, maternal stress and changes in obstetric practices, such as indications for induced delivery and artificial reproductive technologies. Birth, or parturition, which is the process of giving birth, involves a complex switch of the uterus from a static and docile environment to the generator of contractile force sufficient to expel a baby. Little is known about the factors that regulate this dynamic switch. Approximately one half of all preterm births are idiopathic (Muglia and Katz, 2010) with no recognized precipitating factor. Increased insight into the etiology of spontaneous idiopathic preterm birth is necessary to effectively model and address this rising public health concern.

Risk factors for preterm birth

Genetic factors influence preterm birth. A family history of preterm birth is a key risk factor, such that women whose mothers and sisters have had a preterm delivery are more likely to enter labor prematurely (Porter et al., 1997; Winkvist et al., 1998). A small but significant association also links the paternal genome to preterm labor; this is probably because of the influence of paternally contributed fetal genes, as demonstrated by segregation analyses and twin studies (Kistka et al., 2008; Plunkett et al., 2009). Rates of preterm birth in specific ethnic groups, with genetic variation arising from geographic history, also indicate a role for genetics in preterm birth. For example, a higher incidence of preterm birth has been demonstrated when either the mother (Adams et al., 2000; Kistka et al., 2007) or father (Palomar et al., 2007) is African American. Several studies indicate that environmental risk factors are not sufficient to explain racial differences in preterm birth (e.g. Goldenberg et al., 1996; Kistka et al., 2007). These population-based findings indicate a role for genetic variation in human birth timing and the risk for prematurity. Clearly, identification of the genetic factors underlying preterm birth would help researchers understand and model the disease.

Initial attempts to reveal the specific genetic variants that contribute to preterm birth involved candidate gene association studies comparing women giving birth to premature infants, or the infants themselves, with women or infants experiencing term births. Several common risk-conferring polymorphisms in inflammation, connective tissue remodeling and detoxification enzymes were identified (Crider et al., 2005;
The association of these polymorphisms with disease is small and variable, but one emerging finding links racial differences in preterm birth frequency with a functional polymorphism in the promoter of a chaperone that is essential for collagen synthesis, SERPINH1. The mutation associated with preterm birth reduces the activity of the SERPINH1 promoter (Wang et al., 2006). This variant is increased in populations of African descent, and is associated with a 3.22-fold increase (95% confidence interval: 1.50-7.22) in the incidence of preterm birth associated with premature rupture of the fetal membranes.

Spontaneous idiopathic preterm birth may reflect acceleration of the normal gestational clock. Microarray data from uterine tissue reveals similar gene regulation patterns among women who labor prematurely and those who do not labor until their infants are full term (Bethin et al., 2003). The lack of distinguishing pathways between preterm and full-term gestation suggests that normal pathways may be accelerated in preterm birth. Thus, factors involved in normal pathway timing may be targets for predicting or preventing preterm birth.

Infection deregulates the normal timing of parturition mechanisms. Mothers who deliver preterm infants, particularly at very early gestational ages, display an increased frequency of colonization with possibly pathologic microorganisms, even when they do not demonstrate overt evidence of infection (Watts et al., 1992; Onderdonk et al., 2008). Several animal models have been utilized to explore the normal timing mechanisms of parturition and the consequences of infection to elucidate pathways for preterm birth. Although they do not recapitulate the human disease in full, they do offer valuable insights.

**Animal studies of parturition**

The use of humans in controlled studies on parturition is severely limited by ethical considerations. However, studies of other animals, notably sheep and mice, have made key contributions to the understanding of parturition. The use of each of these model systems has its own advantages and disadvantages.

**Sheep studies**

Sheep have been a relevant and valuable model for preterm birth. Their relatively large size allows for specific manipulation of either fetus or pregnant ewe. Also, the gestation length of humans is closer to that of sheep than other common models like mice and rats. Both humans and sheep experience a luteal-placental shift during pregnancy (Challis et al., 2000), when the responsibility for steroid hormone production shifts from the corpus luteum to the placenta as gestation progresses. As with humans, sheep have a small number of offspring, with typically one or two fetuses per gestation. However, sheep have a bicornuate uterus as opposed to the pyriform, unicorneate uterus in humans.

