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## Preeclampsia and other pregnancy complications as an adaptive response to unfamiliar semen

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### Preeclampsia

Preeclampsia is a leading cause of prenatal infant mortality (Mac Gillivray, 1983; Robillard, Dekker, & Hulsey, 2002). Preeclampsia occurs as a consequence of abnormal invasion by the trophoblast in the uterine spiral arteries and endothelial cell dysfunction (Friedman, 1993), and as a consequence the fetus may not receive adequate nutrition resulting in growth retardation. Whereas all mammalian embryos undergo implantation shortly after conception, humans are the only mammalian species known to undergo a second phase of deep trophoblastic implantation at the end of the first trimester (Robillard *et al.*, 2003). In normal development, this second stage of implantation provides for the modification of spiral arteries that result in an increase in the blood flow to the placenta. Preeclampsia is believed to be the result of a failure to achieve or to complete this second implantation phase (Robillard *et al.*, 2003). It is clinically diagnosed by maternal hypertension and proteinuria. The hypertension results from cytotrophic factors that are released by the fetus and serve to increase the amount of blood flowing to the placenta (Haig, 1993).

It has been theorized that the origins of preeclampsia in humans are linked to the increase in cranial capacity associated with the genus *Homo* (Robillard *et al.*, 2003). The greater nutritional needs of the developing brain in the human fetus, compared to the more modest needs of developing brains in species with lower cranial capacities, has been hypothesized to explain the second wave of implantation characteristic of humans. To support normal brain development, the human fetal brain requires approximately 60% of the total nutritional supplies of the developing fetus at the end of the third trimester, whereas in other

mammalian species developing fetal brains require only about 20% of the total nutritional needs of the fetus toward the end of fetal development (Cunnane, Harbige, & Crawford, 1993; Martin, 1996). Thus, the second wave of implantation may be an important accommodation to the evolution of relative large brains in humans.

In this chapter we develop the thesis that this second phase of implantation in humans also may have evolved to enable females to unwittingly terminate pregnancies that were not in their long-term reproductive interests.

### **The role of unfamiliar semen**

Preeclampsia involves a host of immunologic and genetic factors (Pridjian & Puschett, 2002; Scott & Beer, 1976), but because the underlying cause remains unknown it has been referred to as “mysterious” (Takakuwa *et al.*, 1999) and the “disease of theories” (Pipkin & Rubin, 1994).

We begin our analysis by exploring the potential significance and ostensible impact of unfamiliar semen on preeclamptic pregnancies. Guided by an evolutionary perspective, we contend that unfamiliar semen may be a biological correlate of paternal investment. According to our hypothesis, pregnancies and children that result from unfamiliar semen have a lower probability of receiving sufficient paternal investment than do pregnancies and children that result from familiar semen. We theorize that preeclampsia is a biological mechanism that evolved to terminate maternal investment under circumstances in which the likelihood of investment by the sire is doubtful.

### **The importance of paternal investment**

Lack of paternal investment poses substantial risks to both the mother and her infant. Ancestral women who lacked the care, protection, and provisioning afforded by a committed adult male would have put themselves and their infants at an increased risk of predation, had a more difficult time acquiring necessary resources, and lowered their chances of finding another provisioning male with whom to have children. In modern times, the costs incurred from the lack of paternal investment remain high. When children’s mental, physical, and emotional development has been investigated as a function of paternal investment, the presence and involvement of fathers has consistently been shown to have a positive impact on their child’s health.

For instance, children who are involved with their fathers tend to be more psychologically well adjusted, do better in school, engage in less anti-social behavior, and have more successful intimate relationships (Amato & Rivera,

1999; Flouri & Buchanan 2002, 2003; Hwang & Lamb, 1997). Father involvement also has been associated with positive intellectual development, social competence, and the ability to empathize (Fagan and Iglesias, 1999; Yongman, Kindlon & Earls 1995). Conversely, the absence of the father is related to poorer scores on measures of cognitive ability and academic achievement, and these children have a heightened risk for delinquency and deviant behavior (Dornbusch *et al.*, 1985; Mulkey, Crain, & Harrington, 1992).

