Preterm labor: One syndrome, many causes

Roberto Romero *et al.*

Science **345**, 760 (2014);
DOI: 10.1126/science.1251816

30. X. Tian, F. J. Diaz, *Dev. Biol.* **376**, 51–61 (2013).
31. K. M. Luzzo *et al.*, *PLOS ONE* **7**, e49217 (2012).
32. L. L. Wu *et al.*, *Endocrinology* **151**, 5438–5445 (2010).
33. T. Wai *et al.*, *Biol. Reprod.* **83**, 52–62 (2010).
34. R. Dumollard, M. Duchen, J. Carroll, *Curr. Top. Dev. Biol.* **77**, 21–49 (2007).
35. M. Mitchell, S. L. Schulz, D. T. Armstrong, M. Lane, *Biol. Reprod.* **80**, 622–630 (2009).
36. T. Fullston, M. Mitchell, S. Wakefield, M. Lane, *Reprod. Fertil. Dev.* **23**, 691–701 (2011).
37. K. Selesniemi, H. J. Lee, A. Muhlhauser, J. L. Tilly, *Proc. Natl. Acad. Sci. U.S.A.* **108**, 12319–12324 (2011).
38. D. Nehra *et al.*, *Aging Cell* **11**, 1046–1054 (2012).
39. K. M. Lee *et al.*, *Leuk. Res.* **33**, 250–258 (2009).
40. I. D. van Balkom *et al.*, *PLOS ONE* **7**, e45090 (2012).
41. R. Figueroa-Colon, R. B. Arani, M. I. Goran, R. L. Weinsier, *Am. J. Clin. Nutr.* **71**, 829–834 (2000).
42. O. J. Rando, *Cell* **151**, 702–708 (2012).
43. J. R. Gannon, B. R. Emery, T. G. Jenkins, D. T. Carrell, *Adv. Exp. Med. Biol.* **791**, 53–66 (2014).
44. M. E. Pembrey *et al.*, *Eur. J. Hum. Genet.* **14**, 159–166 (2006).
45. A. Soubry *et al.*, *BMC Med.* **11**, 29 (2013).
46. B. R. Carone *et al.*, *Cell* **143**, 1084–1096 (2010).
47. J. C. Jimenez-Chillaron *et al.*, *Diabetes* **58**, 460–468 (2009).
48. S. F. Ng *et al.*, *Nature* **467**, 963–966 (2010).
49. S. F. Ng *et al.*, *FASEB J.* **28**, 1830–1841 (2014).
50. M. D. Anway, A. S. Cupp, M. Uzumcu, M. K. Skinner, *Science* **308**, 1466–1469 (2005).
51. B. G. Dias, K. J. Ressler, *Nat. Neurosci.* **17**, 89–96 (2014).
52. K. Gapp *et al.*, *Nat. Neurosci.* **17**, 667–669 (2014).
53. S. S. Hammoud *et al.*, *Hum. Reprod.* **26**, 2558–2569 (2011).
54. A. Noblanc *et al.*, *Free Radic. Biol. Med.* **65**, 719–723 (2013).
55. A. Kong *et al.*, *Nature* **488**, 471–475 (2012).
56. R. J. Aitken, T. B. Smith, M. S. Jobling, M. A. Baker, G. N. De Iuliis, *Asian J. Androl.* **16**, 31–38 (2014).
57. W. S. Ward, *Mol. Hum. Reprod.* **16**, 30–36 (2010).
58. N. O. Palmer, T. Fullston, M. Mitchell, B. P. Setchell, M. Lane, *Reprod. Fertil. Dev.* **23**, 929–939 (2011).
59. M. Mitchell, H. W. Bakos, M. Lane, *Fertil. Steril.* **95**, 1349–1353 (2011).
60. T. Fullston *et al.*, *FASEB J.* **27**, 4226–4243 (2013).
61. E. J. Radford *et al.*, *Science* 1255903 (2014).
62. M. Manikkam, C. Guerrero-Bosagna, R. Tracey, M. M. Haque, M. K. Skinner, *PLOS ONE* **7**, e31901 (2012).
63. M. Miao *et al.*, *Andrology* **2**, 138–144 (2014).
64. R. P. Yadav, N. Kotaja, *Mol. Cell. Endocrinol.* **382**, 498–508 (2014).
65. J. Brennecke *et al.*, *Science* **322**, 1387–1392 (2008).
66. G. C. Ostermeier, D. Miller, J. D. Huntriss, M. P. Diamond, S. A. Krawetz, *Nature* **429**, 154 (2004).
67. V. Grandjean *et al.*, *Development* **136**, 3647–3655 (2009).
68. A. Soubry, C. Hoyo, R. L. Jirtle, S. K. Murphy, *BioEssays* **36**, 359–371 (2014).
69. N. Suh *et al.*, *Curr. Biol.* **20**, 271–277 (2010).
70. W. M. Liu *et al.*, *Proc. Natl. Acad. Sci. U.S.A.* **109**, 490–494 (2012).
71. C. P. Concepcion *et al.*, *PLOS Genet.* **8**, e1002797 (2012).
72. S. A. Robertson, *Cell Tissue Res.* **322**, 43–52 (2005).
73. C. L. Wong *et al.*, *Theriogenology* **68**, 654–662 (2007).
74. J. J. Bromfield *et al.*, *Proc. Natl. Acad. Sci. U.S.A.* **111**, 2200–2205 (2014).
75. H. K. Poon, K. H. Lee, C. L. Wong, W. S. O, P. H. Chow, *Theriogenology* **71**, 1367 (2009).
76. J. K. Kafka *et al.*, *AIDS* **26**, 27–36 (2012).

ACKNOWLEDGMENTS

M.L., R.L.R., and S.A.R. are funded by the National Health and Medical Research Council (Australia). We thank L. Wu for the oocyte image in Fig. 2, and R. Richards and J. Thompson for critical comments. M.L. is an employee of Repromed Ltd. (Australia), and S.A.R. receives royalties on a patent describing use of granulocyte-macrophage colony-stimulating factor in IVF, licensed to Origio A/S (Denmark).

10.1126/science.1254400

REVIEW

Preterm labor: One syndrome, many causes

Roberto Romero,[1,2,3]* Sudhansu K. Dey,[4] Susan J. Fisher[5]

Preterm birth is associated with 5 to 18% of pregnancies and is a leading cause of infant morbidity and mortality. Spontaneous preterm labor, a syndrome caused by multiple pathologic processes, leads to 70% of preterm births. The prevention and the treatment of preterm labor have been long-standing challenges. We summarize the current understanding of the mechanisms of disease implicated in this condition and review advances relevant to intra-amniotic infection, decidual senescence, and breakdown of maternal-fetal tolerance. The success of progestogen treatment to prevent preterm birth in a subset of patients at risk is a cause for optimism. Solving the mystery of preterm labor, which compromises the health of future generations, is a formidable scientific challenge worthy of investment.

