REVIEW

Uterine natural killer cells: Time for a re-appraisal? [version 1; peer review: 2 approved]

Judith N. Bulmer¹, Gendie E. Lash²

¹Institute of Cellular Medicine, Newcastle University, William Leech Building, Medical School, Framlington Place, Newcastle upon Tyne, NE2 4HH, UK
²Guangzhou Institute of Pediatrics, Guangzhou Women and Children's Medical Center, 9 Jinsui Road, Guangzhou, Guangdong, 510623, China

Abstract
The presence of unusual natural killer cells in human endometrium has been recognized for 30 years, but despite considerable research effort, the in vivo role of uterine natural killer (uNK) cells in both normal and pathological pregnancy remains uncertain. uNK cells may differentiate from precursors present in endometrium, but migration from peripheral blood in response to chemokine stimuli with in situ modification to a uNK cell phenotype is also possible. uNK cells produce a wide range of secretory products with diverse effects on trophoblast and spiral arteries which may play an important role in implantation and early placentation. Interactions with other decidual cell populations are also becoming clear. Recent evidence has demonstrated subpopulations of uNK cells and the presence of other innate lymphoid cell populations in decidua which may refine future approaches to investigation of the role of uNK cells in human pregnancy.

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uterine natural killer cell, uNK cell, human pregnancy, decidua
Corresponding author: Judith N. Bulmer (j.n.bulmer@ncl.ac.uk)

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Introduction
Granulated cells were recognized in endometrial stroma almost a century ago, but despite light and electron microscopic evidence for a lymphocyte origin in humans, mouse, and rat, they were regarded as stromal cells until identified as unusual natural killer (NK) cells using monoclonal antibodies. The term uterine NK (uNK) cell has been commonly adopted, although “decidual NK cell” and “endometrial NK cell” are also used to reflect their presence only in endometrium. uNK cells, characterized as CD45^−CD56^brightCD16^−CD9^+CD10^+ cells, increase in number in luteal phase endometrium and early pregnancy decidua. A substantial number remain in late pregnancy and early pregnancy decidua; although fewer have cytoplasmic granules, explaining why early studies relying on identifying cytoplasmic granules reported their virtual absence at full term. This distribution suggests a role in pregnancy and this has been the focus of studies over the last 30 years.

Despite suggestions of a detrimental role of NK cells in early pregnancy failure, uNK cells are considered to be a positive force for healthy pregnancy, although their precise role remains uncertain. The recent identification of molecularly distinct uNK cell subgroups and other innate lymphoid cells (ILCs) in human decidua suggests that a re-appraisal may be timely. The aim of this review is to provide a brief overview of views on the origin and function of uNK cells that have developed over the last 30 years and consider future directions.

Origin of uterine natural killer cells
There is no consensus regarding the origin of uNK cells; their gene expression patterns differ from those of peripheral blood NK (pbNK) cells, but whether they differentiate locally or are recruited to endometrium (or both) is uncertain. Hematopoietic precursor cells (HPCs) have been reported in non-pregnant endometrium and early pregnancy decidua at a frequency of 0.1% to 4%. HPCs purified from decidua and cultured in decidual stromal cell (DSC)-conditioned medium or various cytokine combinations produced CD56^brightCD16^−CD9^+ uNK-like cells. Additional evidence for local differentiation comes from detection of increased CD56^+ uNK cells in human proliferative endometrium transplanted into non-obese diabetic/severe combined immunodeficiency (NOD/SCID) immunodeficient mice subjected to menstrual cycle-mimicking hormone treatment. In contrast, Male et al. did not detect HPCs in non-pregnant endometrium and suggested the possibility of local differentiation from stage 3 immature NK cells, although the cells detected in these studies express markers that are characteristic of type 3 ILCs and produce interleukin-22. Human endometrium produces several factors implicating in NK cell differentiation, including IL-15, IL-7, Flt3L, SCF (KL), and transforming growth factor beta 1 (TGFβ1), many of which are increased in the luteal phase and early pregnancy.