Sheep studies demonstrate fetal regulation of parturition events. In the 1960s, Liggins and colleagues (Liggins et al., 1967; Liggins, 1968) demonstrated the importance of the fetal hypothalamic-pituitary-adrenal (HPA) axis in determining birth timing in the sheep. During late gestation, the levels of adrenocorticotropic hormone (ACTH) and cortisol in sheep fetal plasma increase (Challis et al., 2000). Rising cortisol levels cause a change in how pregnenolone is metabolized in the placenta; at this stage pregnenolone that had previously become progesterone is converted to 17α-hydroxypregnenolone and 17β-estradiol. The resulting decrease in circulating maternal progesterone levels, and rise in circulating maternal estrogen, triggers increased uterine levels of the contractile agonist prostaglandin F2α (PGF2α) and subsequent uterine contraction, leading to parturition. Rising cortisol levels also promote maturation of fetal lungs and other organs just before birth. This is evident in the viability of fetuses born prematurely owing to fetal infusion with ACTH or cortisol (Liggins, 1968). Thus, fetal ACTH and cortisol from the fetus help coordinate parturition events with fetal maturity.

Kitts and colleagues also used embryo transfer in sheep to establish that birth timing is determined by the shorter gestation-length twin (Kitts et al., 1984). These results further demonstrate the important role of the fetus in precipitating changes that are required for the start of parturition in sheep.

**Mouse studies**

Despite several important differences in mouse and human pregnancy (Fig. 1), the genetic tractability of the mouse makes it an attractive mammalian model system (Ratajczak and Muglia, 2008). This allows for the generation of knockout models to examine the role of genes that might influence parturition. Mice also have a short gestation time of 19.5 days, which is convenient for experimentation. However, there are distinct differences between mouse and human reproductive physiology. Mice have a bicornuate uterus and a large litter size, averaging between six and ten pups (Fig. 1). Furthermore, whereas humans experience a luteal-placental shift, the mouse corpora lutea are responsible for steroid hormone production throughout gestation (for a review, see Ratajczak and Muglia, 2008).

As with sheep, mouse parturition involves progesterone withdrawal. Whereas in the sheep, the placenta has a role in steroid hormone production during pregnancy, the corpora lutea of the mouse ovaries are responsible for steroid production throughout pregnancy. In the mouse, PGF2α stimulates luteolysis, the structural and functional degradation of the corpora lutea. Levels of circulating maternal progesterone then drop and uterine contractility increases. Accordingly, ovariectomy induces preterm labor through surgical removal of the site of endogenous progesterone production, whereas administration

**Case study**

J.M. was the 1000-gram product of a 26-week gestation pregnancy to an 18-year-old mother without previous pregnancies. This pregnancy was uneventful until the onset of preterm labor that could not be controlled with medical therapy. J.M. was delivered vaginally in breech position, and required cardiopulmonary resuscitation in the delivery room. After placement of an endotracheal tube for assisted lung ventilation, she was transferred to the neonatal intensive care unit for further management. There, J.M. suffered several complications including: (1) mechanical ventilation for 7 weeks, after which chronic steroids and supplemental oxygen were needed; (2) cerebral bleeding (intraventricular hemorrhage) causing hydrocephalus, which was treated with spinal taps and ultimately needed placement of a ventricular shunt to drain fluid; (3) retinopathy of prematurity that significantly impaired vision; (4) cognitive and motor deficits in childhood; and (5) sustained impairment in growth. These deficits are common following preterm birth. Although neonatal care continues to improve outcomes, the potential for preventing preterm birth offers the greatest hope for the future health of children.
of exogenous progesterone delays the commencement of labor in mice (Skarnes and Harper, 1972). The importance of progesterone withdrawal for murine labor has been highlighted by the observed phenotypes of several genetically modified mouse lines. Mice that are deficient in 20α-hydroxysteroid dehydrogenase, an enzyme that converts progesterone to an inactive metabolite and that is expressed in the ovary of term mice (Wiest, 1968), exhibit no progesterone withdrawal and a failure to initiate labor at term (Piekorz et al., 2005). Similarly, mice that are deficient in the PGF2α receptor (FP) do not experience a serum progesterone withdrawal at term and fail to initiate parturition (Sugimoto et al., 1997). Mice that are deficient in enzymes involved in the synthesis of prostaglandins, such as cytoplasmic phospholipase A2 and cyclooxygenase-1, also experience delayed labor that can be reversed by progesterone receptor antagonist or exogenous PGF2α (Langenbach et al., 1995; Bonventre et al., 1997; Uozumi et al., 1997; Gross et al., 1998).