Preterm birth, defined as birth before 37 weeks of gestation, affects 5 to 18% of pregnancies. It is the leading cause of neonatal death and the second cause of childhood death below the age of 5 years (*1*). About 15 million preterm neonates are born every year, and the highest rates occur in Africa and North America (*2*). Neonates born preterm are at an increased risk of short-term complications attributed to immaturity of multiple organ systems as well as neurodevelopmental disorders, such as cerebral palsy, intellectual disabilities, and vision and hearing impairments (*3*). Preterm birth is a leading cause of disability-adjusted life years [the number of years lost because of ill health, disability, or early death (*4*)], and the annual cost in the United States is at least $26.2 billion per year and climbing (*5*).

Two-thirds of preterm births occur after the spontaneous onset of labor, whereas the remainder is medically indicated because of maternal or fetal complications, such as preeclampsia or intrauterine growth restriction (*6*). Herein, we propose that preterm labor is a syndrome caused by multiple pathologic processes, summarize important strategies in the prevention of spontaneous preterm birth, and highlight promising areas for investigation.

Preterm labor: Not just labor before term

A tacit assumption underlying the study of parturition is that preterm labor is merely labor that starts too soon. In other words, the main difference between preterm and term labor is when labor begins. This is perhaps understandable given that both involve similar clinical events: increased uterine contractility, cervical dilatation, and rupture of the chorioamniotic membranes (*7*). These events represent the "common pathway" of labor. The current understanding of this process is that the switch of the myometrium from a quiescent to a contractile state is accompanied by a shift in signaling from anti-inflammatory to pro-inflammatory pathways, which include chemokines [interleukin-8 (IL-8)], cytokines (IL-1 and -6), and contraction-associated proteins (oxytocin receptor, connexin 43, prostaglandin receptors). Progesterone maintains uterine quiescence by repressing the expression of these genes. Increased expression of the microRNA-200 (miR-200) family near term can derepress contractile genes and promote progesterone catabolism (*8*). Cervical ripening in preparation for dilatation is mediated by changes in extracellular matrix proteins, which include a loss in collagen cross-linking, an increase in glycosaminoglycans, as well as changes in the epithelial barrier and immune surveillance properties (*9*). This decreases the tensile strength of the cervix, key for cervical dilatation. Decidual or membrane activation refers to the anatomical and biochemical events involved in withdrawal of decidual support for pregnancy, separation of the chorioamniotic membranes from the decidua, and eventually membrane rupture. Increased expression of inflammatory cytokines [tumor necrosis factor–α (TNF-α) and IL-1] and chemokines, increased activity of proteases [matrix metalloprotease 8 (MMP-8) and MMP-9], dissolution of extracellular matrix components such as fibronectin, and apoptosis have been implicated in this process (*10*, *11*) (Fig. 1).

In our view, the common pathway is activated physiologically in the case of labor at term, whereas several disease processes activate one or more of the components of the common pathway in the case of preterm labor. This conceptual framework has implications for the diagnosis, treatment,

[1]Perinatology Research Branch, Program for Perinatal Research and Obstetrics, Division of Intramural Research, Eunice Kennedy Shriver National Institute of Child Health and Human Development (NICHD), National Institutes of Health, Bethesda, MD, Wayne State University/the Detroit Medical Center, Detroit, MI, USA. [2]Department of Obstetrics and Gynecology, University of Michigan, Ann Arbor, MI, USA. [3]Department of Epidemiology and Biostatistics, Michigan State University, East Lansing, MI, USA. [4]Division of Reproductive Sciences, Perinatal Institute, Cincinnati Children's Hospital Medical Center, Cincinnati, OH, USA. [5]Department of Obstetrics, Gynecology and Reproductive Sciences, Department of Anatomy, and Center for Reproductive Sciences, University of California San Francisco, San Francisco, CA, USA.
***Corresponding author. E-mail: romeror@mail.nih.gov**

and prevention of spontaneous preterm labor. For example, interest in myometrial contractility, the most recognizable sign of preterm labor, has led clinical and translational research to focus on the use of pharmacologic agents to arrest or decrease uterine contractility (i.e., tocolytics) with the goal of preventing preterm delivery. Yet, after decades of investigation, there is no persuasive evidence that inhibiting or arresting uterine contractility per se decreases the rate of preterm delivery or improves neonatal outcome, although these agents can achieve short-term prolongation of pregnancy for steroid administration and maternal transfer to tertiary care centers. We consider that, in most cases, tocolytic agents address a symptom and not the underlying cause(s) that activate the parturitional process. The extent to which the physiologic signals that mediate labor at term can be co-opted in the context of pathologic processes in preterm labor remains to be elucidated.

Preterm labor as a syndrome associated with multiple mechanisms of disease

Spontaneous preterm labor is often treated implicitly or explicitly as if it were a single condition. Accumulating evidence suggests that it is a syndrome attributable to multiple pathologic processes (*7*). Figure 2 illustrates the mechanisms of disease implicated in spontaneous preterm labor. Of these, only intra-amniotic infection has been causally linked to spontaneous preterm delivery (*12*). The others largely have their bases in associations reported by clinical, epidemiologic, placental pathologic, or experimental studies.

Microbial-induced inflammation

One of every four preterm infants is born to mothers with an intra-amniotic infection that is largely subclinical (*12*). Microorganisms isolated from the amniotic fluid are similar to those found in the lower genital tract, and, therefore, an ascending pathway is considered the most frequent route of infection. Bacteria involved in periodontal disease have been found in the amniotic fluid, suggesting that hematogenous dissemination with transplacental passage can also occur (*13*). Microbial-induced preterm labor is mediated by an inflammatory process. Microorganisms and their products are sensed by pattern recognition receptors, such as toll-like receptors (TLRs), which induce the production of chemokines [e.g., IL-8, and C-C motif ligand 2 (CCL2)], cytokines (e.g., IL-1β and TNF-α), prostaglandins, and proteases leading to activation of the common pathway of parturition (*12*, *14*, *15*) (Fig. 3A).