Rather than differentiation from HPCs, it is possible that locally secreted chemokines/cytokines could attract pbNK cells to endometrium and also mediate further local differentiation. Purified CD16^−CD9^+ pbNK cells converted into CD16^−CD9^+ uNK-like cells after culture with DSC-conditioned medium or TGFβ1, and a uNK cell-type phenotype (CD56^brightCD16^−CD9^+KIR^+VEGF-A producing, low cytotoxicity) was induced by exposure of pbNK cells to hypoxia, TGFβ1, and demethylating agents. DSCs produce chemokine-implanted in recruitment of pbNK cells to endometrium, including C-X-C motif chemokine 10 (CXCL10), CXCL12, CX3CL1, and chemerin, and compared with non-pregnant and male cells, pbNK cells from pregnant women have increased ability to migrate through DSCs. Furthermore, pbNK cells acquire a uNK cell-type chemokine receptor pattern after co-culture with DSCs. NK cell populations could also be recruited into endometrium in pregnancy in response to trophoblast.

uNK cells consistently localize to areas of stromal decidualization, including progesterone-treated endometrium, intrauterine decidua in ectopic pregnancy, and extrauterine decidua in normal pregnancy. This indicates a role for DSCs in uNK cell differentiation or recruitment (or both) and clearly demonstrates that they are not (all) dependent on trophoblast. It seems likely that both recruitment from blood and local differentiation play a role but perhaps with different contributions in non-pregnant and pregnant endometrium. A developing population is suggested by phenotypic differences with increasing gestation, and there is reduced expression of HLA-C–specific killer immunoglobulin-like receptors (KIRs) from 6 to 12 weeks, increased NKGD2 expression from 8 to 12 weeks, increased expression of NKp80 and NKGD2, and a population with reduced CD56 brightness in second (13 to 20 weeks) compared with first (6 to 12 weeks) trimester of pregnancy. Functional changes may also reflect an evolving population. Altered cytokine/growth factor expression and differing effects on trophoblast invasion have been reported in CD56^− uNK cells from 8 to 10 compared with 12 to 14 weeks of gestational age, and a reduced proportion of cells expressing granzyme and perforin, reduced CD56^− cells in proximity to extravillous trophoblast (EVT), and altered interactions with HTR-8/SVneo trophoblast-like cells have been reported in the second compared with the first trimester of pregnancy. These phenotypic and functional variations reflect further local differentiation of immature NK cells or recruitment and further differentiation of additional populations from peripheral blood. CD56^− cells also proliferate in endometrium, and the highest expression of the proliferation marker Ki67 is in the mid/late luteal phase and this could account for phenotypic differences as the menstrual cycle and pregnancy progress. The biological significance of the phenotypic and functional changes related to gestational age is not known. In addition, whether any altered decidual NK cell populations in pathological pregnancy represent alteration of a resident uNK cell population or recruitment of an additional population has not been established.

Interaction with trophoblast
uNK cells express a range of receptors, including KIRs and leukocyte immunoglobulin-like receptors (LILRs) that can recognize HLA-E, HLA-G, and HLA-C, which are expressed by EVT. uNK cell expression of these receptors differs from that of pbNK cells and is biased toward HLA-E and HLA-C1.
There were early suggestions that uNK cells may limit EVT invasion by cytotoxicity, and some studies have suggested that uNK cells are capable of cytotoxic activity. Co-culture of IL-2–activated CD56+ decidual NK cells with an EVT-like cell line HTR-8/SV40neo led to granulolysin accumulation in the EVT cells, and transfection of granulolysin into HTR-8/SC40neo cells induced their apoptosis. Furthermore, a more recent study detected cytotoxic activity by IL-2–stimulated CD56+ cells (>90% purity) from early pregnancy decidualia against both cytotrophoblast and the NK target K562, an activity that was inhibited by decidual macrophages. Nevertheless, in most studies, uNK cells have been poorly cytotoxic to both classic NK cell targets and trophoblast, and the consensus is that uNK cells are not cytotoxic in healthy pregnancy. uNK cells can acquire cytotoxic ability when decidualia is infected by pathogens such as cytomegalovirus and toxoplasma, suggesting a possible role in protection against infection.

