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The role of the maternal immune system in the regulation of human birthweight

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Human birthweight is subject to stabilizing selection. Large babies are at risk of obstetric complications such as obstructed labour, which endangers both mother and child. Small babies are also at risk with reduced survival. Fetal growth requires remodelling of maternal spiral arteries to provide an adequate maternal blood supply to the placenta. This arterial transformation is achieved by placental trophoblast cells, which invade into the uterine wall. Under-invasion is associated with fetal growth restriction; but if invasion is excessive large babies can result. A growing body of evidence suggests that this process is controlled by interactions between killer-cell immunoglobulin-like receptors (KIRs) expressed on maternal uterine natural killer cells (uNK) and their corresponding human leukocyte antigen-C (HLA-C) ligands on invading trophoblast. Mothers with the *KIR AA* genotype and a fetus with a paternal *HLA-C2* allele tend to have small babies, because this combination inhibits cytokine secretion by uNK. Mothers with the activating *KIR2DS1* gene and an *HLA-C2* fetus are more likely to have large babies. When *KIR2DS1* binds to *HLA-C2* this increases secretion of cytokines that enhance trophoblast invasion. We conclude that specific combinations of the highly polymorphic gene systems, *KIR* and *HLA-C*, contribute to successful reproduction by maintaining birthweight between two extremes.

1. Introduction

The role of the immune system in the development of both the brain and the placenta during the evolution of modern humans may not be immediately obvious. This paper reviews the part played by the immune system at the moment in human life history when brain size and pelvic anatomy interact in a way that is critical to success or failure of pregnancy. Human brains are now so large that it is an extremely tight fit for them to squeeze through the pelvis. Indeed, babies often do get stuck during the passage through the birth canal resulting in obstructed labour. It is not just pregnancies with very large babies where mothers and their babies are at risk of morbidity and mortality. At the opposite end of the spectrum when babies are too small this can have equally damaging consequences. Karn and Penrose first noted this selective pressure at the extremes of the birthweight spectrum in the 1930s, but it was Bodmer who pointed out that human birthweight is a prime example of balancing or stabilizing selection [1,2]. Although death of babies is now less frequent due to advances in neonatal medicine, there is still considerable morbidity. Our recent study in Norway shows babies were most frequently admitted to the neonatal ward when they were born at the extremes of the birthweight spectrum [3]. This suggests there is still strong selective pressure to maintain human birthweight between these two extremes. This situation, encapsulated in the notion of the Obstetric Dilemma, is a particular problem for humans.

2. Placentation and fetal growth

Growth of the fetus and size at birth must depend on the delivery of sufficient nutrients and oxygen to the placenta. The supply line in the uterus is via the maternal arteries supplying blood to the placenta—the so-called spiral arteries.

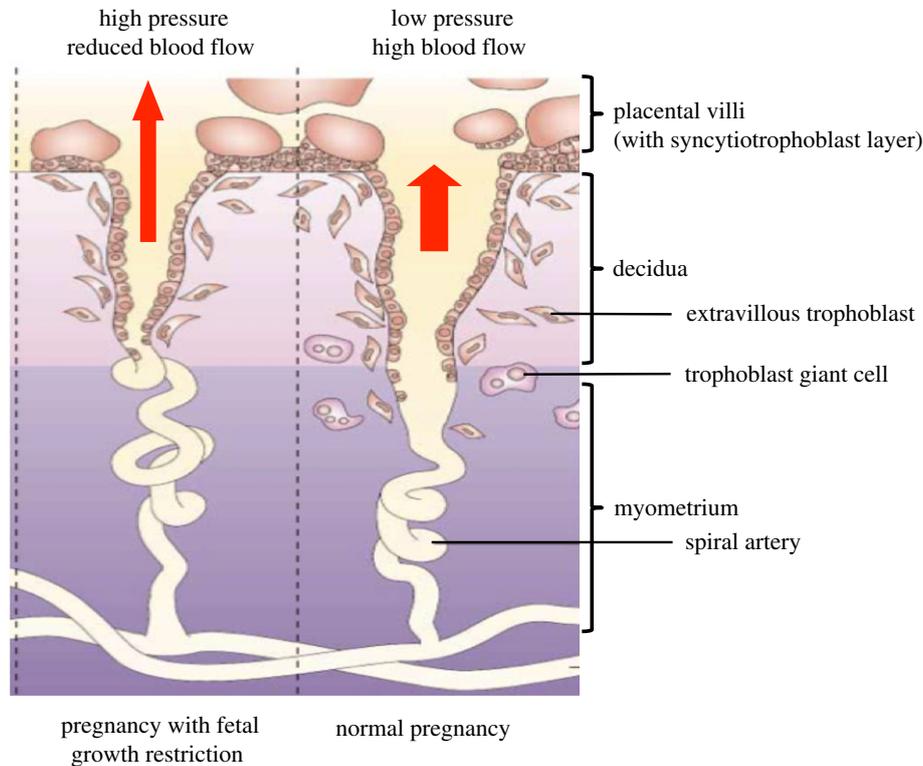


Figure 1. Fetal growth restriction is associated with reduced remodelling of maternal spiral arteries by trophoblast cells. In normal pregnancy (right-hand panel), extravillous trophoblast cells migrate as far as the myometrium and also infiltrate into the arterial media and endothelium of maternal spiral arteries. This results in dilatation and increased flow of maternal blood at low pressure into the intervillous space (red arrow). In pregnancies affected by pre-eclampsia or FGR (left-hand panel), the depth of trophoblast invasion is reduced with less spiral artery remodelling. Blood flows at higher pressure and is more pulsatile, resulting in placental stress, reduced placental development and poor fetal growth. (Figure adapted from Moffett-King [5], with permission.)

In humans, these are structurally transformed during early pregnancy to allow blood flow to increase about 100-fold [4]. Arterial transformation depends on an unusual process during placentation, whereby fetal trophoblast cells from the placenta infiltrate into the uterine wall, home to the arteries, and destroy the smooth muscle media. As a result of this trophoblast modification, the arteries become conduits capable of high conductance at low pressure with a reduction in velocity of the blood entering the placenta. Terminal dilatation of the arteries results in a further reduction in the flow rate into the intervillous space. This permits adequate time for gas exchange, especially towards the end of the pregnancy when fetal demands are highest. When there is failure of arterial conversion by trophoblast, then arterial blood will jet into the intervillous space from the non-transformed arteries causing damage to the villous tree (figure 1). Transport of oxygen and nutrients to the fetus is reduced and this manifests as fetal growth restriction (FGR). In more severe cases, the mother may develop pre-eclampsia, a systemic syndrome that occurs when the placenta becomes stressed as a result of the reduced blood flow [5]. Soluble factors released from the stressed placenta can trigger an inflammatory condition with diverse clinical manifestations. These include oedema, proteinuria and high blood pressure and can progress to eclampsia and maternal death. This is one of the principal reasons for clinical problems in both mothers and babies in pregnancies with very low birthweights. There are other clinical conditions besides pre-eclampsia and FGR resulting from defective placentation. Known collectively as the Great Obstetric Syndromes (GOS), they include unexplained stillbirth, placental abruption and preterm labour [6].