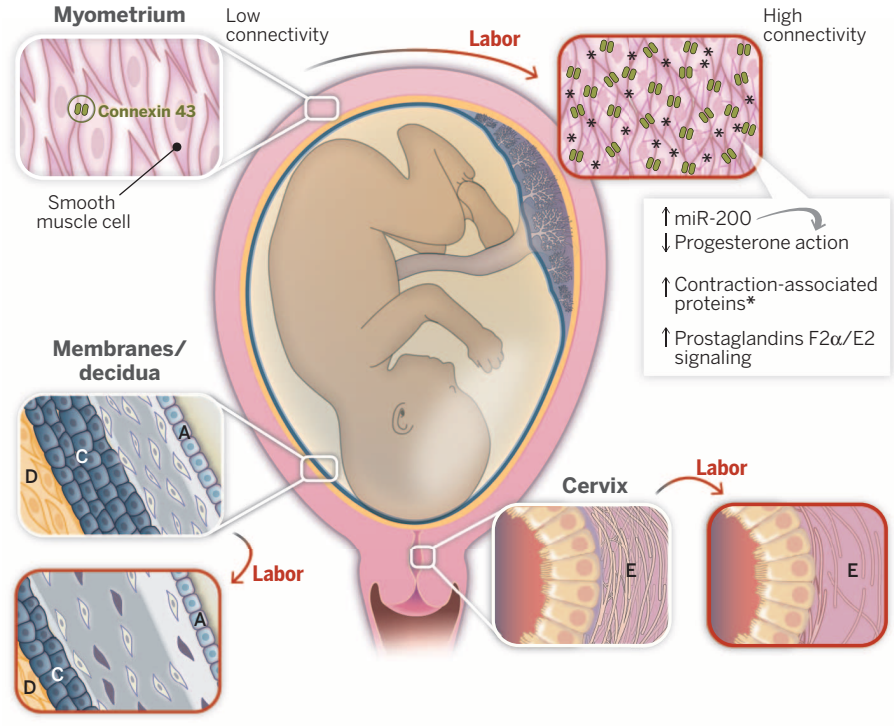

Fig. 1. Labor (term and preterm) is characterized by increased myometrial contractility, cervical dilatation, and rupture of the chorioamniotic membranes. Collectively, these events have been referred to as the common pathway of parturition. The switch of the myometrium from a quiescent to a contractile state is associated with a change in nuclear progesterone receptor isoforms and an increase in the expression of the miR-200 family, as well as an increase in estrogen receptor α signaling. Cervical ripening is mediated by changes in extracellular matrix proteins, as well as alterations in epithelial barrier and immune surveillance properties. Decidual or membrane activation, in close proximity to the cervix, occurs in preparation for membrane rupture and to facilitate separation of the chorioamniotic membranes and placenta from the uterus. E denotes extracellular matrix; M, mucus; Os, cervical os.

In 30% of cases of intra-amniotic infection, bacteria are identified in the fetal circulation (*16*), resulting in a fetal systemic inflammatory response (*17*). Such fetuses have multiorgan involvement and are at risk for long-term complications, such as cerebral palsy and chronic lung disease, underscoring that complications of infants born preterm are not only due to immaturity but also to the inflammatory process responsible for preterm labor. This has important implications because recent evidence suggests that down-regulation of congenital systemic inflammation in the neonatal period using nanodevices coupled with anti-inflammatory agents can reverse a cerebral palsy–like phenotype in an animal model (*18*).

From an evolutionary perspective, the onset of preterm labor in the context of infection can be considered to have survival value, because it allows the mother to expel infected tissue and maintain reproductive fitness. In a remarkable example of evolutionary co-option, the molecular mechanisms developed for host defense against infection in primitive multicellular organisms (e.g., pattern-recognition receptors in sponges) have been deployed in viviparous species to initiate parturition. This unique mechanism of maternal host defense comes at a price: prematurity. In terms of the fetus, inflammation may also have survival value near term, contributing to infant host defense against infection and accelerating lung maturation (*19*).

A central question is why some women develop an ascending intra-amniotic infection, whereas most do not. The relationship between the mucosa of the lower genital tract (vagina and cervix) and the microbial ecosystem appears key. Bacterial vaginosis, a change in the microbial ecosystem in which there is proliferation of anaerobic bacteria, confers risk for intra-amniotic infection and spontaneous preterm delivery. However, antibiotic treatment of asymptomatic women with bacterial vaginosis has not reduced the rate of preterm delivery. A comprehensive understanding of microbial ecology and genetic factors that control susceptibility to infection and the inflammatory response is required, particularly in light of evidence that gene-environment interactions may predispose some women to preterm labor (*20*). Viral infection has recently been shown to alter mucosal immunity in the lower genital tract and to predispose one to ascending bacterial infection (*21*).

Early studies of the vaginal microbiota in normal pregnancy using sequence-based techniques suggested that this ecosystem, which is different from that of the nonpregnant state, is more stable (*22*). Whether the vaginal microbiota and the local immune response of the vagina are different between women who subsequently deliver preterm and those who deliver at term are important unanswered questions (*23*, *24*). The factors responsible for changes in the vaginal microbiota during pregnancy remain to be established. Sex steroid hormones are attractive candidates, given that estrogens can induce the accumulation of glycogen in the vaginal

epithelium and also modify glycosylation (*25*). Carbohydrate structures are key for bacterial adherence to mammalian cells; therefore, sex steroid hormones could alter the microbiota of the lower genital tract.

At a mechanistic level, little is known about how preterm labor-related infections occur. On the pathogen side, the Group B *Streptococcus* pigment plays a role in the hemolytic and cytolytic activity required for ascending infection related to preterm birth (*26*). Further work is required to elucidate the role of the host. One intriguing possibility involves the "glyco-code," specific aspects of human carbohydrate structures that mediate the binding of bacteria via lectins and, subsequently, adherence. For example, *Helicobacter pylori* adhere via the Lewis b blood group glycan, making participants that express this antigen more susceptible to infection. Conversely, blood group O provides a selective advantage for surviving malaria (*27*). Whether similar mechanisms may help explain the increased frequency of spontaneous preterm birth in some ethnic groups is a question for in-depth exploration.

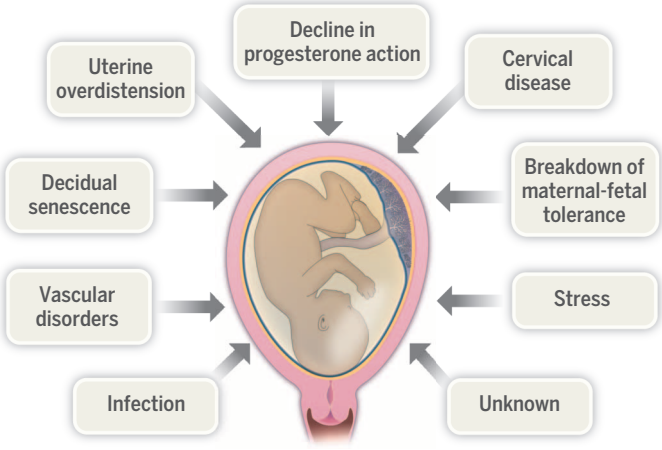

Fig. 2. Proposed mechanisms of disease implicated in spontaneous preterm labor. Genetic and environmental factors are likely contributors to each mechanism.