There are many reports of cytokine, chemokine, and growth factor production by uNK cells, mainly at a gestational age of 8 to 14 weeks, when trophoblast invasion and spiral artery remodeling are maximal; a summary is given in Table 1 but the list is not exhaustive. Several different approaches have been used for tissue disaggregation, uNK cell purification, and mechanisms and durations of cell activation; this may explain the variation between different studies.

Given the phenotypic changes, it is not surprising that the uNK cell secretome varies with gestational age. uNK cell production of IL-1β, IL-6, CXCL8, granulocyte-macrophage colony-stimulating factor (GM-CSF), and interferon-gamma (IFNγ) was increased at 12 to 14 weeks compared with 8 to 10 weeks of gestation, whereas angiopoietin 2 (Ang2) and vascular endothelial growth factor-C (VEGF-C) secretion were higher at the earlier gestational age. Increased cytokine levels at 12 to 14 weeks may tie in with reports that interactions between pbNK cells and soluble HLA-G induce a pro-inflammatory/pro-angiogenic senescence-associated secretory phenotype with increased secretion of, among others, IL-1β, IL-6, and CXCL8, although this has not been demonstrated for uNK cells. uNK cell secretory products are also altered by trophoblast; uNK cell secretion of Ang1, VEGF-C, IL-6, CXCL8, and TGFβ1 were reduced by coculture with EVT and cytotrophoblast. In contrast, increased IFNγ mRNA was reported after incubation of uNK cells with cytotrophoblast. Interaction of HLA-C (expressed by EVT) with the activating receptors KIR2DS1 and KIR2DS4 expressed by uNK cells stimulates their production of cytokines, including GM-CSF, which can stimulate trophoblast invasion in vitro. Furthermore, a recent study demonstrated that, when co-cultured with EVT, a subset of uNK cells (CD49a/Eomes+) secrete growth-promoting factors, including pleiotrophin and osteoglycin; this effect is stimulated by HLA-G/ILT2 crosstalk.

Among other chemokines and growth factors, uNK cells stimulate trophoblast invasion by production of CXCL8 and CXCL10, although decidual CD3+ T cells, which produce higher levels of CXCL8, did not stimulate EVT invasion. Other cytokines produced by uNK cells, such as tumor necrosis factor alpha (TNFα) and IFNγ, inhibit invasion of EVT cells by various mechanisms, including trophoblast apoptosis, inhibition of proliferation, and reduced matrix metalloproteinase (MMP) production. The effect of uNK cells on EVT invasion may also depend on gestational age; in keeping with increased production of cytokines such as CXCL8, uNK cell supernatants at 12 to 14 weeks of gestation stimulated trophoblast invasion, whereas those at 8 to 10 weeks had no effect. In contrast, others have reported reduced trophoblast migration from villous explants co-cultured with decidual CD56+ cells, and the effect was mediated by IFNγ.

uNK cells have a complex array of secretory products which may alter with different approaches to purification and activation. Despite the many and varied reports, the in vivo relevance of these studies remains unclear. Examination of any one cytokine is unlikely to reflect its importance in vivo, which may vary with gestational age; for example, a role in spiral artery remodeling may shift in later gestation to promoting trophoblast invasion. In regard to the role of uNK cells in the regulation of trophoblast invasion, it is important to remember that the cells are confined to decidua/endometrium, whereas even in the first trimester of normal pregnancy, interstitial trophoblast invades into inner myometrium. Trophoblast also invades into myometrium in placenta accreta spectrum disorders, in which decidua (and uNK cells) are absent. Therefore, other factors, including the inherent invasive capacity of EVT following epithelial–mesenchymal transition and other maternal cell populations, must play a role.