3. The Obstetric Dilemma

Very large babies (approx. more than 4 kg) represent the other extreme of the birthweight spectrum, and these pregnancies are also at risk of clinical problems due to the difficulty of the passage of their head through the pelvis. Fetal obstruction results in prolonged labour, fetal death from asphyxia, soft tissue damage to pelvic organs and post-partum haemorrhage [7]. Estimation of placental size by sonography shows that, similar to the GOS, the origins of macrosomia are present early in gestation [8]. The risk of cephalopelvic disproportion has arisen because of the anatomical adaptations necessary for efficient bipedalism. These resulted in narrowing of the birth canal, imposing considerable constraints during parturition that are characteristic of modern humans even in comparison with Neanderthals [9]. The human head followed by the shoulders needs to rotate to fit the three planes of the pelvis that all have different shapes and orientations unlike other primates [10].

The combination of a narrow birth canal and the enlarged brain means that the Obstetric Dilemma is a particular problem for humans. Fetal growth *in utero* depends on the development of a good maternal blood supply to the placenta that requires modification of the uterine spiral arteries. Trophoblast cells from the placenta invade deeply into the stroma to effect arterial conversion. The extravillous trophoblast cells (EVT) encircle the arteries, and then cause direct destruction of the smooth muscle of the arterial wall with complete loss of vasoconstriction. By contrast, trophoblast invasion is much more limited in extent in Old World monkeys, where trophoblast cells only move down the inside of the arteries to replace the endothelium and functionally modify the media [11,12]. Among

primates, deep trophoblast invasion through the decidua and into the inner myometrium is characteristic of human placentation, probably as a consequence of the increased blood supply needed to support the *in utero* development of the large brain. Indeed, brain development continues for some years after birth in humans [13]. Thus, the extent of trophoblast invasion has a critical effect on fetal access to maternal oxygen and nutrients. Under-invasion is associated with GOS such as FGR and pre-eclampsia, a condition only occurring in humans; over-invasion can result in obstructed labour due to the large fetus. A consequence of the balancing selection operating to prevent obstructed labour and the birthweight from being too large is the persistence of pregnancies with pre-eclampsia and FGR in all populations. The Obstetric Dilemma means that the birthweight must therefore be kept closely between the two dangerous extremes.

4. Regulation of placentation by the decidual immune system

Because trophoblast transformation of the arteries affects the growth and development of the fetus and placenta, there is much interest in how trophoblast invasion is controlled and thus how the supply line to the fetus is regulated. *In vivo* and *in vitro* observations show that human trophoblast cells are inherently highly invasive and can penetrate right through the wall of the uterus—*unless* they are controlled. This is seen, for example, after a caesarian section if the placenta implants on the scar in a subsequent pregnancy. Because the mucosal lining of the uterus (decidua) is missing at the site of the scar, trophoblast invasion proceeds unchecked, a condition known as placenta percreta, which can lead to uterine rupture [14]. The same behaviour occurs in ectopic pregnancy where implantation occurs in the fallopian tube, which also lacks decidua. This suggests decidual tissue must be essential for regulation of trophoblast invasion.

To understand how decidua regulates placentation, we have focused on the decidual immune system [15,16]. Hints that the immune system was involved came initially from studying the epidemiology of pre-eclampsia [17]. Classically, this is a disease of first pregnancies, giving rise to the idea that women became ‘immune’ afterwards. Change of male partners after a normal first pregnancy can trigger the condition; conversely, women who have already had pre-eclampsia may then be protected when they have a baby with a new partner [18]. These features, memory and specificity, are characteristic of the immune system. The familial and genetic contribution from the mother is well established, but, importantly, several studies have also shown that there is a paternal contribution to both pre-eclampsia and birthweight [19–21]. There is therefore circumstantial evidence that interactions between maternal and fetal immune system genes may determine successful pregnancy outcome.

There are two sites where fetal cells are in direct contact with maternal immune cells. Placental villi are covered by syncytiotrophoblast and present a large surface area in contact with maternal blood. Intermingling of maternal and fetal cells also occurs in the uterus at the site of placental attachment where EVT invade into decidua (figure 1). A territorial boundary must be defined here between two individuals. Because of the need to regulate the blood flow to the placenta and thus the birthweight, this boundary needs to be established in the right

place. If the placenta (fetus) is too intrusive, the mother is at risk of uterine rupture and death. If trophoblast invasion is not far enough, spiral arteries are not sufficiently transformed, the blood flow to placenta is reduced, fetal growth is compromised and the mother is at risk of pre-eclampsia. There is growing evidence for the role of the decidual immune system in the subtle delineation of this uterine maternal/fetal interface. Because these two individuals are genetically different, the invading trophoblast cells will express molecules encoded by paternal genes meaning that, in immunological terms, the fetus is ‘non-self’ to the mother. How do maternal immune cells recognize and respond to the fetal trophoblast cells in the decidua, and do these interactions regulate trophoblast invasion?

5. T cells and allorecognition in pregnancy

T cells recognize antigenic peptides presented by major histocompatibility complex (MHC) molecules. These genes were originally discovered by Peter Medawar as the gene system whose products determine rejection or acceptance of transplants [22]. Unlike somatic cells, syncytiotrophoblast lacks expression of both MHC class I and II molecules, so cannot be recognized by T cells. However, maternal T-cell responses against fetal alloantigens do occur during pregnancy, generating fetal-specific T cells and humoral responses [23]. During pregnancy, temporary breaks in the syncytiotrophoblast layer can permit fetal cells to enter the maternal circulation. It is likely that these deported cells give rise to most of the fetal antigen-specific responses that have been described in T cells in maternal blood such as that to male HY minor histocompatibility antigen [24]. There is no evidence that any of these responses can directly affect syncytiotrophoblast.