Although the maternal-fetal interface has traditionally been considered sterile, bacteria and viruses have been identified in first- and second-trimester decidua (*28*). Moreover, a placental microbiota has been described by using sequence-based techniques (*29*), along with differences reported between patients who delivered preterm and term (*29*). Large studies, such as those under consideration by the Human Placenta Project initiated by NICHD/NIH (*30*), are required to clarify the role of a putative placental microbiota and the maternal and fetal immune responses in normal pregnancy and spontaneous preterm labor. Recent studies using a combination of cultivation and molecular techniques suggest that intra-amniotic inflammation associated with spontaneous preterm labor occurs in the absence of demonstrable microorganisms, indicating a role for sterile intra-amniotic inflammation (*31*).

Extrauterine infections are also associated with spontaneous preterm delivery (e.g., malaria, pyelonephritis, and pneumonia). Indeed, from a global health perspective, malaria may be a major contributor to preterm birth in endemic areas. The mechanisms whereby malaria leads to preterm labor remain to be determined.

Decidual hemorrhage and vascular disease

A subset of patients with preterm labor with intact membranes and preterm prelabor rupture of membranes have vaginal bleeding attributed to defective decidual hemostasis. Thrombin generated during the course of decidual hemorrhage can stimulate myometrial contractility and degrade the extracellular matrix in the chorioamniotic membranes, predisposing to rupture (*32*, *33*). Mothers with evidence of increased thrombin generation are at greater risk for spontaneous preterm labor. Uterine bleeding has also been observed with vascular lesions of the placenta. During normal pregnancy, cytotrophoblast invasion physiologically transforms uterine spiral arteries—small-diameter, high-resistance vessels—into large-diameter, low-resistance conduits that perfuse the chorionic villi of the placenta (Fig. 4, A, B, and D). About 30% of patients with preterm labor have placental lesions consistent with maternal vascular underperfusion, and a similar number have failure of physiologic transformation of the myometrial segments of the spiral arteries (*34*). In these cases, the vessel lumen fails to expand (Fig. 4, C and E), a pathological feature that is commonly associated with preeclampsia (maternal high blood pressure and protein in the urine) (*35*). An abnormal maternal plasma antiangiogenic profile in the midtrimester, which predates the symptoms of preeclampsia (*36*), has also been reported in a subset of patients who deliver preterm and have placental vascular lesions of underperfusion (*37*). Understanding why some women with these vascular lesions and an abnormal angiogenic profile develop preeclampsia and others preterm labor can provide insight into the pathophysiology of both conditions.

Decidual senescence

Around the time of implantation, the endometrium undergoes anatomical and functional changes to become the decidua, which is crucial for successful implantation, pregnancy maintenance, and parturition. Decidualization is characterized by extensive proliferation and differentiation of uterine stromal cells into specialized cell types called decidual cells. The tumor suppressor protein p53 plays an important role in decidual growth, and its deletion causes implantation failure or, if pregnancy is established, inadequate decidualization. Premature decidual senescence has been implicated in implantation failure, fetal death, and preterm birth. In mice, conditional deletion of uterine *Trp53* leads to spontaneous preterm birth in 50% of cases (*38*), which is associated with decidual senescence demonstrated by increased mammalian target of rapamycin (mTOR) complex 1 signaling, p21 levels, and β-galactosidase staining but without progesterone withdrawal (*38*, *39*). The administration of rapamycin (an mTOR inhibitor) and/or progesterone attenuates premature decidual senescence and preterm birth. Evidence of decidual senescence has been demonstrated adjacent to the basal plate of the placenta (placental surface in direct contact with the uterine wall) in cases with preterm labor but not in women who delivered at term (*39*). Whether other mechanisms of preterm labor (e.g., infection and uterine bleeding) converge on decidual senescence is an open question. Additionally, it would be interesting to determine whether tissue stiffness, measured by atomic force microscopy, is a proxy for decidual senescence and therefore a biomarker (*40*).

Disruption of maternal-fetal tolerance

The fetus and placenta express both maternal and paternal antigens and are therefore semiallografts (*41*). Immune tolerance is required for successful pregnancy (*42*, *43*), and a breakdown in tolerance can lead to a pathologic state (Fig. 2) with features of allograft rejection. Chronic chorioamnionitis, the most common placental lesion in late spontaneous preterm birth, is characterized by maternal T cell infiltration of the chorioamnion with trophoblast apoptosis and resembles allograft rejection (*44*). Maternal sensitization to fetal human leukocyte antigens is frequently found in patients with chronic chorioamnionitis and is accompanied by C4d deposition in umbilical vein endothelium (*45*, *46*). A novel form of fetal systemic inflammation characterized by overexpression of T cell chemokines (e.g., C-X-C motif ligand 10) (*47*) has been observed in chronic chorioamnionitis. Breakdown of maternal-fetal tolerance may be particularly relevant to preterm labor occurring after fetal surgery or stem cell transplantation, interventions that increase in the number of maternal T cells in the fetal circulation (*48*). The mechanisms linking disorders in tolerance and spontaneous preterm labor remain to be defined.

Decline in progesterone action

Progesterone is key to pregnancy maintenance, and a decline in its progesterone action precedes labor in most species, which can be mediated by a reduction in serum levels of progesterone, local changes in metabolism, and/or alterations in receptor isoforms/coactivators (*49*, *50*). The administration

of progesterone receptor antagonists, such as mifepristone (RU-486), induces cervical ripening, spontaneous abortion, and labor in both animals and humans—hence the concept that a decline in progesterone may be responsible for some cases of preterm labor. Indeed, progesterone has effects on each component of the common pathway of parturition. Throughout gestation, progesterone promotes myometrial quiescence by reducing the expression of contraction-associated proteins (*51*) and inflammatory cytokines/chemokines (e.g., IL-1, IL-8, and CCL2) (*50*). Near term, increased myometrial expression of miR-200 family members counteracts many actions of progesterone, increasing its catabolism and inducing expression of proinflammatory cytokines/chemokines and prostaglandin synthase 2 (*8*). Progesterone's effects on the decidua and chorioamniotic membranes include inhibition of basal- and TNF-α–induced apoptosis, which protects the component cells from calcium-induced cell death and attenuates cytokine-induced MMP expression and activity (*52*). Progesterone has been implicated in the control of cervical ripening by regulating extracellular matrix metabolism (*9*). It is possible that the efficacy of progesterone in reducing preterm birth is due to a pharmacological effect rather than treatment of a progesterone deficiency.