**Interaction with spiral arteries**

Remodeling of spiral arteries in decidua basalis and underlying superficial myometrium is essential for healthy pregnancy and it is now accepted that, in addition to trophoblast, maternal uterine cells play a role, although the presence of trophoblast may be required for the uNK cell effect. Morphological changes in spiral arteries and arterioles in luteal phase endometrium and intrauterine decidua in ectopic pregnancy also suggest a trophoblast-independent effect.

uNK cells from decidua of 8 to 10 weeks, but not 12 to 14 weeks, of gestation can induce separation of vascular smooth muscle...
| Publication | Cytokines, chemokines, and growth factors detected | Cell preparation | Conditions |
|------------|-----------------------------------------------|----------------|------------|
| El Costa et al. | IFN, TNF, MIP-1α, GM-CSF | MACS-negative selection, >96% CD3−CD56+ | 8–12 weeks |
| Higuma-Myojo et al. | TGF, minor populations of CD56+ cells producing other cytokines | Ficoll, flow cytometry | 6–12 weeks |
| Lash et al. | Ang1, Ang2, PDGF-BB (low), KGF (low), ICAM-1 (low), VEGF-C, PGE2, TGF, EGF, VEGF, | MACS-positive selection, >95% CD56+ | 8–10 weeks, 12–14 weeks |
| Lash et al. | IL-1β, IL-4, IL-6, IL-8, IL-10, IL-13, GM-CSF, IFNγ, RANTES, TNFα | MACS-positive selection >95% CD56+ | 8–10 weeks, 12–14 weeks |
| Hanna et al. | CXCL8 (IL-8), CXCL10 (IP-10), CCL5 (RANTES), CCL22 | Flow cytometry cell sorting, >99% CD56 bright CD16−CD3− | First trimester |
| Sotnikova et al. | IFNγ | Dynabeads-positive selection | 7–10 weeks |
| Engert et al. | GRO, MCP-1, IL-309, RANTES, IL-8, IL-10, IL-12, TNFα, IL-2, TPO, M-CSF, ENA, angiogenin, IL-1α, IL-4, IL-12p40p70, IFNγ, SCF, SDF-1, MCP-2 (detected in >50% samples) | MACS, >90% pure | 7–8 weeks |
| Saito et al. | G-CSF, GM-CSF, M-CSF, TNFα, INFγ, IL-1α, IL-2, IL-4, IL-6, IL-8, IL-10, IL-12, TNFα, IL-15, SCF | Flow cytometry sorting | Flow-culture with EVT |
| Frasier et al. | CXCL10, IL-8, CXCL10, IL-1β, IL-18, TNFα, I-309, RANTES, IL-8, IL-10, IL-12, IFNγ, IL-15, SCF | MACS-negative selection, >90% CD56+ | 7–9 weeks |
| Wallace et al. | Angiogenin, sIL2-R, endostatin, PlGF, IL-1RA, MIG, MIP-1α, MIP-1β, RANTES, IL-15, SCF | MagCellect-negative selection, CD56+ 93.6 ± 1.3%, viability after 6 hours 84.6 ± 2.8% | 9–14 weeks |
| Kennedy et al. | GM-CSF, CCL3, CCL1, XCL1 | Flow cytometry and intracellular cytokine detection; or MACS positive selection and ELISA | First trimester |
| Chen et al. | Angiogenin, bFGF, VEGF-A, VEGFR-1, IL-1α | MACS-positive selection, 91.9% CD56+ | 1–7 non-pregnant endometrium |