Gaudino, Jenkins, and Rouchat (1999) examined the risk posed to children by the presence or absence of the father's name on the birth certificate. Presumably, acknowledgment of the father's name on the birth certificate would be an indicator of the father being more likely to have a closer relationship with the mother and the infant, and that these fathers are more likely to be involved in the support and care of their infants. Gaudino *et al.* found that infants without reported fathers' names were 2.3 times more likely to die in the first year of life. Even after controlling for variables such as marital status, maternal variables such as age, race, education, gravidity, and smoking, and factors that may affect infants, such as congenital malformations and birth weight, the absence of the father's name on the birth certificate remained an independent risk factor for infant mortality.

Other studies suggest that paternal involvement reduces the risk of low birth weight and preterm delivery (Mutale *et al.*, 1991; Oakley, 1985; Ramsey, Abell, & Baker, 1986; Turner, Grindstaff, & Phillips, 1990). Low birth weight is an index of overall infant health and is related to infant mortality, health problems in the first few years of life, and developmental problems later in life (Hack, Klein, & Taylor, 1995).

Unmarried women are consistently at greater risk of delivering low-birth-weight babies (Jones & Bond, 1999; Shapiro *et al.*, 1992). Among unmarried women, the extent to which the father is involved also influences birth weight. In a sample of unmarried women, Padilla and Reichman (2001) found that low birth weight varied as a function of the mother's relationship to the father. Mothers who did not live with the infant's father were more likely to deliver low-birth-weight infants. In contrast, mothers who received financial support from the baby's father were at decreased risk of delivering low-birth-weight babies.

### **Semen familiarity and paternity**

In humans, paternal investment has far-reaching implications for both the mother and the infant. One adaptation that may have evolved to solve the ancestral problem posed by both the mother's and offspring's need for a caring, committed father is a maternal mechanism that could distinguish between

familiar and unfamiliar semen. Frequent insemination by the same male over an extended period of time would be a relatively good index of a committed pair bond and, therefore, semen familiarity might predict the likelihood of long-term provisioning, protection, and care of the mother and child by the father following parturition. Therefore, we hypothesize that preeclampsia may be a mechanism that evolved to terminate pregnancies that result from exposure to unfamiliar semen.

In support of this hypothesis, exposure to unfamiliar semen (as would be true in cases of barrier contraception, artificial insemination, instances of changed paternity in multiple pregnancies, and a short period of cohabitation before pregnancy) increases the risk of developing preeclampsia (Astin, Scott, & Worley, 1981; Chng, 1982; Dekker, Robillard, & Hulsey, 1998; Feeney & Scott, 1980; Ikedife, 1980; Klonoff-Cohen *et al.*, 1989; Koelman *et al.*, 2000; Marti & Hermann, 1977; Robillard *et al.*, 1993; Robillard, Hulsey, & Alexander, 1980).

For example, Hoy *et al.* (1999) studied the outcomes of 1552 donor-insemination pregnancies and 7717 normally conceived pregnancies in Australia. They found that the donor-insemination group was more likely to develop preeclampsia than the controls, even after controlling for maternal age and parity. In another study, the incidence of preeclampsia also was found to be more common in donor inseminations, especially in multiparous women (Need, Bell, Meffin, & Jones 1983). As evidence that these effects are not a consequence of artificial insemination *per se*, Smith, *et al.* (1997) report that preeclampsia was more common in women who received donor insemination than in patients who were artificially inseminated with their committed partner's sperm.

The extended presence of semen in the female reproductive tract as a byproduct of repeated insemination has a significant effect on improving rates of both implantation and pregnancy (Bellinge *et al.*, 1986; Marconi *et al.*, 1989). Thaler (1989) suggests that familiar semen may exert a priming effect on pregnancy acceptance. This prediction is supported by clinical trials in which females are given prior exposure to semen before conception is attempted (Bellinge *et al.*, 1986; Marconi *et al.*, 1989).