In addition to their role in luteolysis, prostaglandins serve as a uterine contractile agonist at parturition. The importance of this additional role of prostaglandins is demonstrated in studies of mice with reduced 15-hydroxyprostaglandin dehydrogenase (15-HPGD). This enzyme metabolizes PGF2α and prostaglandin E2 (PGE2) (Okita and Okita, 1996; Tai et al., 2002). Its expression decreases in the chorionic trophoblast of women in labor (Sangha et al., 1994; Van Meir et al., 1997). 15-HPGD hypomorphic mouse litters deliver about one day early (Roizen et al., 2008). Although progesterone withdrawal is not observed, the levels of PGF2α and PGE2 rise early in these females, demonstrating the importance of a non-luteolytic role of prostaglandins in inducing labor (Roizen et al., 2008). The 15-HPGD hypomorphic mice provide an interesting genetic model for spontaneous preterm birth, and highlight the limited physiological changes that shift parturition from progesterone withdrawal to a mechanism that does not require progesterone withdrawal.

The study of genetically altered mice indicates conserved gene expression changes in the uterus at term, which display some functional redundancy. The expression of contractile-associated proteins such as FP, oxytocin receptor (Oxtr) and connexin-43 (Cx43) increase in the myometrium of both humans and mice at term (Garfield et al., 1997; Fuchs et al., 1982; Brodt-Eppley and Myatt, 1999; Cook et al., 2000). Oxytocin is a strong uterine contractile agonist and expression of its receptor (Oxtr) increases tenfold in the uterus at term (Challis and Lye, 1994; Gainer and Wray, 1994; Zingg et al., 1995). Surprisingly, both oxytocin-deficient and Oxtr-deficient mice exhibit normal parturition (Nishimori et al., 1996; Young et al., 1996; Takayanagi et al., 2005). By contrast, mice that are deficient in both oxytocin and cyclooxygenase-1 undergo prolonged parturition that begins at normal term (Gross et al., 1998). This suggests that oxytocin has a luteotropic role that opposes the luteolytic role of cyclooxygenase-1, which results in normal progesterone withdrawal in these double knockout animals (Gross et al., 1998). However, cyclooxygenase-1 deficiency affects the presence of the contractile agonist PGF2α (Gross et al., 1998). Deficiencies in both oxytocin and PGF2α appear to diminish uterine contractility enough to prolong labor.

Studies of Cx43-deficient mice demonstrate its importance in parturition. Cx43 coordinates myometrial cells to produce contractions during labor. Mice with a global deficiency for Cx43 die during the neonatal period (Reaume et al., 1995). Therefore, mice that are deficient for Cx43 specifically in smooth muscle tissues, including the myometrium, were used to examine the role of Cx43 in parturition (Doring et al., 2006). These mice experienced somewhat-delayed parturition despite normal Oxtr and FP upregulation and progesterone withdrawal (Doring et al., 2006).