EVT in the decidua also express an unusual MHC profile: they lack class II expression and do not express the human leukocyte antigen-A (HLA-A) or -B molecules normally found on all somatic cells [25]. Instead EVT express classical HLA-C as well as non-classical molecules, HLA-E and -G. The latter two are essentially monomorphic in human populations so will not vary from pregnancy to pregnancy [25]. Since most T cells are restricted to recognize self-HLA-A or -B molecules in association with a non-self-peptide, the unusual MHC profile of EVT means that only HLA-C-restricted T cells are capable of directly recognizing EVT in the decidua. A recent study has shown that in HLA-C mismatched pregnancies there are decidual T cells present that can recognize fetal HLA-C when stimulated with fetal cord blood. These are not present in HLA-C matched pregnancies. HLA-C mismatched pregnancies were also associated with an increase in CD4⁺CD25^{bright} regulatory T cells (Tregs) in the decidua [26]. Tregs represent a subset of CD4⁺ T cells that act to suppress immune responses against self-antigens. They are characterized by expression of the transcription factor Foxp3 [27]. However since EVT does not express MHC class II, these CD4⁺ Tregs presumably recognize fetal HLA-C through indirect allorecognition via presentation of HLA-C peptides on maternal antigen presenting cells (APC). To date there is no evidence that T cells are present in human decidua that can directly recognize fetal alloantigens presented by HLA-C on trophoblast. However, decidual Tregs are generated in HLA-C mismatched pregnancies, and these may contribute to generation of a tolerogenic environment in the decidua.

Although there are significant differences in placental anatomy and trophoblast MHC expression compared to humans,

elegant experiments possible in mice have given broadly similar results to those seen in humans. T cells specific for paternal antigens are generated in allogeneic matings but do not lead to pregnancy failure in normal pregnancies [28]. Adoptive transfer of CD8⁺ T cells specific for H2-K^b, to H2-K^b-negative females carrying H2-K^b-positive pups, did not result in pregnancy failure even though H2-K^b is expressed on trophoblast [29,30]. However, expansion of Tregs is seen during both syngeneic and allogeneic pregnancies and depletion of Tregs during pregnancy results in fetal resorption only in allogeneic matings [31]. Tregs appear to play an important role in preventing rejection of allogeneic pregnancies but the exact mechanism is unclear. In both mouse and humans, multiple other mechanisms have been described that contribute to T-cell tolerance. These include: 'trapping' of APCs within the decidua which decreases migration to regional lymph nodes, reduced T-cell entry into decidua by silencing of chemokine expression, stimulation of APCs by HLA-G to induce tolerogenic cytokine secretion and many others (reviewed in [16,32]). However, in humans there is no evidence that T-cell-dependent adaptive responses to fetal antigens, either systemically or in decidua, are involved in damaging placental cells or causing pregnancy failure.

6. Uterine natural killer cells and recognition of trophoblast HLA class I molecules

T cells comprise only 5–20% of decidual leukocytes. The overwhelming majority of leukocytes in the decidua are uterine natural killer cells (uNK). These are uniquely found in the endometrium during the luteal phase of the menstrual cycle when implantation occurs, and in decidua during early pregnancy [5]. Uterine NK cells are phenotypically and functionally quite distinct from NK cells circulating in peripheral blood and do express a range of receptors that can bind molecules expressed by placental cells [33,34]. Of these, our focus has been on those receptors that could be involved in specific recognition of paternal difference [5,16]. We have therefore studied NK receptors that can bind the MHC molecules expressed by EVT: HLA-C, -E and -G. The latter two are essentially monomorphic in human populations so will not vary from pregnancy to pregnancy [25]. Uterine NK cells express killer-cell immunoglobulin-like receptors (KIRs) that can recognize HLA-C, and invading trophoblast cells abundantly express both maternal and paternal HLA-C molecules [35]. However, the usual simple relationship between receptor and ligand is complicated by extreme polymorphism of both the KIR expressed by uNK and their trophoblast HLA-C ligands, with many different variants found within all populations. This means that there is a range of possible interactions between variants of maternal KIR and alleles of fetal HLA-C ligands to which uNK cells bind. Each pregnancy will thus bring together different combinations of maternal KIR and fetal HLA-C, with potentially different outcomes.

7. Killer immunoglobulin-like receptors expressed by natural killer cells

The *KIR* gene family is complex with a wide range in both the number of *KIR* genes inherited by the mother as well as allelic variation of individual *KIR* genes [36]. Up to 14 different *KIR* genes are present in a linear array in the Leucocyte Receptor

Complex (LRC) on chromosome 19q13.4. KIRs are major regulators of NK cell function with different KIR conferring either an inhibitory or activating signal to the NK cell. Their most important known ligands are HLA-C molecules. KIRs are named based on the number of extracellular Ig-like domains (two or three domains) and whether they have a long or short cytoplasmic tail (e.g. KIR2DL1 or KIR2DS1). Binding of KIR with a long cytoplasmic tail to their cognate ligands results in transduction of an inhibitory signal, whereas ligation of KIR with a short tail results in activation of NK cells. This complexity has been simplified by the clear distinction between two *KIR* haplotypes, *A* and *B*. The *KIR A* haplotype is the most common and contains six inhibitory genes in most individuals. The *KIR B* haplotype is much more variable in gene content and many of the additional KIR are activating. An individual's *KIR* genotype can thus be designated 'AA', 'AB' or 'BB' (figure 2). Although there are over 1000 alleles of HLA-C, these can be distinguished by KIR as two distinct groups, HLA-C1 and -C2, based on a dimorphism at position 80 of the α 1 domain of the HLA-C molecule [36]. To date, there is evidence that five members of the KIR family are capable of binding to HLA-C allotypes. The known KIR specificities for HLA-C are shown in figure 2. The strongest and most specific binding is of KIR2DL1 to HLA-C2 allotypes resulting in a strong inhibitory signal to NK cells.