Semen familiarity also varies as a function of whether couples use barrier methods of contraception. In a study comparing the contraceptive histories of nulliparous females with and without preeclampsia, twice as many of those with preeclampsia used barrier methods of birth control (Klonoff-Cohen *et al.*, 1989). After controlling for gravidity, marital status, smoking, and alcohol consumption during pregnancy, family history of preeclampsia, working status during pregnancy, and history of hypertension in the subjects' mothers, they found that single women who used barrier contraception had a 2-fold higher risk of developing preeclampsia. A dose-response effect was also observed,

suggesting that the risk of preeclampsia increased as exposure to sperm and seminal fluid decreased.

The effect of semen familiarity may not be confined to the reproductive tract. In a recent study, it was discovered that women who engaged in oral sex with their partners prior to pregnancy displayed significantly lower rates of preeclampsia (Koelman *et al.*, 2000). Among the preeclamptic women, 44% reported having oral sex with their partner, compared to 88% of those without preeclampsia. Furthermore, only 17% of the preeclamptic women, compared to 48% of the nonpreeclamptic women, reported ingesting their partner's semen.

The length of cohabitation prior to conception has been identified as another risk factor for preeclampsia. Women with an extended period of cohabitation with the child's father prior to becoming pregnant experienced a lower incidence of preeclampsia (Marti & Hermann, 1977). One account of this effect is that, other things being equal, semen familiarity would be proportional to the length of cohabitation.

A change in paternity, from one pregnancy to the next, also increases the risk of developing preeclampsia. Trupin, Simon, and Eskenazi (1996) examined a sample of 10 868 women, including 5068 nulliparous and 5800 multiparous females. Socioeconomic characteristics, reproductive and medical history, health behavior, and marital history information was obtained from a personal interview. Consistent with data from other studies implicating the importance of semen familiarity, new-partner multiparous women had a 29% higher risk of developing preeclampsia than their multiparous counterparts for whom paternity did not change.

Additional evidence also implicates changing paternity as a risk factor for preeclampsia. In a study of Caribbean women (Robillard *et al.*, 1993), 61.7% of those with preeclampsia had new-partner pregnancies, compared to only 10% among women with chronic hypertension, and 16.6% in controls. Furthermore, when they examined three or four consecutive pregnancies, rates of preeclampsia appeared to summate with each additional change in paternity. Other researchers have found similar results. In Nigeria, Ikedife (1980) documented over a period of 10 years that nearly three out of every four (74%) preeclamptic multiparous women had experienced changes in paternity.

### **Familiar semen as an index of paternal investment**

Under conditions that prevailed hundreds of thousands of years ago, without a committed male partner to provide protection and care, the costs of reproduction for females would have increased dramatically. The existence of a maternal mechanism that could distinguish between familiar and unfamiliar

semen, as a means of distinguishing between committed and less committed males, would have had considerable adaptive significance. Thus, the application of evolutionary meta-theory may provide insight into the etiology of preeclampsia. It may be useful to think about preeclampsia not simply as a medical anomaly, but as an adaptation that may have evolved to terminate pregnancies where future paternal investment was questionable or unlikely.

Sexual intercourse has the potential to be very costly for females. In addition to becoming pregnant, the burden of the infant's primary source of food and care is borne principally by mammalian females. Because pregnancy precludes further impregnation and lactation suppresses ovulation (Anderson, 1983), prior to bottle feeding when a woman became pregnant the result was a 2–4 year period in which she foreclosed on other reproductive opportunities. These costs would be exaggerated in situations where there was little or no chance of receiving care, protection, and investment from the father.

Unlike many other species, humans produce very few offspring and invest heavily in each one (Bjorklund & Shackelford, 1999; Geary, 2000). Human infants are more reliant on their parents for protection and provisioning over longer periods than any other species (Bjorklund, 1997). During human evolutionary history, in order for offspring to survive, investment of considerable time and resources was needed from both parents. Because the burden of child rearing falls more heavily on females, evolutionary pressures may have operated on women to distinguish between potential mates according to whether they were likely to enter into long-term, committed provisioning and protective arrangements with the female and her offspring (Buss, 1994).