Genetically altered mice also provide insight into the process of cervical ripening. Toward the end of gestation, softening and remodeling of the cervix is important in readying the birth canal for labor (Leppert, 1995). Mice deficient for the hormone relaxin or its receptor (LGR7) exhibit a low-penetration, nonproductive labor phenotype (Zhao et al., 1999; Krajnc-Franken et al., 2004). This is probably caused by defects in cervical ripening, as relaxin-deficient females have more collagen in the pubic symphysis, cervix and vagina one day before term (Zhao et al., 2000). Mice that are deficient for 5α-reductase type 1 (5α-R1), a progesterone-metabolizing enzyme, also have increased cervical collagen at term (Mahendroo et al., 1999). 5α-R1−/− females experience prolonged labor 2-3 days post-term (Mahendroo et al., 1996). Their serum progesterone at term decreases and progesterone levels in the uterus and cervix are high (Mahendroo et al., 1999). Ovariectomy, progesterone receptor antagonists, oxytocin or relaxin can all reverse the labor phenotype in these females (Mahendroo et al., 1996; Mahendroo et al., 1999). Thus, genetic mutation may accelerate parturition rather than impair cervical ripening.

Approximately 25% of human preterm births are associated with infection (Muglia and Katz, 2010). Experiments in normal and genetically altered mice have been used to elucidate the role of cytokines and inflammation in this process. Intraperitoneal administration of lipopolysaccharide (LPS), a component of the cell membrane of Gram-negative bacteria that activates Toll-like receptor 4 (TLR4) and a host proinflammatory response, causes preterm labor in mice (Fidel et al., 1998; Gross et al., 2000).
This systemic immune activation resembling sepsis leads to progesterone withdrawal and induction of uterine contractility. As progesterone withdrawal occurs in this model, its extension to human infection-associated preterm birth remains limited. More recently, the intratracheal application of heat-killed {Escherichia coli} (HKE) to mimic local inflammation has been evaluated (Hirsch and Muhle, 2002). In this model, preterm labor reliably ensues, but the mechanism appears distinct from progesterone withdrawal increasing its relevance to human preterm birth. Using this paradigm, essential roles for TLR4 and its downstream adapter molecule MyD88 have been demonstrated in HKE-induced preterm birth (Wang and Hirsch, 2003; Filipovich et al., 2009). By contrast, redundant signaling by the cytokines tumor necrosis factor-alpha (TNF-α) and interleukin-1 (IL-1) maintains susceptibility to preterm birth in mice, with the signaling of each of these cytokines being individually compromised (Hirsch et al., 2006).

Two novel pathways regulating birth timing in mice were recently described. Premature elevation of surfactant protein-A, a putative activator of macrophage proinflammatory cascades and fetal lung maturation signals, in the amniotic fluid leads to early birth (Condon et al., 2004). Similar changes in human infants in surfactant protein-A in the amniotic fluid, however, have not been found. In addition, uterine-specific disruption of p53 results in early uterine senescence and an increased frequency of preterm birth in mice (Hirota et al., 2010). Whether p53 mutations in humans are associated with preterm birth risk remains to be analyzed.

Other models of parturition
Although the sheep and mouse models are the most common, there are other valuable models for human parturition. Rats, guinea pigs, dogs and primates have all contributed to our understanding of preterm birth. The guinea pig offers a tractable small animal system, which lends itself to useful comparative genomic and physiological analysis (Mitchell and Taggart, 2009). Guinea pigs maintain high maternal serum progesterone concentrations at the time of parturition, and might be used to identify key regulatory pathways that differ in relation to closely related species that undergo progesterone withdrawal. Technical considerations prevent the widespread use of guinea pigs as a parturition model. Unlike other small mammalian model systems, such as mice, a fully sequenced guinea pig genome is not yet available. Furthermore, comparatively fewer experimental protocols and reagents have been adapted for this species. However, some of the physiological similarities between guinea pig and human gestation may increase its use in the future.

Human parturition
In humans, in contrast to sheep and other ruminants, the HPA axis of the fetus does not appear to play the pivotal role in determining birth timing. In cases of human pregnancies with anencephalic fetuses (fetuses lacking pituitary and adrenal glands), gestation lengths are normal after corrections for variables such as polyhydramnios in the populations studied (Swaab et al., 1977). However, the fetal maturational effects of glucocorticoids found in animal studies (Liggins, 1968; Muglia et al., 1995) extend to humans, and glucocorticoids are commonly used to accelerate fetal lung maturation in women who are likely to enter labor preterm.