**Footnotes:**
- FIC, flow cytometry
- ELISA, enzyme-linked immunosorbent assay
- ENA, epithelial neutrophil-activating protein
- EVTs, extravillous trophoblasts
- MIP, monocyte chemotactic protein
- M-CSF, macrophage colony-stimulating factor
- MIG, monokine induced by interferon-gamma
- MIP, macrophage inflammatory protein
- PDGF-BB, platelet-derived growth factor beta
- TGF, transforming growth factor, TNF, tumor necrosis factor alpha, TPO, thrombopoietin
- UPA, urokinase-type plasminogen activator
- VEGFR, vascular endothelial growth factor receptor.
cells and loss of extracellular matrix via secretion of Ang1, Ang2, VEGF-C, and IFNγ. uNK cells (and macrophages) also produce MMPs that can break down collagen in an in vitro spiral artery model. uNK cell supernatants also mediate vascular smooth muscle cell dedifferentiation and this effect is seen at 12 to 14 weeks but not 8 to 10 weeks of gestation. Other chemokines and growth factors have been implicated in the uNK cell effect on spiral arteries. For example, Choudhury et al. suggested that IL-6 and CXCL8 secreted by EVT activate secretion of C-C motif chemokine 14 (CCL14) and CXCL6 by endothelial cells which then recruit uNK cells and macrophages to spiral arteries. Both IL-6 and CXCL8 also induce dedifferentiation of vascular smooth muscle cells in a choric plate artery model.

Altered decidual leucocytes have been reported in pre-eclampsia, although results have varied, there have been reports of reduced, unchanged, and increased uNK cells compared with controls. Uterine artery Doppler studies in early pregnancy can predict women at increased risk of developing pre-eclampsia in later pregnancy; compared with post-delivery samples, these high-risk samples allow investigation when the pathogenetic lesion develops, before compensatory measures are in place, and this approach has been used to investigate uNK cell function in pregnancies at high risk of developing pre-eclampsia. uNK cells from 9- to 14-week gestational age pregnancies with abnormal Doppler wave forms showed reduced expression of KIR2DL/S1,3,5 and LILRB1, reduced stimulation of trophoblast outgrowth from villous explants, reduced in vitro induction of apoptosis in vascular smooth muscle cells and endothelial cells, increased angiogenic growth factor secretion, and reduced ability to destabilize endothelial structures. These results all suggest that uNK cells from pregnancies at increased risk of pre-eclampsia display altered effects on trophoblast invasion and spiral arteries and emphasize the likely importance of uNK cells in early pregnancy. Nevertheless, in common with trophoblast invasion, spiral artery remodeling extends into inner myometrium. CD14+ macrophages and CD3+ T cells are present in the wall and adventitia of spiral arteries in both decidua and superficial myometrium, suggesting that these cells also have a role, either alone or in collaboration with uNK cells.

Interactions with other cells

uNK cells may also interact with other cell types in non-pregnant and pregnant endometrium. uNK cells interact with CD14+ cells in decidua to produce IDO (indoleamine-2,3-dioxygenase), which induces regulatory T cells. This interaction appears to be mediated by IFNγ and TGFβ and is not seen with pbNK cells or CD14+ cells. uNK cells also form conjugates with immature dendritic cells in first-trimester decidua which can induce uNK cell proliferation and cytotoxicity. It has also been suggested that uNK cells induce apoptosis of CD209 (DC-SIGN) dendritic cells in decidua. Evidence from mouse pregnancy suggests that IL-10 secreted by uNK cells regulates dendritic cell phenotype and function, and IL-10 deficiency and dendritic cell expansion are associated with early pregnancy failure. In addition to affecting their recruitment or differentiation (or both), DSCs may affect uNK cell function; cultured first-trimester DSCs inhibited proliferation, cytotoxicity, IFNγ production, and upregulation of activation receptor expression by pbNK cells. In non-pregnant endometrium, uNK cells may clear senescent decidual cells at the end of the menstrual cycle, playing a crucial role in endometrial homeostasis.