Other mechanisms of disease

Uterine overdistension has been implicated in spontaneous preterm birth associated with multiple gestations and polyhydramnios (an excessive amount of amniotic fluid). In nonhuman primates, inflation of intra-amniotic balloons can stimulate uterine contractility, preterm labor, and an "inflammatory pulse," which is characterized by increased maternal plasma concentrations of IL-1β, TNF-α, IL-8, and IL-6 (*53*). This finding is consistent with the observation that stretching human myometrium results in the overexpression of inflammatory cytokines.

Maternal stress is also a risk factor for preterm birth. Stressful stimuli range from a heavy workload to anxiety and depression, occurring at any time during the preconceptional period and/or pregnancy. Stress signals increase the production of maternal and fetal cortisol, which in turn could stimulate placental production of corticotropin-releasing hormone and its release into the maternal and fetal circulations (*54*).

Cell-free fetal DNA

Cell-free fetal (cff) DNA has recently been proposed as a signal for the onset of labor (*55*). In pregnant women, cffDNA is normally present in the plasma, and concentrations increase as a function of gestational age—peaking at the end of pregnancy just before the onset of labor. cffDNA (in contrast with adult cell-free DNA) is hypomethylated, can engage TLR-9 (*56*, *57*), and induce an inflammatory response. The downstream consequences could include activating the common pathway of labor. Interestingly, patients who have an elevation of cffDNA in the midtrimester are at increased risk for spontaneous preterm delivery later in gestation (*58*), and those with an episode of preterm labor and high plasma concentrations of cff DNA are also at increased risk for preterm delivery (*59*, *60*). The concept that cff DNA can mediate a fetal/placental/maternal dialogue to signal the onset of labor in normal pregnancy, as well as preterm labor after insult, is a fascinating hypothesis worthy of investigation.

Progress in the prevention of spontaneous preterm birth

After decades of clinical and basic investigation, major progress has been made toward the prediction and prevention of spontaneous preterm birth. The two most important predictors of spontaneous preterm birth are a sonographic short cervix in the midtrimester (*61*) and spontaneous preterm birth in a prior pregnancy. As for prevention, vaginal progesterone administered to asymptomatic women with a short cervix in the midtrimester reduces the rate of preterm birth at <33 weeks by 45% and decreases the rate of neonatal complications, including neonatal respiratory distress syndrome (*62*). In women with a previous spontaneous preterm birth, the administration of 17-alpha hydroxyprogesterone caproate reduces the rate of preterm birth at <37 weeks by 34% and decreases the need for oxygen supplementation in singleton gestation (*63*). Cervical cerclage in patients with a previous spontaneous preterm birth and a short cervix reduces the rate of preterm birth at <35 weeks by 30%, as well as composite perinatal mortality and morbidity. However, vaginal progesterone is as efficacious as cervical cerclage in these patients and does not require anesthesia or a surgical procedure.

The combination of transvaginal ultrasound in the midtrimester to identify women with a short cervix and treatment with vaginal progesterone represents an important step in reducing the rate of preterm birth. This approach is anchored in the knowledge that progesterone plays a role in cervical ripening and has the potential to save the U.S. health care system $500 million to $750 million per year.

Looking forward

Progress in the understanding and prevention of preterm labor will require recognition that preterm parturition has multiple etiologies and further elucidation of the mechanisms underlying each. The definition of pathologic processes, identification of specific biomarkers, and implementation of therapeutic interventions within the unique complexity of pregnancy are particularly challenging. In pregnancy, two individuals with different genomes and exposomes coexist, largely with overlapping interests but occasionally in potential conflict. Inaccessibility

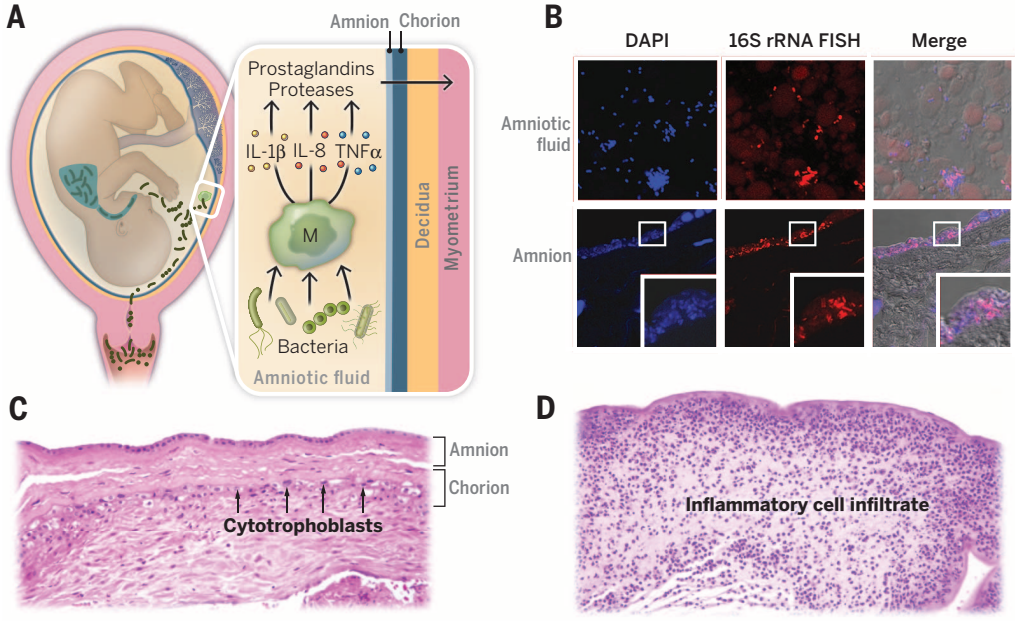

Fig. 3. Mechanisms of microbial-induced preterm labor. (**A**) Bacteria from the lower genital tract gain access to the amniotic cavity and stimulate the production of chemokines (IL-8 and CCL2) and cytokines (IL-1α and TNF-α), as well as other inflammatory mediators (prostaglandins and reactive oxygen radicals) and proteases. These products can initiate myometrial contractility and induce membrane rupture. (**B**) (Top left) Amniotic fluid containing bacteria that was retrieved by amniocentesis from a patient with preterm labor. Bacteria and nuclei stained with DAPI (4′,6-diamidino-2-phenylindole) (blue). (Top middle) Bacteria identified with a probe against 16S ribosomal RNA (rRNA) using fluorescent in situ hybridization. (Bottom left and middle) Bacteria invading the amnion epithelium. Note the absence of bacteria in the subepithelial part of the amnion, suggesting that the pathway of microbial invasion is ascending into the amniotic cavity (*74*). (**C**) Chorioamniotic membranes without evidence of inflammation. Amnion and chorion are identified. (**D**) A similar membrane section as (C) from a patient with intra-amniotic infection. Inflammatory cells from the mother infiltrate the chorion and amnion.

