Nitric oxide (NO) is a major paracrine mediator of various biological processes, including vascular functions and inflammation. In blood vessels, NO is produced by the low-input constitutive endothelial NO synthase (eNOS) and is a potent vasodilator and platelet aggregation inhibitor. The inducible NOS isoform (iNOS) is capable of producing NO at high concentrations which have pro-inflammatory properties. Immuno-histochemical and molecular studies of endometrial NOS expression, as well as animal experiments with NOS inhibitors, indicate that NO plays an important role in endometrial functions such as endometrial receptivity, implantation and menstruation. In rodents, both iNOS and eNOS are highly up-regulated in the implantation sites, and NOS inhibitors show synergistic effects with antiprogestins in inhibiting the establishment of pregnancy. In the human endometrium, eNOS have been localized in the glandular epithelium and in endometrial microvascular endothelium, primarily during the luteal phase. iNOS has been found in the endometrial epithelium during menstruation, in immunocompetent endometrial cells, and in decidualized stromal cells. In primates, NO may be involved in the initiation and maintenance of menstrual bleeding by inducing tissue breakdown and vascular relaxation as well as by inhibiting platelet aggregation. Endometrium-derived NO may also play a role in myometrial relaxation during menstruation. These studies open up new applications for NO-donating and -inhibiting agents in uterine disorders. NO donors may be useful in the treatment of dysmenorrhoea and for promoting fertility. Antiprogestins, progesterone receptor modulators and iNOS inhibitors may find applications in the treatment and prevention of abnormal uterine bleeding.

Key words: antiprogestins/dysfunctional bleeding/implantation/nitric oxide/progesterone

Introduction

The primate endometrium is a highly specialized organ composed of different cell components, including luminal and glandular epithelium, endometrial stroma, lymphoid and non-lymphoid cells and vessels. During the reproductive age, the entire endometrium undergoes cyclic changes in order to assure optimum conditions for implantation. These changes are closely controlled by the ovarian hormones 17β-oestradiol and progesterone, which regulate, directly or indirectly, endometrial proliferation and differentiation as well as endometrial angiogenesis. If implantation does not occur, the upper part of the endometrium, the functionalis, is shed during menstruation in response to progesterone withdrawal at the end of the luteal phase. This process is accompanied by leukocyte subpopulations infiltrating the endometrium, the dissolution of the extracellular matrix, epithelial apoptosis, and dramatic vascular changes similar to inflammation (Finn, 1986). The endometrium represents a unique
Nitric oxide in implantation and menstruation
tissue with regard to vascular changes during the cycle. Cyclic changes of the endometrial blood vessels such as their damage during menstruation, neovascularization and an increase in the growth and number of blood vessels occur within a single month. During implantation, the endometrial stroma undergoes a dramatic proliferation and differentiation into a well-vascularized decidua tissue in order to provide an optimum environment for the embryo. This process is accompanied by a substantial remodelling of the extracellular matrix, intensive blood vessel growth and dilatation, similar to inflammation. However, the exact regulation of endometrial blood vessels during the menstrual cycle and implantation still remains poorly understood.

Steroid hormones may act directly on both stromal and epithelial cells, as well as on endometrial vessels (spiral arterioles) during the proliferative and luteal phases of the menstrual cycle. However, many steroid hormone effects—particularly during menstruation and implantation—are mediated by local factors, including growth factors, cytokines, chemokines, and vasoactive agents such as prostaglandins (PG), endothelin (ET), vascular endothelial growth factor (VEGF), platelet-activating factor (PAF) and nitric oxide (NO). Since NO relaxes the myometrial and vascular smooth muscles, inhibits platelet aggregation, and plays a role in inflammation, it is a strong candidate for mediating various steroid hormone and cytokine effects in the endometrium and decidua. In this brief review we aim to discuss the role of NO in controlling such endometrial functions as menstruation and implantation. We will also address the potential involvement of NO during pathological conditions such as dysfunctional uterine bleeding and dysmenorrhoea.

The nitric oxide generating system
The discovery of an endothelium-derived relaxing factor (EDRF) (Furchgott and Zawadzki, 1980), and its later identification as NO, have to be considered as one of the most exciting discoveries in medicine in the 1980s. NO is a small uncharged gas molecule that is a highly reactive free radical. Although NO has an extremely short half-life in vivo of ~4 s, it can penetrate the surrounding tissues and can activate a variety of targets, including enzymes such as guanylate cyclase, cytochrome P450 enzymes, protein kinases and phosphatases, as well as other cellular signalling pathways. Consequently, NO functions as a major mediator of numerous biological processes, including vascular homeostasis, smooth muscle relaxation and neurotransmission. NO has also been shown to inhibit platelet aggregation, stimulate angiogenesis, reduce blood pressure, and alter the function of the immune system (Ignarro, 1989; Moncada and Higgs, 1993).