Although mice and sheep experience a dramatic decline in circulating maternal progesterone before the induction of myometrial contractility, like the predominance of mammals, such a progesterone withdrawal is not observed in term women. This lack of overt progesterone withdrawal at the end of human pregnancy has made the labor-induction pathways that are downstream of progesterone withdrawal, identified in animal models, of uncertain relevance to human pregnancy. A functional withdrawal of progesterone has been hypothesized to occur at the onset of human labor (Mendelson, 2009), thus maintaining the centrality of progesterone action for birth timing. Several potential mechanisms for such a functional withdrawal in humans have been analyzed, although they have not yet been established as the key event for parturition.

The role of progesterone is known to change during human gestation owing to the presence of the progesterone receptor isoforms PR-A and PR-B, whose relative levels fluctuate during pregnancy and birth. The receptors have unique functions. PR-B induces progesterone-responsive genes. PR-A represses the transcriptional activity of PR-B. It is still difficult to identify specific isoforms, and little is known about the relative expression of these progesterone receptor isoforms in laboring and non-laboring human myometrium. One promising study identified an increase in the PR-A:PR-B ratio, at the protein level, in the laboring human myometrium using two isoform-specific antibodies (Merlino et al., 2007). An increase in the PR-A:PR-B ratio is also observed in the uterus of laboring rhesus macaques (Haluška et al., 2002). As with humans, rhesus macaques do not experience a decline in serum progesterone levels at term, so progesterone may be functionally withdrawn by a change in progesterone receptor isoform expression in primates.

Coactivators may also regulate functional progesterone levels in humans. Decreased expression of coactivators with acetylase activity is observed in the uterus of humans and mice at term (Condon et al., 2003). The administration of histone deacetylase inhibitor to mice during late gestation delayed the start of parturition (Condon et al., 2003). These data suggest that a decrease in coactivators and acetylation at term may impair the transcriptional activity of the progesterone-progesterone receptor complex, and implement a functional progesterone withdrawal (Condon et al., 2003).
These findings suggest that regulation of progesterone action may be a crucial step in precipitating parturition in humans. Accordingly, progesterone receptor antagonists precipitate labor in women in some cases (Herrmann et al., 1982). In addition to promoting uterine contractility, administration of progesterone receptor antagonist may increase cervical ripening in pregnant women (Radestad et al., 1993). The upregulation of contractile-associated proteins is an important component of labor induction in humans as in other species. The levels of Oxtr, Cx43 and FP are increased in the human myometrium at term (Garfield et al., 1977; Fuchs et al., 1982; Brodt-Eppley and Myatt, 1999). Accordingly, oxytocin is commonly used to induce labor in women (Challis and Lye, 1994; Gainer and Wray, 1994). Furthermore, 15-HPGD is decreased in the chorionic trophoblast cells in laboring women (Sangha et al., 1994; Van Meir et al., 1997), contributing to increasing levels of prostaglandins, which are another important contractile agonist. Although these final common mediators that are involved in enhancing uterine contractility and cervical ripening appear to be conserved across species, their functional redundancy has limited their utility as therapeutic targets. Currently, no effective pharmacological agents have been developed to prevent prematurity, other than perhaps progesterone supplementation in some high-risk cases (Iams et al., 2008). Understanding the timing mechanisms that initiate the induction of these final common mediators, which are less clearly conserved across mammals, remains elusive.