8. Combinations of maternal KIR and paternal HLA-C genotypes regulate birthweight

To discover how this great polymorphism of maternal *KIR* and fetal *HLA-C* genes affects human reproductive success, we have studied pregnancies where the *KIR* genotype of the mother and *HLA-C* group of her fetus is known. Our results show that there is a consistent relationship between particular combinations of maternal *KIR* and fetal *HLA-C* ligands and birthweight [3,35,37,38]. We compared maternal *KIR* and fetal *HLA-C* genotypes from a large number of first pregnancies selected from the Norwegian Mother–Baby cohort (MoBa) with known birthweight corrected for gestational age and fetal sex. A HLA-C2 group in the fetus is associated with pregnancies at the two extremes of birthweight especially when the *HLA-C2* allele is inherited from the father rather than the mother [3]. If the mother has two *KIR A* haplotypes (*KIR AA* genotype), then she will have inherited two copies of the inhibitory *KIR* for HLA-C2 allotypes, namely *KIR2DL1*. Functionally, when uNK cells from a *KIR AA* woman bind trophoblast expressing a paternal HLA-C2 allotype this results in a strong inhibitory signal. By contrast, high birthweight pregnancies are associated with a paternally derived *HLA-C2* allele, when the mother has inherited the activating *KIR* for HLA-C2, *KIR2DS1* that is located on the *KIR B* haplotype [3]. This effect is quite significant; the average increase in birthweight in pregnancies with a fetus with paternal *HLA-C2* and *KIR2DS1* in the mother is approximately 200 g, more than the differences found with sex of the baby (approx. 50 g) and high altitude (100 g decrease per 1000 m increase in altitude).

This immune interaction is not comparable to other situations such as organ transplantation where there is clear self/non-self discrimination, because it is only *HLA-C* alleles carrying the C2 epitope that confer any effect.

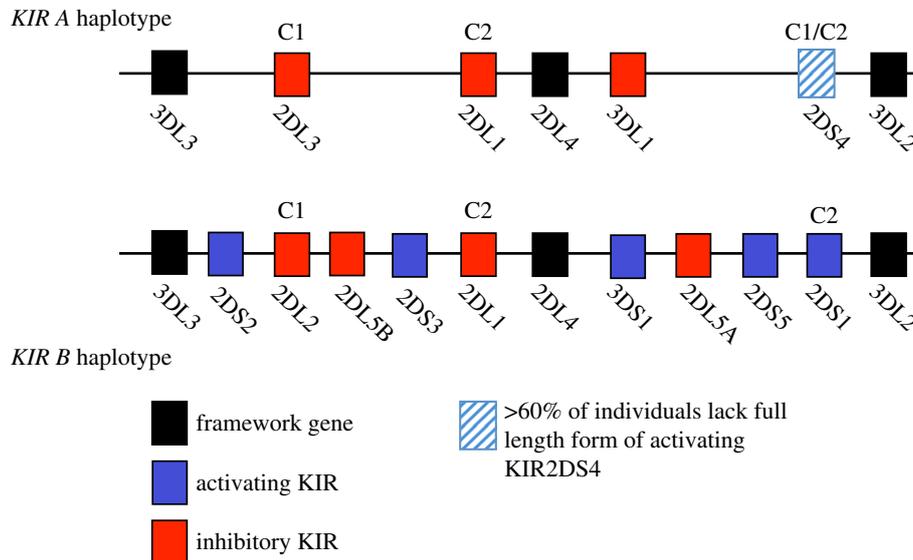


Figure 2. Representative *KIR A* and *B* haplotypes of the *KIR* gene family, together with their known HLA-C binding specificities (C1 and C2) depicted above their cognate *KIR* receptors. *KIR2DS4* binds a limited number of C1 and C2 allotypes. Activating *KIR* are shown as blue boxes, inhibitory *KIR* are shown in red. Framework *KIR* genes that are present in all haplotypes are shown in black. Note that many of the *KIR* shown on the *B* haplotype are not present in all individuals.

To date, in pregnancies where the fetus is homozygous for *HLA-C1* there is no influence of any *KIR* genotype on any clinical outcome in pregnancy that we have studied. This may be due to the tight specificity and strong inhibition conferred by *KIR2DL1*/*HLA-C2* interactions compared with the weaker and more promiscuous *KIR2DL2/3* interactions with *HLA-C* molecules [39]. To summarize, at the site of placentation all the influences of *HLA-C* in pregnancy are mediated by paternal *HLA-C2* with the maternal *KIR* genotype determining the outcome (high or low birthweight). In pregnancies where the fetus is homozygous for *HLA-C1*, then the effect of the maternal *KIR* is neutral and no associations are seen [3,35].

9. Functions of uterine natural killer cells during placentation

The functional effects mediated by uNK cells at the uterine/placental interface relating to these different *KIR*/*HLA-C* combinations are hard to determine given the ethical and logistical problems of studying the site of placentation in early pregnancy in humans. The great disparity in placental strategies in different species also means animal models are generally uninformative. Furthermore, *KIR* genes are only a feature of simian primates, but even in these species there are fundamental differences in placentation with interstitial trophoblast invasion only a feature of the great apes [11]. A further major difficulty has been the lack of any reproducible and reliable *in vitro* model systems to study human trophoblast function *in vitro*. Nonetheless, uNK cells can be isolated and, despite their name, are poorly cytotoxic [40,41]. The input NK cells receive from *KIR* is either activating or inhibitory, and NK function is a result of integrating this information and responding accordingly. When uNK cells receive an overall activating signal in a woman with a *KIR B* haplotype containing *KIR2DS1*, the output of soluble mediators like chemokines and cytokines (e.g. GM-CSF) is increased after co-culture with target cells bearing *HLA-C2* molecules. This supernatant containing GM-CSF stimulates

trophoblast invasion and migration *in vitro* [42]. By contrast, when uNK cells from *KIR AA* women who only have the inhibitory *KIR2DL1* for *HLA-C2* were ligated with *HLA-C2*, trophoblast migration was not stimulated. This suggests that there is reduced cytokine output by uNK cells in a woman with a *KIR AA* genotype when the overall signal is inhibitory. Thus, women with too much uNK cell inhibition (*KIR AA*) or too much activation (*KIR B* haplotype with *KIR2DS1* present) are more likely to have babies with low or high birthweight, respectively, when their uNK cells encounter trophoblast cells displaying a paternal *HLA-C2* allotype. The interpretation we have made based on the genetic and functional evidence is that the overall uNK response determines how far the trophoblast moves into the uterus and modifies the arteries (figure 3). Thus, there is a direct link between the function of the uterine immune system and the birthweight of the baby. This specialized immune interaction may be essential to maintain the birthweight within the strict limits dictated by the Obstetric Dilemma.