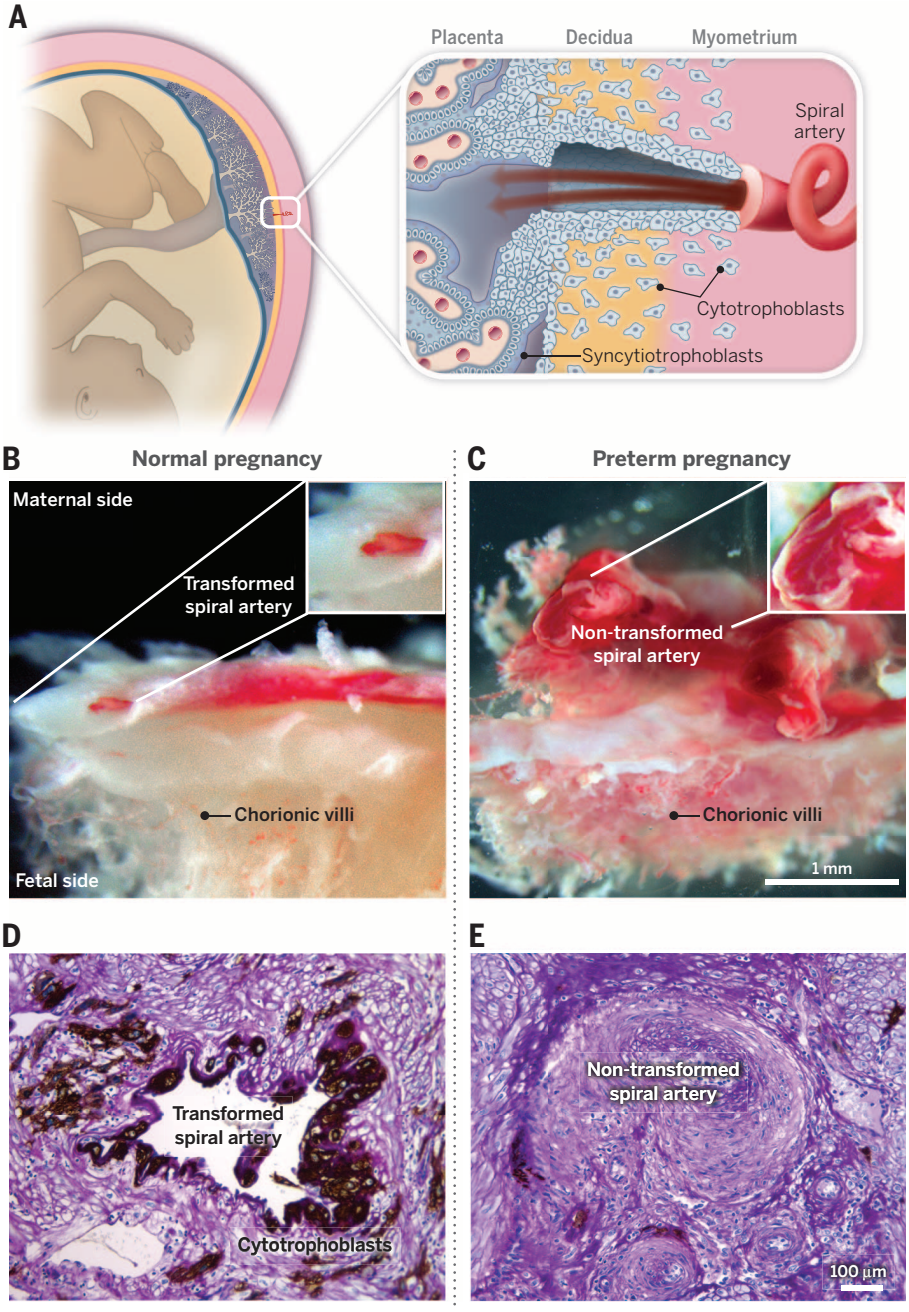

Fig. 4. A subset of patients with preterm labor has placental vascular lesions, including failure of physiologic transformation of the uterine spiral arteries. (**A**) Schematic drawing of the maternal-fetal interface in normal pregnancy. A physiologically transformed uterine spiral artery with a wide lumen delivers blood to the chorionic villi of the placenta. (**B**) A spiral artery with an expanded ostium that normally enables adequate perfusion of the chorionic villi. (**C**) Ostium of a narrow spiral artery with failure of physiologic transformation in a patient with spontaneous preterm labor. (**D**) Periodic acid–Schiff staining of a histological section of the maternal-fetal interface in normal pregnancy shows a spiral artery transformed by cytokeratin 7–positive cytotrophoblasts (brown) that line the lumen. (**E**) Failure of physiologic transformation of a spiral artery in a patient with preterm labor. The lumen is narrow, and cytotrophoblasts have not invaded the muscular wall.

of the human fetus also poses a formidable obstacle to elucidating the physiology of fetal development, maternal responses to this process, and the changes in both when pathologic processes arise.

High-throughput techniques and systems biology can be used to improve the understanding of the preterm labor syndrome. Early studies using unbiased genomic/epigenomic (*64*–*66*), transcriptomic (*67*, *68*), proteomic (*69*, *70*), and metabolomic approaches (*71*) have been informative yet require verification and validation. Progress will also depend on the generation and availability of multidimensional data sets, with detailed phenotypic characterization of disaggregated patient groups according to the mechanisms of disease. Longitudinal studies are required to determine whether any of the discriminators, at molecular or pathway levels, can serve as biomarkers during the preclinical disease stage and enable risk assessment and/or noninvasive monitoring of fetal health and disease. In vivo monitoring of cell-free RNA during human pregnancy can provide information about fetal tissue-specific transcription is an exciting development (*72*, *73*). Since a stereotypic blood transcriptome has been identified in fetuses with acute and chronic placental inflammatory lesions, there are opportunities to determine whether and when, during the course of pregnancy, these changes can be detected in maternal blood. This information could have enormous diagnostic and prognostic value to inform the selection of therapeutic interventions. Thus, we envision that the goal of reducing the rate of spontaneous preterm birth will be grounded in a deeper understanding of the mechanisms of disease responsible for this syndrome.