Conception as a result of nonconsensual intercourse, or rape, represents an extremely costly pregnancy. It is highly unlikely the child's father will care for the mother and her infant. Moreover, women who conceive a child as a result of rape often face abandonment from their current partner and a reduced chance of attracting committed mates in the future (Shields & Shields, 1983; Thornhill & Thornhill, 1983, 1990). Forced copulation also precludes exercising mate choice; females have an important vested interest in the other 50% of the genes being carried by each of their offspring. As a result, it would be in a female's best interests to minimize the chances of conception as a consequence of rape. Indeed, there is recent evidence that human females may have an ensemble of evolved strategies that function to reduce the likelihood of being raped during the ovulatory phase of the menstrual cycle when they would be more likely to conceive.

Chavanne and Gallup (1998) found that instances of sexual risk-taking behavior were inversely proportional to the chance of becoming pregnant. Female college students who were in the ovulatory phase of their menstrual cycle were less likely to go out alone, walk in dimly lit areas, or go to drinking in bars. In a

follow-up study, handgrip strength (as an indirect measure of a woman's ability to resist sexual assault) also varied as a function of the menstrual cycle. After reading a passage containing sexually coercive overtones, females in the ovulatory phase (but not other phases) showed significant increases in handgrip strength (Petralia & Gallup, 2002). Taken together, these studies suggest that women may have been selected during human evolutionary history to behave in ways that reduce the likelihood of conception as consequence of rape, a situation in which the chances of future paternal provisioning are slim to none.

However, should conception occur following rape, a mechanism that could distinguish between pregnancies as a function of the likelihood of future investment from the father would have considerable adaptive value. In our view preeclampsia may be one of several candidate mechanisms that evolved to reduce the likelihood that such pregnancies would go full term.

### **Categories of unfamiliar semen**

One simple algorithm that may have evolved to solve the adaptive problem posed by both the mother's and infant's need for a caring, committed adult male would be a mechanism that could distinguish between familiar and unfamiliar semen. Frequent insemination of a female by the same male over an extended period of time would be a relatively good biochemical index of the existence of a committed pair bond and, therefore, semen familiarity would predict the likelihood of long-term provisioning, protection, and care of the mother and the child during pregnancy and following parturition.

There are at least three categories of unfamiliar semen that define situations in which it might be in the female's reproductive interests to terminate a pregnancy. Forced copulation or rape is usually represented by a single instance of exposure to unfamiliar semen. Should conception occur as a result of being raped the likelihood of assistance and commitment by the father is negligible. In terms of a single exposure to unfamiliar semen, artificial insemination represents the closest approximation to rape. Semen unfamiliarity also characterizes dishonest mating strategies (Shields & Shields, 1983). For example, it is not uncommon for males to feign good intentions and commitment to females as a means of attempting to gain sexual access (Tooke & Camire, 1991). Should conception occur under such circumstances, the likelihood of paternal investment is low. Finally, semen unfamiliarity also characterizes the early phases of honest courtship in which the status of the relationship has yet to be determined. Should pregnancy occur prior to the development of a strong, committed bond between the male and female, the likelihood of abandonment by the father may still be relatively high.

In each of these situations, semen familiarity can be used to assay the likelihood of future paternal investment. A mechanism (i.e. a preeclampsia trigger) that could distinguish between familiar and unfamiliar semen as a means of differentiating between committed and uncommitted males could have had considerable adaptive significance.

Recurrent insemination by the same male not only serves as an indicator of the likelihood of future paternal investment. After conception occurs continued insemination by the father may have other adaptive consequences. The cytokines interleukin 6 and 8 and tumor necrosis factor found in semen (Maegawa *et al.*, 2002) are involved with mechanisms that regulate placentation, implantation, and fetal maturation. Likewise, the high levels of prostaglandins in semen may diminish the immune response of the mother to the fetus. The presence of prostaglandins, placental hormones 5, 12, and 14, human chorionic gonadotropin, luteinizing hormone, and follicle-stimulating hormone in human semen (see Chapter 8 in this volume) are all components that have been implicated in preeclampsia (Ney, 1986; Pridjian and Puschett, 2002; Seppälä *et al.*, 1985). Therefore, the absence of recurrent insemination by the father during the initial stages of pregnancy may lead to a series of events that eventuate in the failure to achieve implantation or spontaneous abortion. Consistent with the fact that humans are the only species to undergo a second phase of implantation, there may be a critical period of prenatal development in which the presence of the father's semen facilitates the second phase of implantation.