Uterine NK cells also occur in the decidua in mice and appear to play an important role in vascular remodelling during placentation. Murine trophoblast invades into the decidua to a lesser degree than in humans and does not express non-classical MHC, so there are significant differences compared to human trophoblast [30]. Although the major murine NK receptors that recognize MHC are the Ly49 family of receptors, they appear to function analogously to the human *KIR*. Mouse studies in which a single additional MHC molecule H2-D^d was introduced, showed impaired vascular remodelling and reduced fetal growth compared with identical mice lacking only H2-D^d [43]. This MHC molecule binds the inhibitory receptor Ly49A and can inhibit additional uNK subsets when present. Particularly notable was the fact that reduced fetal growth was seen regardless of the parental origin of the H2-D^d molecule. These results confirm the idea that certain combinations of maternal NK receptors and paternal (or maternal) MHC molecules can influence trophoblast invasion and vascular remodelling. In both human and murine pregnancies, excessive inhibition of NK cell function is associated with reduced fetal growth.

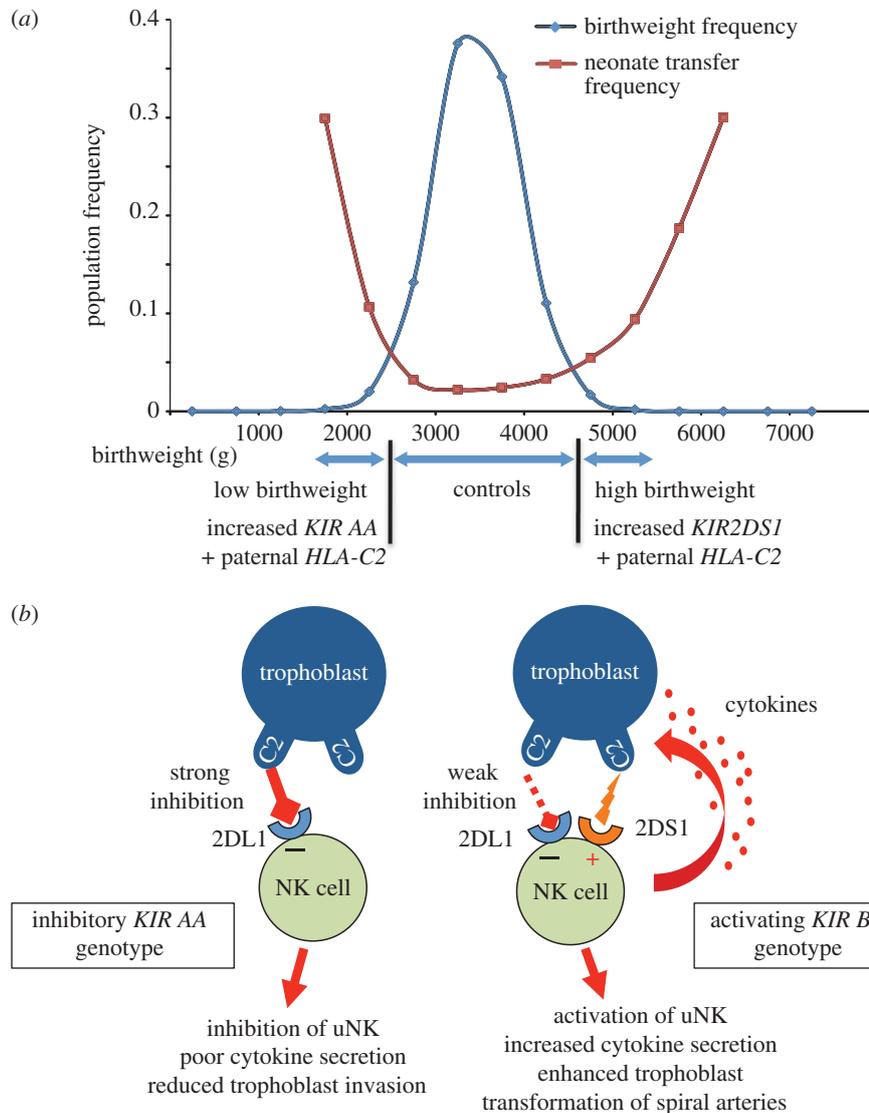


Figure 3. Presence of maternal *KIR2DS1* is associated with increased birthweight. (a) Distribution of birthweights in the Norwegian MoBa cohort correlates with increased neonatal morbidity (frequency of transfer to special care baby unit) at the extremes of birthweight [3]. The cohort was divided into low (less than 5th centile) normal (6–89th centile) and high (more than 90th centile) birthweight babies. The frequency of maternal *KIR AA* genotype + fetal *HLA-C2* is increased in the small babies. Presence of maternal *KIR2DS1* and fetal *HLA-C2* is associated with increased birthweight. (b) Proposed model for maternal KIR/fetal HLA-C interactions at the site of placentation. In this model, the fetus has inherited a paternal *HLA-C2* allele and is homozygous for *HLA-C2*. If the mother has a *KIR AA* genotype, then *KIR2DL1* binds strongly to trophoblast *HLA-C2* molecules resulting in strong inhibition of uNK cells. This is associated with defective placentation. In contrast, when the mother has a *KIR AB* or *BB* genotype, the *KIR2DL1* alleles on the B haplotype tend to inhibit uNK function more weakly when they bind C2. The *KIR B* haplotypes also contain the activating *KIR2DS1*. In this situation, uNK cells are stimulated to produce increased levels of cytokines such as GM-CSF that can enhance placentation.

10. Variation of *KIR* and *HLA-C* genes affects other diseases of pregnancy

There is other independent evidence that will substantiate this model in humans. In common with low birthweight, obstetric syndromes such as pre-eclampsia and recurrent miscarriage are associated with reduced uterine invasion by trophoblast [44]. Mothers at highest risk of these diseases are homozygous for the *KIR A* haplotype, and carry a fetus that has inherited *HLA-C2* from the father [35,37,38]. Women with a *HLA-C2* fetus are protected from these disorders by the *KIR B* haplotype that contributes to protection in two possible ways. Firstly, many *KIR B* haplotypes include the activating *KIR2DS1* that enhances trophoblast migration through enhanced secretion of ‘pro-invasion’ cytokines as described above. Secondly, the commonest *KIR2DL1* allele on the B haplotype is *KIR2DL1*004*. This binds more weakly to

HLA-C2 than *KIR2DL1*003*, the most common allele on the A haplotype [45]. We predict that there would be reduced inhibition of uNK cells by *KIR2DL1*004* on the *KIR B* haplotype. The fact that diverse GOS with a common underlying pathology of reduced trophoblast invasion also exhibit a similar *KIR/HLA-C* risk profile, supports the idea that uNK/trophoblast interactions play an important role in all these pregnancy disorders.