REFERENCES AND NOTES

1. L. Liu *et al.*, *Lancet* **379**, 2151–2161 (2012).
2. H. Blencowe *et al.*, *Lancet* **379**, 2162–2172 (2012).
3. M. K. Mwaniki, M. Atieno, J. E. Lawn, C. R. Newton, *Lancet* **379**, 445–452 (2012).
4. C. J. Murray *et al.*, *Lancet* **380**, 2197–2223 (2012).
5. National Research Council, in *Preterm Birth: Causes, Consequences, and Prevention*, R. E. Behrman, A. S. Butler, Eds. (National Academies Press, Washington, DC, 2007), p. 400.
6. R. L. Goldenberg, J. F. Culhane, J. D. Iams, R. Romero, *Lancet* **371**, 75–84 (2008).
7. R. Romero *et al.*, *BJOG* **113** (suppl. 3), 17–42 (2006).
8. N. E. Renthal, K. C. Williams, C. R. Mendelson, *Nat. Rev. Endocrinol.* **9**, 391–401 (2013).
9. M. Mahendroo, *Reproduction* **143**, 429–438 (2012).
10. R. Menon, S. J. Fortunato, *Best Pract. Res. Clin. Obstet. Gynaecol.* **21**, 467–478 (2007).
11. R. M. Moore, J. M. Mansour, R. W. Redline, B. M. Mercer, J. J. Moore, *Placenta* **27**, 1037–1051 (2006).
12. R. Romero *et al.*, *Paediatr. Perinat. Epidemiol.* **15** (suppl. 2), 41–56 (2001).
13. P. N. Madianos, Y. A. Bobetsis, S. Offenbacher, *J. Periodontol.* **84** (suppl.), S170–S180 (2013).
14. M. A. Elovitz, Z. Wang, E. K. Chien, D. F. Rychlik, M. Phillippe, *Am. J. Pathol.* **163**, 2103–2111 (2003).
15. V. Agrawal, E. Hirsch, *Semin. Fetal Neonatal Med.* **17**, 12–19 (2012).
16. S. G. Carroll *et al.*, *Arch. Dis. Child. Fetal Neonatal Ed.* **72**, F43–F46 (1995).
17. R. Gomez *et al.*, *Am. J. Obstet. Gynecol.* **179**, 194–202 (1998).
18. S. Kannan *et al.*, *Sci. Transl. Med.* **4**, 130ra46 (2012).
19. A. H. Jobe, *Pediatr. Neonatol.* **51**, 7–13 (2010).
20. G. A. Macones *et al.*, *Am. J. Obstet. Gynecol.* **190**, 1504–1508, discussion 3A (2004).
21. K. Racicot *et al.*, *J. Immunol.* **191**, 934–941 (2013).
22. R. Romero *et al.*, *Microbiome* **2**, 4 (2014).
23. R. W. Hyman *et al.*, *Reprod. Sci.* **21**, 32–40 (2014).
24. R. Romero *et al.*, *Microbiome* **2**, 4 (2014).
25. O. Genbacev, Y. Zhou, J. W. Ludlow, S. J. Fisher, *Science* **277**, 1669–1672 (1997).
26. C. Whidbey *et al.*, *J. Exp. Med.* **210**, 1265–1281 (2013).
27. D. J. Anstee, *Blood* **115**, 4635–4643 (2010).
28. S. McDonagh *et al.*, *J. Infect. Dis.* **190**, 826–834 (2004).
29. K. Aagaard *et al.*, *Sci. Transl. Med.* **6**, 237ra65 (2014).
30. Eunice Kennedy Shriver NICHD, The Human Placenta Project: Placental Structure and Function in Real Time (2014); www.nichd.nih.gov/about/meetings/2014/Pages/052814.aspx.
31. R. Romero *et al.*, *Am. J. Reprod. Immunol.* 10.1111/aji.12296 (2014).
32. M. A. Elovitz, T. Saunders, J. Ascher-Landsberg, M. Phillippe, *Am. J. Obstet. Gynecol.* **183**, 799–804 (2000).

33. C. S. Han, F. Schatz, C. J. Lockwood, *Clin. Perinatol.* **38**, 407–421 (2011).
34. Y. M. Kim *et al.*, *Am. J. Obstet. Gynecol.* **189**, 1063–1069 (2003).
35. I. Brosens, R. Pijnenborg, L. Vercruysse, R. Romero, *Am. J. Obstet. Gynecol.* **204**, 193–201 (2011).
36. R. J. Levine *et al.*, *N. Engl. J. Med.* **350**, 672–683 (2004).
37. T. Chaiworapongsa *et al.*, *J. Matern. Fetal Neonatal Med.* **22**, 1122–1139 (2009).
38. Y. Hirota *et al.*, *J. Clin. Invest.* **120**, 803–815 (2010).
39. J. Cha *et al.*, *J. Clin. Invest.* **123**, 4063–4075 (2013).
40. P. Lu, V. M. Weaver, Z. Werb, *J. Cell Biol.* **196**, 395–406 (2012).
41. A. Erlebacher, *Nat. Rev. Immunol.* **13**, 23–33 (2013).
42. J. E. Mold *et al.*, *Science* **322**, 1562–1565 (2008).
43. J. H. Rowe, J. M. Ertelt, L. Xin, S. S. Way, *Nature* **490**, 102–106 (2012).
44. C. J. Kim *et al.*, *Mod. Pathol.* **23**, 1000–1011 (2010).
45. J. Lee *et al.*, *PLOS ONE* **6**, e16806 (2011).
46. J. Lee *et al.*, *Am. J. Reprod. Immunol.* **70**, 162–175 (2013).
47. J. Lee *et al.*, *Am. J. Reprod. Immunol.* **70**, 265–284 (2013).
48. M. Wegorzewska *et al.*, *J. Immunol.* **192**, 1938–1945 (2014).
49. J. C. Condon, D. B. Hardy, K. Kovaric, C. R. Mendelson, *Mol. Endocrinol.* **20**, 764–775 (2006).
50. H. Tan, L. Yi, N. S. Rote, W. W. Hurd, S. Mesiano, *J. Clin. Endocrinol. Metab.* **97**, E719–E730 (2012).
51. O. Shynlova, P. Tsui, S. Jaffer, S. J. Lye, *Eur. J. Obstet. Gynecol. Reprod. Biol.* **144** (suppl. 1), S2–S10 (2009).
52. J. F. Strauss 3rd, *Reprod. Sci.* **20**, 140–153 (2013).
53. K. M. Waldorf *et al.*, *Reprod. Sci.* **21**, 96A (2014).
54. F. Petraglia, A. Imperatore, J. R. Challis, *Endocr. Rev.* **31**, 783–816 (2010).
55. M. Phillippe, *N. Engl. J. Med.* **370**, 2534–2536 (2014).
56. J. E. Thaxton, R. Romero, S. Sharma, *J. Immunol.* **183**, 1144–1154 (2009).
57. A. Scharfe-Nugent *et al.*, *J. Immunol.* **188**, 5706–5712 (2012).
58. T. R. Jakobsen, F. B. Clausen, L. Rode, M. H. Dziegiel, A. Tabor, *Prenat. Diagn.* **32**, 840–845 (2012).
59. T. N. Leung, J. Zhang, T. K. Lau, N. M. Hjelm, Y. M. Lo, *Lancet* **352**, 1904–1905 (1998).
60. A. Farina *et al.*, *Am. J. Obstet. Gynecol.* **193**, 421–425 (2005).
61. R. Romero *et al.*, *J. Perinat. Med.* **41**, 27–44 (2013).
62. R. Romero *et al*, *Am. J. Obstet. Gynecol.* **206**, 124.e1 (2012).
63. P. J. Meis *et al.*, *N. Engl. J. Med.* **348**, 2379–2385 (2003).
64. H. Wang *et al.*, *Hum. Mol. Genet.* **17**, 1087–1096 (2008).
65. L. J. Muglia, M. Katz, *N. Engl. J. Med.* **362**, 529–535 (2010).
66. K. Y. Bezold, M. K. Karjalainen, M. Hallman, K. Teramo, L. J. Muglia, *Genome Med* **5**, 34 (2013).
67. Y. J. Heng, C. E. Pennell, H. N. Chua, J. E. Perkins, S. J. Lye, *PLOS ONE* **9**, e96901 (2014).
68. R. Haddad *et al*, *Am. J. Obstet. Gynecol.* **195**, 394.e1 (2006).
69. M. G. Gravett *et al.*, *JAMA* **292**, 462–469 (2004).
70. M. S. Esplin *et al*, *Am. J. Obstet. Gynecol.* **204**, 391.e1 (2010).
71. R. Romero *et al.*, *J. Matern. Fetal Neonatal Med.* **23**, 1344–1359 (2010).
72. W. Koh *et al.*, *Proc. Natl. Acad. Sci. U.S.A.* **111**, 7361–7366 (2014).
73. D. W. Bianchi, *Nat. Med.* **18**, 1041–1051 (2012).
74. M. J. Kim *et al.*, *Lab. Invest.* **89**, 924–936 (2009).