There are other etiological factors involved in preeclampsia and ours is not the only evolutionary account. Takiuiti, Kahale, and Zugaib (2003) have advanced the hypothesis that preeclampsia is a maladaptation to stress. They argue that because pregnant females are more vulnerable to predation as a consequence of being slower, heavier, sleepier, and less agile, higher blood pressure during pregnancy and a heightened alarm response may minimize the risk of predation. However, this hypothesis fails to explain why human females are the only mammals that are prone to preeclampsia, and it does not account for the evidence implicating semen unfamiliarity as a risk factor for preeclampsia.

Preeclampsia can be fatal not only for fetuses, but occasionally for mothers as well (Duley, 1992). In our view, however, the costs associated with preeclampsia for the mother would typically be outweighed by the benefits that derive from terminating a costly pregnancy before the child has been born.

### **Other pregnancy complications**

We suspect that there are two broad categories of reproductive termination mechanism. The first operates primarily during the prenatal period. We

have argued that preeclampsia is a biological adaptation that evolved to terminate investment in a pregnancy in which the likelihood of future investment from the father is low or when overall infant viability is low. Spontaneous abortion may be another example of evolved pregnancy-termination mechanisms. It is estimated that about 50% of all fertilized eggs are spontaneously aborted before women even know they are pregnant (Elish *et al.*, 1996; Garcia-Enguidanos *et al.*, 2002). Even among known pregnancies, the spontaneous abortion rate is about 12–15% (Garcia-Enguidanos *et al.*, 2002; Zinaman *et al.*, 1996).

Spontaneous abortion usually results from fetal genetic abnormalities, but can also result from infection, and maternal immune responses and health problems. A study examining the risk factors for spontaneous abortion in Italy from 1978 to 1995 found that unmarried women were at an increased risk of having a spontaneous abortions compared to their married counterparts (Osborn, Cattaruzza, & Spinelli, 2000). Similarly, another study focusing on late spontaneous abortions (those that occur in weeks 14–21 of pregnancy) found that women who were living alone were at greater risk of late abortions than those who were married (Ancel *et al.*, 2000). Thus, in some instances, spontaneous abortion may also be an adaptation that terminates investment in offspring under circumstances where re-insemination by the father stops (as an indicator of abandonment) and, as a consequence, the mother faces a lack of paternal support.

The second category of termination mechanisms includes those that operate during the postnatal period. Daly and Wilson (1984, 1988) suggest that rather than a feature of abnormal psychological processes, postpartum depression may be a functional component of human parental decision-making. A review of the literature provided by Hagan (1999) supports this view. Hagan proposed the defection hypothesis, which posits that postpartum depression functions to inform mothers that they have suffered or are suffering a fitness cost. The psychological symptoms associated with depression motivate them to reduce or to terminate investment in the infant. This prediction is supported by a large body of evidence showing that postpartum depression can be triggered by a lack of social support, particularly from the father (see Hagan, [1999] for review). Consistent with this hypothesis is evidence that receiving more social support can lead to the remission of depressive symptoms (O'Hara, 1985). Thus, infanticide may be another postpartum psychological mechanism that evolved to terminate investment by the mother (Daly & Wilson, 1984, 1988). As an extension of our hypothesis, it would be interesting to see if the probability of postpartum depression or infanticide is related to the frequency with which the mother is exposed to the father's semen during both the pre- and postnatal period.

### Conclusion

Because the costs of reproduction for females are so high and human infants require extended care and provisioning, increasingly during human evolution successful reproduction (i.e. producing children that live long enough to produce children of their own) came to depend on parental investment by both the mother and the father. Females without committed, caring male partners would have been at an enormous disadvantage when it came to child-bearing and child-rearing. We theorize that because of the growing importance of paternal investment, mechanisms may have evolved to terminate pregnancies under conditions in which support and provisioning by the child's father were doubtful. One reliable means of indexing paternal commitment would have been frequent and recurrent insemination of the female by the child's father. Subtle differences between males in semen chemistry could have been the basis for the evolution of an ensemble of pregnancy termination mechanisms triggered by impregnation as a byproduct of exposure to unfamiliar semen.

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