If *KIR AA* and *HLA-C2* combinations are significantly disadvantageous in pregnancy, this raises the question as to why they have not been eliminated from human populations by natural selection. All populations have both *KIR A* and *KIR B* haplotypes and *HLA-C* alleles with both C1 and C2 epitopes, suggesting that a balance of *KIR A* and *B* haplotypes and their ligands is essential for the survival of a community [46]. However, different populations across the world have different frequencies of *KIR AA* genotypes and *HLA-C2*

alleles. Evidence that there is strong selective pressure from reproduction comes from the inverse correlation between *KIR AA* and *HLA-C2* frequencies [37,47].

11. Pregnancy in African women

There are a few populations that do not fit this picture as they have high frequencies of both *KIR AA* genotypes and *HLA-C2* alleles. Notably, these are all found in sub-Saharan Africa where high *HLA-C2* frequencies are characteristic. Sub-Saharan Africa is especially important in consideration of reproduction and birth, as maternal mortality rates are the highest in the world. Figures of 600/100 000 births compared with only approximately 15 in high-income countries mean this is one of the most extreme disparities in any health outcome [48,49]. Obviously, poverty and lack of access to medical care are major problems but there are several indications that pregnancy and parturition in women from sub-Saharan Africa have many different features compared with women in other parts of the world [50]. Indeed, it appears that the Obstetric Dilemma is more of a problem for African women. Although there are no reliable records from Africa itself, studies of women of recent African ancestry in Europe and the Americas all indicate that all the GOS (pre-eclampsia, stillbirth, FGR and prematurity) occur more commonly as would be predicted by the high prevalence of *HLA-C2* combined with *KIR AA* genotypes in these African populations [51]. One explanation for maintenance of these 'reproductively risky' genotypes is the observation that an individual's resistance to infections such as hepatitis C virus is correlated with a *KIR AA* genotype and *HLA-C1* [52]. A simple model would be that human populations must maintain the *KIR A* haplotype and *HLA-C1* in order to ensure resistance to pathogens. By contrast, reproductive success and the development of the larger human brain and more robust progeny are dependent on maintenance of *KIR B* haplotypes and *HLA-C2*. In each human population, the relative frequencies of these haplotypes will be subject to natural selection depending on pathogen load, reproductive pressure and of course will change with time [12]. The fact that all human populations maintain both *KIR A* and *B* haplotypes as well as *HLA-C1* and *-C2*, suggests that populations that lose one of these components are doomed to extinction when subjected to extreme selection by events such as infection, famine and warfare.

While the factors responsible for the high incidence of *HLA-C2* and the *KIR A* haplotype in current African populations are not yet clear, this undoubtedly contributes to the high frequency of pre-eclampsia, stillbirth and FGR found in sub-Saharan Africa. It is interesting to note that in such populations there is also an increased frequency of obstructed labour [50]. This may be connected to the bony pelvis as measurements obtained by pelvimetry indicate that in African women some aspects of the birth canal are smaller [53]. A high

frequency of *HLA-C2* and the *KIR A* haplotype may therefore reflect selection to reduce the birthweight, but this will also result in an increased risk of the GOS. In keeping with this, the development of the fetal organs is accelerated and the gestational age is shorter at 38 compared with 40 weeks [50,54]. This clearly illustrates how the complex selective pressures acting on the evolution of the *KIR/HLA-C* system could regulate human reproductive fitness, brain size, pathogen resistance and even the rate of fetal development.

12. Conclusion

The adaptations of the pelvis associated with bipedalism coupled with the larger human brain, severely limit human birthweight. Conversely, neonatal survival of smaller babies is greatly reduced. Human birthweight is thus subject to stabilizing selection. Although the control of birthweight is complex, adequate placentation to permit access to nutrients in maternal blood is essential for normal fetal growth. In humans, this is achieved by trophoblast cells, which remodel maternal spiral arteries. Inadequate trophoblast invasion is associated with obstetric syndromes, including pre-eclampsia, recurrent miscarriage and FGR. We have shown that recognition of *HLA-C* on invading trophoblast by *KIR* receptors on maternal uNK plays a role in controlling trophoblast invasion and hence birthweight. Because both *KIR* and *HLA-C* genes are highly polymorphic, each pregnancy will bring together different combinations of maternal activating or inhibitory *KIR* that can recognize fetal *HLA-C*. Our findings suggest that binding of strongly inhibitory *KIR* to *HLA-C2* expressed on trophoblast is detrimental to placentation. This combination is found more frequently in small babies. The presence of maternal activating receptor *KIR2DS1* together with fetal *HLA-C2* is associated with increased birthweight, suggesting the activation of uNK favours placentation. The association is strongest when a fetal *HLA-C2* allele is inherited from the father. These findings suggest that a balance of maternal activating and inhibitory *KIR* and *HLA-C2* genotype frequencies act to maintain birthweight at an optimum for maternal and fetal survival.

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References

1. Karn MN, Penrose LS. 1951 Birth weight and gestation time in relation to maternal age, parity and infant survival. *Ann. Eugen.* **16**, 147–164. (doi:10.1111/j.1469-1809.1951.tb02469.x)
2. Cavalli-Sforza LL, Bodmer WF. 1971 *The genetics of human populations*, pp. 612–613. San Francisco, CA: W. H. Freeman and Company.
3. Hiby SE, Apps R, Chazara O, Farrell LE, Magnus P, Trogstad L, Gjessing HK, Carrington M, Moffett A. 2014 Maternal *KIR* in combination with paternal *HLA-C2* regulate human birth weight. *J. Immunol.* **192**, 5069–5073. (doi:10.4049/jimmunol.1400577)
4. Burton GJ, Woods AW, Jauniaux E, Kingdom JC. 2009 Rheological and physiological consequences of