Summary

Knowledge has increased dramatically since their recognition as unusual NK cells, but despite considerable research effort, the in vivo role of uNK cells remains unclear. Recent advances suggest that a re-appraisal may be timely. Whether uNK cell phenotype and function differ between non-pregnant and pregnant endometrium, between decidua basalis and parietalis, or at different sites within decidua (such as those related to spiral arteries) and at different gestational ages remains largely unknown. Pre-eclampsia, fetal growth restriction, and recurrent pregnancy failure have been associated with altered uNK cell numbers and function and specific KIR/HLA-C combinations but the significance of these observations is not fully established. uNK cells produce a wide range of chemokines, cytokines, growth factors, and MMPs, and many have been shown to have specific effects on trophoblast or spiral arteries, but in vivo translation is difficult. Gestational age differences in phenotype and function suggest that including samples across a range of gestational weeks in the first trimester may result in skewing of data.

The starting point for most studies of uNK cell function is decidua retrieved from pregnancy terminations or miscarriages. uNK cells within these samples have been exposed directly to EVT or to soluble HLA-G with possible functional effects. Investigations of uNK cells purified from non-pregnant endometrium are relatively infrequent, although several studies have reported increased uNK cells in luteal phase endometrium in recurrent early pregnancy failure. A recent study of uNK cells from timed luteal phase endometrium reported increased expression of angiogenin, VEGF-A, and basic fibroblast growth factor (bFGF) in women with recurrent miscarriage compared with fertile controls. Recent studies indicate that menstrual blood may act as a surrogate for endometrial NK cells and this approach may increase the scope for future studies.
Similar studies of pathological pregnancy and non-pregnant endometrium, including endometrial NK cell populations in women with recurrent early pregnancy failure, may clarify the roles of specific uNK cell subsets in pathological pregnancy. The suggestion that there are subsets of NK cells in human decidua is supported by a report of production of growth-promoting factors by CD49a+Eomes+ uNK cells via interactions with HLA-G\(^6\), as well as the demonstration of a subpopulation of “pregnancy-trained” uNK cells in repeated compared with first pregnancies, characterized by high expression of the receptors NKG2C and LILRB1 and increased IFN\(\gamma\) and VEGF-A secretion\(^8\).

Besides uNK cells, other innate lymphoid cells have been identified in human decidua\(^5\)–\(^7\), including CD56\(^{-}\)CD94\(^{+}\)– non-cytotoxic type 1 ILCs (ILC1s), CD56\(^{-}\)CD117\(^{+}\)CD127\(^{+}\) lymphoid tissue inducer (LIIT)-like cells, and CD56\(^{-}\)CD94\(^{+}\)CD117\(^{-}\)CD127\(^{-}\)NKp44\(^{+}\) type 3 ILCs (ILC3s). These ILCs may contribute to the cytokine production reported by decidual CD56\(^{+}\) cells. For example, ILC1s may contribute to IFN\(\gamma\) production, while ILC3s produce IL-22 and CXCL8, which may regulate neutrophil recruitment\(^9\). The distribution and function of the different ILC populations are still unknown, although it has been suggested that ILC3 cytokine production may be regulated by programmed cell death (PD-1) expressed by ILC3s and its ligand PD-L1 expressed by EVT\(^10\).

It is now clear that “uNK cells” are not a single population and the relative importance of these subpopulations may change as gestation progresses. ILCs in decidua may contribute to the reported cytokine production by CD56\(^{-}\) uNK cells and this may differ according to different purification and activation protocols. Abnormal function in pathological pregnancy could affect specific uNK cell subpopulations or ILCs. Rather than referring to “uNK cells”, perhaps we should dissect populations more precisely and consider the functional contribution of ILCs. Technical advances may allow localization of different subpopulations, and investigation of pathological pregnancies may provide valuable clues to function. The advent of scRNA-seq technology provides an exciting way forward to unravel the role of uNK cells in normal and pathological pregnancy, making it possible to target specific cell populations for more accurate diagnosis and potential intervention.

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