ACKNOWLEDGMENTS

The authors regret that, because of page limitations, the contributions of many investigators to the study of parturition could not be credited in this article. The authors thank S. Curtis for editing the manuscript. The work of R.R. is supported by the Division of Intramural Research of the Eunice Kennedy Shriver NICHD, NIH/Department of Health and Human Services. Studies from S.K.D.'s lab were supported in part by grants from the NIH (HD068524 and DA06668) and March of Dimes (21-FY12-127 and 22-FY14-470). The work of S.F. is supported by R37 HD076253 and U54 HD055764. We thank M. Gormley for assistance preparing the figures.

10.1126/science.1251816

REVIEW

Neural control of maternal and paternal behaviors

Catherine Dulac,[1]* Lauren A. O'Connell,[2] Zheng Wu[1]

Parental care, including feeding and protection of young, is essential for the survival as well as mental and physical well-being of the offspring. A large variety of parental behaviors has been described across species and sexes, raising fascinating questions about how animals identify the young and how brain circuits drive and modulate parental displays in males and females. Recent studies have begun to uncover a striking antagonistic interplay between brain systems underlying parental care and infant-directed aggression in both males and females, as well as a large range of intrinsic and environmentally driven neural modulation and plasticity. Improved understanding of the neural control of parental interactions in animals should provide novel insights into the complex issue of human parental care in both health and disease.

Parental behavior aims at caring for conspecific young and increasing their survival. Among oviparous animals, parenting can include behaviors such as egg-laying site selection, nest building, burrowing, egg attending, and brooding and carrying the young; among viviparous animals, it can include food provisioning, nursing, defense of offspring, and even teaching of skills. Parenting occurs in a surprisingly large variety of vertebrates and invertebrates, including insects, arachnids, mollusks, fishes, amphibians, reptiles, birds, and mammals. In mammals, mothers commonly take the primary responsibility of parental care, whereas fathers often ignore or even attack the young. However, in many species, direct engagement of fathers has been observed; in some species, fathers participate equally or even exclusively in parental duties (Fig. 1).

Nurturing and affiliative behavior toward infants is sensitive to physiological and environmental factors such as stress and hormone levels. In humans, the quality of parental care is affected by stress and mental illnesses such as postpartum depression (PPD), which affects more than 10% of mothers in the United States (*1*). How is the diversity of parental behavior generated in males and females, across different species, and in various physiological or pathological conditions? Recent studies have begun to uncover the nature and function of circuits underlying parental interactions with young. Here, we review data suggesting the existence of highly conserved and antagonistic circuits controlling affiliative and aggressive behavior toward offspring, respectively. Circuits underlying these opposing behaviors are present in both male and female brains irrespective of the normal expression of parenting displays and are modulated by intrinsic and environmental factors.

Diversity in parental care

Parental care has evolved repeatedly across vertebrate and invertebrate taxa (*2*). The involvement of males and/or females in the care for offspring varies across taxa and even between populations within a species (Fig. 2). In many systems, the parent that cares for offspring can be partially correlated with certainty in parentage and/or adult sex ratio. In mammals, male involvement is rare because internal fertilization ensures maternity but not paternity, and because only females lactate (*3*). In some rodents, canids, and primates, males assist and invest substantially in the care of offspring (*4*–*8*), whereas closely related species are exclusively maternal (*9*–*12*). For example, prairie voles and California mice are biparental, with males showing all female-typical parental displays except nursing (*4*, *5*), but closely related species in the same genus—such as the montane vole, meadow vole, or deer mouse—are female uniparental (*9*–*12*). Cross-fostering experiments showed that meadow vole males reared by biparental prairie voles exhibited significantly more paternal care to their offspring than in-fostered counterparts (*13*). This result demonstrates the influence of early social environment, in addition to genetic differences between congeneric species, on parental behavior.

Male involvement in offspring care is common in many taxa other than mammals. In teleost fish species, males provide care more often than females, including nest building and egg attendance (*14*). In the well-known case of the three-spined stickleback, males set up the territory, build nests, and defend their offspring (*15*). In birds, 90% of the species are biparental, with both parents sharing the responsibilities of building a nest, incubating eggs, and defending and feeding the young (*16*). The sex ratio of individuals available to mate in a bird population largely determines which parent cares for offspring. For example, male shorebirds are more likely to care for offspring in populations where males are more abundant than females (*17*).

Amphibians display striking diversity in parental care. Many species of anurans and salamanders display care for offspring beyond egg laying, with roughly 50 independent evolutionary transitions to parental care (*18*). These behaviors include preparation of foam nests (*19*), egg guarding, transport of offspring piggyback

[1]Howard Hughes Medical Institute, Department of Molecular and Cellular Biology, Center for Brain Science, Harvard University, Cambridge, MA 02138, USA. [2]FAS Center for System Biology, Harvard University, Cambridge, MA 02138, USA.
*Corresponding author. E-mail: dulac@fas.harvard.edu