- conversion of the maternal spiral arteries for uteroplacental blood flow during human pregnancy. *Placenta* **30**, 473–482. (doi:10.1016/j.placenta.2009.02.009)
5. Moffett-King A. 2002 Natural killer cells and pregnancy. *Nat. Rev. Immunol.* **2**, 656–663. (doi:10.1038/nri886)
 6. Brosens I, Pijnenborg R, Vercruyse L, Romero R. 2011 The ‘Great Obstetrical Syndromes’ are associated with disorders of deep placentation. *Am. J. Obstet. Gynecol.* **204**, 3193–3201. (doi:10.1016/j.ajog.2010.08.009)
 7. Wittman AB, Wall LL. 2007 The evolutionary origins of obstructed labor: bipedalism, encephalization, and the human obstetric dilemma. *Obstet. Gynecol. Surv.* **62**, 739–748. (doi:10.1097/01.ogx.0000286584.04310.5c)
 8. Schwartz N, Quant HS, Sammel MD, Parry S. 2014 Macrosomia has its roots in early placental development. *Placenta* **35**, 684–690. (doi:10.1016/j.placenta.2014.06.373)
 9. Weaver TD, Hublin JJ. 2009 Neandertal birth canal shape and the evolution of human childbirth. *Proc. Natl Acad. Sci. USA* **106**, 8151–8156. (doi:10.1073/pnas.0812554106)
 10. Abitbol MM. 1996 *Birth and human evolution: anatomical and obstetrical mechanics in primates*, pp. 8–18. Westport, CT: Bergin & Garvey.
 11. Carter AM, Pijnenborg R. 2011 Evolution of invasive placentation with special reference to non-human primates. *Best Pract. Res. Clin. Obstet. Gynaecol.* **25**, 249–257. (doi:10.1016/j.bpobgyn.2010.10.010)
 12. Parham P, Moffett A. 2013 Variable NK cell receptors and their MHC class I ligands in immunity, reproduction and human evolution. *Nat. Rev. Immunol.* **13**, 133–144. (doi:10.1038/nri3370)
 13. Coqueugniot H, Hublin JJ. 2012 Age-related changes of digital endocranial volume during human ontogeny: results from an osteological reference collection. *Am. J. Phys. Anthropol.* **147**, 312–318. (doi:10.1002/ajpa.21655)
 14. Hannon T, Innes BA, Lash GE, Bulmer JN, Robson SC. 2012 Effects of local decidua on trophoblast invasion and spiral artery remodeling in focal placenta creta—an immunohistochemical study. *Placenta* **33**, 998–1004. (doi:10.1016/j.placenta.2012.09.004)
 15. Colucci F, Boulenouar S, Kieckbusch J, Moffett A. 2011 How does variability of immune system genes affect placentation? *Placenta* **32**, 539–545. (doi:10.1016/j.placenta.2011.05.001)
 16. Moffett A, Colucci F. 2014 Uterine NK cells: active regulators at the maternal–fetal interface. *J. Clin. Invest.* **124**, 1872–1879. (doi:10.1172/JCI68107)
 17. Abalos E, Cuesta C, Carroli G, Qureshi Z, Widmer M, Vogel JP, Souza JP. 2014 Pre-eclampsia, eclampsia and adverse maternal and perinatal outcomes: a secondary analysis of the World Health Organization Multicountry Survey on Maternal and Newborn Health. *BJOG* **121**(Suppl. 1), 14–24. (doi:10.1111/1471-0528.12629)
 18. Li DK, Wi S. 2000 Changing paternity and the risk of preeclampsia/eclampsia in the subsequent pregnancy. *Am. J. Epidemiol.* **151**, 57–62. (doi:10.1093/oxfordjournals.aje.a010122)
 19. Esplin MS, Fausett MB, Fraser A, Kerber R, Mineau G, Carrillo J, Varner MW. 2001 Paternal and maternal components of the predisposition to preeclampsia. *N. Engl. J. Med.* **344**, 867–872. (doi:10.1056/NEJM200103223441201)
 20. Magnus P, Gjessing HK, Skrondal A, Skjaerven R. 2001 Paternal contribution to birth weight. *J. Epidemiol. Community Health* **55**, 873–877. (doi:10.1136/jech.55.12.873)
 21. Rice F, Thapar A. 2010 Estimating the relative contributions of maternal genetic, paternal genetic and intrauterine factors to offspring birth weight and head circumference. *Early Hum. Dev.* **86**, 425–432. (doi:10.1016/j.earlhumdev.2010.05.021)
 22. Billingham RE, Brent L, Medawar PB. 1953 Actively acquired tolerance of foreign cells. *Nature* **172**, 603–606. (doi:10.1038/172603a0)
 23. van Kampen CA, Versteeg-vd Voort Maarschalk MF, Langerak-Langerak J, Roelen DL, Claas FH. 2002 Kinetics of the pregnancy-induced humoral and cellular immune response against the paternal HLA class I antigens of the child. *Hum. Immunol.* **63**, 452–458. (doi:10.1016/S0198-8859(02)00396-8)
 24. Lissauer D, Piper K, Goodyear O, Kilby MD, Moss PA. 2012 Fetal-specific CD8+ cytotoxic T cell responses develop during normal human pregnancy and exhibit broad functional capacity. *J. Immunol.* **189**, 1072–1080. (doi:10.4049/jimmunol.1200544)
 25. Apps R, Murphy SP, Fernando R, Gardner L, Ahad T, Moffett A. 2009 Human leucocyte antigen (HLA) expression of primary trophoblast cells and placental cell lines, determined using single antigen beads to characterize allotype specificities of anti-HLA antibodies. *Immunology* **127**, 26–39. (doi:10.1111/j.1365-2567.2008.03019.x)
 26. Tilburgs T, Scherjon SA, van der Mast BJ, Haasnoot GW, Versteeg-vd Voort-Maarschalk M, Roelen DL, van Rood JJ, Claas FH. 2009 Fetal-maternal HLA-C mismatch is associated with decidual T cell activation and induction of functional T regulatory cells. *J. Reprod. Immunol.* **82**, 148–157. (doi:10.1016/j.jri.2009.05.003)
 27. Littman DR, Rudensky AY. 2010 Th17 and regulatory T cells in mediating and restraining inflammation. *Cell* **140**, 845–858. (doi:10.1016/j.cell.2010.02.021)
 28. Tafuri A, Alferink J, Moller P, Hammerling GJ, Arnold B. 1995 T cell awareness of paternal alloantigens during pregnancy. *Science* **270**, 630–633. (doi:10.1126/science.270.5236.630)
 29. Erlebacher A, Vencato D, Price KA, Zhang D, Glimcher LH. 2007 Constraints in antigen presentation severely restrict T cell recognition of the allogeneic fetus. *J. Clin. Invest.* **117**, 1399–1411. (doi:10.1172/JCI28214)
 30. Madeja Z, Yadi H, Apps R, Boulenouar S, Roper SJ, Gardner L, Moffett A, Colucci F, Hemberger M. 2011 Paternal MHC expression on mouse trophoblast affects uterine vascularization and fetal growth. *Proc. Natl Acad. Sci. USA* **108**, 4012–4017. (doi:10.1073/pnas.1005342108)
 31. Aluvihare VR, Kallikourdis M, Betz AG. 2004 Regulatory T cells mediate maternal tolerance to the fetus. *Nat. Immunol.* **5**, 266–271. (doi:10.1038/ni1037)
 32. Nancy P, Erlebacher A. 2014 T cell behavior at the maternal–fetal interface. *Int. J. Dev. Biol.* **58**, 189–198. (doi:10.1387/ijdb.140054ae)
 33. Koopman LA *et al.* 2003 Human decidual natural killer cells are a unique NK cell subset with immunomodulatory potential. *J. Exp. Med.* **198**, 1201–1212. (doi:10.1084/jem.20030305)
 34. Hanna J *et al.* 2006 Decidual NK cells regulate key developmental processes at the human fetal–maternal interface. *Nat. Med.* **12**, 1065–1074. (doi:10.1038/nm1452)
 35. Hiby SE *et al.* 2010 Maternal activating KIRs protect against human reproductive failure mediated by fetal HLA-C2. *J. Clin. Invest.* **120**, 4102–4110. (doi:10.1172/JCI43998)
 36. Parham P. 2005 MHC class I molecules and KIRs in human history, health and survival. *Nat. Rev. Immunol.* **5**, 201–214. (doi:10.1038/nri1570)
 37. Hiby SE, Walker JJ, O’Shaughnessy KM, Redman CW, Carrington M, Trowsdale J, Moffett A. 2004 Combinations of maternal KIR and fetal HLA-C genes influence the risk of preeclampsia and reproductive success. *J. Exp. Med.* **200**, 957–965. (doi:10.1084/jem.20041214)
 38. Hiby SE, Regan L, Lo W, Farrell L, Carrington M, Moffett A. 2008 Association of maternal killer-cell immunoglobulin-like receptors and parental HLA-C genotypes with recurrent miscarriage. *Hum. Reprod.* **23**, 972–976. (doi:10.1093/humrep/den011)
 39. Hilton HG *et al.* 2012 Mutation at positively selected positions in the binding site for HLA-C shows that KIR2DL1 is a more refined but less adaptable NK cell receptor than KIR2DL3. *J. Immunol.* **189**, 1418–1430. (doi:10.4049/jimmunol.1100431)
 40. King A *et al.* 2000 HLA-E is expressed on trophoblast and interacts with CD94/NDG2 receptors on decidual NK cells. *Eur. J. Immunol.* **30**, 1623–1631. (doi:10.1002/1521-4141(200006)30:6<1623::AID-IMMU1623>>3.0.CO;2-M)
 41. Kopcow HD, Allan DS, Chen X, Rybalov B, Andzelm MM, Ge B, Strominger JL. 2005 Human decidual NK cells form immature activating synapses and are not cytotoxic. *Proc. Natl Acad. Sci. USA* **102**, 15 563–15 568. (doi:10.1073/pnas.0507835102)
 42. Xiong S *et al.* 2013 Maternal uterine NK cell-activating receptor KIR2DS1 enhances placentation. *J. Clin. Invest.* **123**, 4264–4272. (doi:10.1172/JCI68991)
 43. Kieckbusch J, Gaynor LM, Moffett A, Colucci F. 2014 MHC-dependent inhibition of uterine NK cells impedes fetal growth and decidual vascular remodelling. *Nat. Commun.* **5**, 3359. (doi:10.1038/ncomms4359)
 44. Pijnenborg R, Vercruyse L, Brosens I. 2011 Deep placentation. *Best Pract. Res. Clin. Obstet. Gynaecol.* **25**, 273–285. (doi:10.1016/j.bpobgyn.2010.10.009)
 45. Bari R, Bell T, Leung WH, Vong QP, Chan WK, Das Gupta N, Holladay M, Rooney B, Leung W. 2009 Significant functional heterogeneity among KIR2DL1 alleles and a pivotal role of arginine 245. *Blood*