New opportunities for progress: capitalizing on interspecies differences

The regulation of progesterone production and its decline at the end of pregnancy differs between ruminants, rodents and apes. Indeed, even amongst primate species, progesterone profiles diverge during pregnancy (Faiman et al., 1981). In humans and great apes, maternal serum progesterone concentrations rise through gestation and are at their highest at the time of delivery (Fig. 2). By contrast, Old World monkeys, such as the macaque and baboon, have much lower concentrations of circulating progesterone that do not rise through gestation, and New World monkeys display overt progesterone withdrawal (Fig. 2). Consistent with these differences in progesterone regulation between mammals, are the morphological differences found in the placenta across phyla. The human placenta is characterized by a hemochorial placental interface (one in which the maternal blood comes in direct contact with the chorion), discoidal shape and villous fetomaternal interdigitation. By using phylogenetic and statistical analyses of molecular and morphological information, Wildman and colleagues demonstrated that the ancestral eutherian mammalian placenta was
One inference emerging from the observed divergence in endocrine physiology and placental morphology between species, is that evolutionary pressures have uniquely optimized the timing and characteristics of pregnancy (number of fetuses, uterine architecture, sites of hormone production, etc.) to enhance the reproductive success and minimize maternal and fetal mortality. In accord with this notion, sequence comparison of human, chimpanzee and mouse genomes revealed that the genes associated with reproduction are one of the most divergent functional categories across these species (Chimpanzee Sequencing and Analysis Consortium, 2005). Are these differences instructional? Using currently available computational biology approaches, together with a growing list of mammalian genomes sequenced at high coverage, the potential exists to identify rapidly diverging genes. Of particular relevance to human-specific parturition biology may be genes that have evolved rapidly along the human lineage. Rapidly evolving genes would be plausible candidates for being involved in human parturition and would not require conformation to present notions about human pregnancy physiology. The progesterone receptor itself exhibits characteristics of rapid adaptive evolution in humans (Fig. 3) (Chen et al., 2008). The intersection of the emerging list of rapidly evolving genes and conserved noncoding sequences (Bustamante et al., 2006; Prabhakar et al., 2006; Pollard et al., 2006) could narrow the spectrum of variants considered by genome-wide association studies, and provide new targets for manipulation in mice and other genetically tractable organisms. By introducing these specific human variants or isoforms (for example, in progesterone receptor A or B) with temporally and spatially regulated transgenic expression systems in mice or other model systems, their ability to affect birth timing could be investigated systematically.

Although animal models are not without their limitations in modeling human parturition biology, they have made important contributions to our current understanding of this complex process. Differences in how parturition is executed in common animal models and humans have been identified, but these differences should not discourage investigators from conducting further research to identify additional important similarities. Specific examples of the aspects of parturition in different animal models are summarized in Table 1. The list in this table is not all encompassing, but highlights areas that are analogous, or discordant, in human pregnancy. Furthermore, combining the established and versatile mouse model system with the computation biology approach outlined here points to an exciting new frontier in the study of human parturition through animal models.

### COMPETING INTERESTS
The authors declare no competing financial interests.

### REFERENCES

### CLINICAL PUZZLE
**Table 1. Relevance of common animal models for studying human parturition**

<table>
<thead>
<tr>
<th>Key advantages for use in exploring human parturition</th>
<th>Sheep</th>
<th>Mice</th>
<th>Guinea pigs</th>
</tr>
</thead>
<tbody>
<tr>
<td>Large mammalian system allows more facile surgical manipulation and acquisition of blood/amniotic fluid measures</td>
<td>Genetic tractability, short gestation</td>
<td>Initiation of parturition without progesterone withdrawal like in humans</td>
<td></td>
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<tr>
<td>Progesterone withdrawal at parturition onset</td>
<td>Progesterone withdrawal at parturition onset</td>
<td>Lack of sequenced genome; less-developed methods and reagents for experimentation than other small mammalian model systems</td>
<td></td>
</tr>
<tr>
<td>Regulation of fetal maturation, control of myometrial contractility</td>
<td>Contribution of specific genes to uterine contractility, cervical ripening and inflammation; exploration of the effects of gene isoforms and variants identified through computational biology approaches</td>
<td>Parturition initiation, mechanisms for labor induction without progesterone withdrawal</td>
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**Clinical and basic research opportunities**
- Identify the evolutionary changes that influence preterm birth
- Determine the physiological changes associated with infection that encourage parturition
- Create new animal models to test the influence of genes suggested by human association studies on parturition
- Develop a physiological model to test theories of ‘functional’ progesterone withdrawal in the induction of human labor

**itself hemochorial and discoid** (Wildman et al., 2006). Thus, surprisingly, the human placenta is a primitive state that emerged before the origin of primates. These findings suggest that the major roles of the placenta in sustaining pregnancy and facilitating fetal growth have persisted throughout the eutherian lineage that has lead to humans.

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