- 114, 5182–5190. (doi:10.1182/blood-2009-07-231977)
46. Gendzekhadze K, Norman PJ, Abi-Rached L, Graef T, Moesta AK, Layrisse Z, Parham P. 2009 Co-evolution of KIR2DL3 with HLA-C in a human population retaining minimal essential diversity of KIR and HLA class I ligands. *Proc. Natl Acad. Sci. USA* **106**, 18 692–18 697. (doi:10.1073/pnas.0906051106)
 47. Single RM, Martin MP, Gao X, Meyer D, Yeager M, Kidd JR, Kidd KK, Carrington M. 2007 Global diversity and evidence for coevolution of KIR and HLA. *Nat. Genet.* **39**, 1114–1119. (doi:10.1038/ng2077)
 48. Khan KS, Wojdyla D, Say L, Gülmezoglu AM, Van Look PF. 2006 WHO analysis of causes of maternal death: a systematic review. *Lancet* **367**, 1066–1074. (doi:10.1016/S0140-6736(06)68397-9)
 49. World Health Organization. 2010 *World Health maternal mortality: 1990 to 2008*. Geneva, Switzerland: WHO.
 50. Nakimuli A, Chazara O, Byamugisha J, Elliott AM, Kaleebu P, Mirembe F, Moffett A. 2014 Pregnancy, parturition and preeclampsia in women of African ancestry. *Am. J. Obstet. Gynecol.* **210**, 510–520.e1. (doi:10.1016/j.ajog.2013.10.879)
 51. Nakimuli A *et al.* 2013 Killer cell immunoglobulin-like receptor (KIR) genes and their HLA-C ligands in a Ugandan population. *Immunogenetics* **65**, 765–775. (doi:10.1007/s00251-013-0724-7)
 52. Khakoo SI *et al.* 2004 HLA and NK cell inhibitory receptor genes in resolving hepatitis C virus infection. *Science* **305**, 872–874. (doi:10.1126/science.1097670)
 53. Handa VL, Lockhart ME, Fielding JR, Bradley CS, Brubaker L, Cundiff GW, Ye W, Richter HE, Pelvic Floor Disorders Network. 2008 Racial differences in pelvic anatomy by magnetic resonance imaging. *Obstet. Gynecol.* **111**, 914–920. (doi:10.1097/AOG.0b013e318169ce03)
 54. Patel RR, Steer P, Doyle P, Little MP, Elliott P. 2004 Does gestation vary by ethnic group? A London-based study of over 122 000 pregnancies with spontaneous onset of labour. *Int. J. Epidemiol.* **33**, 107–113. (doi:10.1093/ije/dyg238)