NO was recently implicated as an important regulatory agent in various female reproductive processes, such as ovulation, implantation, pregnancy maintenance, labour and delivery (reviewed by Chwalisz et al., 1996; Rosselli, 1997; Cameron and Campbell, 1998). Animal studies clearly indicate that during pregnancy, NO is up-regulated in the myometrium and placenta. It contributes to uterine quiescence and controls utero-fetal-placental blood flow (Izumi et al., 1993; Sladek et al., 1993; Buhimschi et al., 1996; Liao et al., 1997). NO is also involved in cervical ripening during labour (Chwalisz et al., 1997; Chwalisz and Garfield, 1998). Moreover, these studies also indicate that the regulation of NO production in the female reproductive tract is mainly controlled by steroid hormones in a tissue-specific manner.

Nitric oxide synthases and their functions
NO is synthesized by a family of nitric oxide synthases (NOS), which are enzymes that convert the amino acid L-arginine to citrulline and NO. Thus far, three related NOS enzymes whose genes are localized on different chromosomes have been isolated and characterized. These include neuronal constitutive NOS (nNOS, b-NOS, type I), inducible NOS (iNOS, type II), and endothelial constitutive NOS (eNOS, type III) (Nathan and Qia-wen, 1994). The constitutive isoforms eNOS and nNOS were originally identified in endothelial and neuronal tissues, respectively. They require calcium/calmodulin for activation, and can rapidly and transiently produce small amounts of NO under basal conditions. The nNOS was the first NOS isoform to be isolated and studied at the molecular level (Huang et al., 1993). It can be found in neuronal tissues...
of the central and peripheral nervous systems, and is thought to act as a neurotransmitter. The eNOS-derived NO is the most important vasodilator and platelet aggregation inhibitor. It maintains a constant vasorelaxation, normal blood pressure and adequate tissue perfusion (Huang et al., 1995a).

The iNOS isoform can be induced by either interleukins (IL-1, IL-2, IL-12), tumour necrosis factor alpha (TNF-α), interferon gamma (IF-γ) or endotoxin (LPS), and produces large quantities of NO in a calcium-independent manner. NO production under the influence of iNOS occurs with a delay of 6–8 h after stimulation. However, once induced, iNOS is active for hours or even days and produces NO in 1000-fold larger quantities than the constitutive isoforms (Moncada and Higgs, 1993; Beck et al., 1999). iNOS was first identified in immune cells (macrophages), but has meanwhile also been discovered in other cells, including epithelial cells, hepatocytes, myocytes, fibroblasts, chondrocytes and bone-forming cells (osteoblasts and osteoclasts). This system also plays a pivotal role in connective tissue remodelling during acute and chronic inflammation. The binding of the nuclear factor κB (NF-κB) to DNA seems to be essential for iNOS expression by pro-inflammatory cytokines (Eberhard et al., 1998). Agents inhibiting NF-κB activation or binding have been shown to diminish the cytokine-stimulated iNOS production. Large quantities of iNOS-derived NO can kill parasites and bacteria, and it has been postulated that this pathway is the most significant in controlling the invasion of pathogens (MacMicking et al., 1995).

**Molecular targets of NO actions**

Guanylate cyclase, which triggers the formation of cyclic guanosine monophosphate (cGMP), seems to be the most relevant target of NO at low concentrations. cGMP is an important cellular messenger regulating intracellular calcium concentrations which mediate physiological functions of NO such as smooth muscle relaxation and platelet aggregation. The cGMP increase activates, in turn, at least three critically important signalling pathways, including: (i) cGMP-regulated ion channels; (ii) cGMP-regulated protein kinases; and (iii) cGMP-dependent protein kinases and phosphatases (reviewed by Beck et al., 1999). It has been shown recently that NO activates the mitogen-activated protein kinase (MAPK) cascades, the key transduction mechanisms of growth factors and cytokines involved in cellular proliferation and differentiation (Lander et al., 1996; Beck et al., 1999).

There is increasing evidence that NO can directly regulate gene expression by modulating the activity of transcription factors such as NF-κB and the activator protein 1 (AP-1) (Sen and Packer, 1996). Since NF-κB inhibits progesterone receptor (PR) action via protein–protein interaction (Kalkhoven et al., 1996), NO may, therefore, modulate progesterone responses in the reproductive tract. The list of genes under the regulatory control of NO is expanding, including those involved in extracellular matrix protein synthesis and their degrading enzymes (Chatziantoniou et al., 1998; Sasaki et al., 1998), cytokines and chemokines, such as interleukin 8 (IL-8) (Villarete and Remick, 1995). Higher concentrations of NO produced by iNOS may also directly interact with various metal-containing proteins, including matrix metalloproteinases (MMP). Indeed, NO has been shown to stimulate gelatinase activity in rat mesangial cells (Trachtman et al., 1996). Similarly, in articular chondrocytes, IL-1β-stimulated MMP-9 (92 kDa metalloproteinase) expression is mediated by NO (Tamora et al., 1996; Sasaki et al., 1998).

NO can interact with other vasoactive and angiogenic agents, including PG, ET, VEGF and PAF. It was discovered in various inflammation models that NO is a powerful inducer of the inducible cyclooxygenase 2 (COX-2), and elevates local PGE2 and PGI2 concentrations in inflamed tissues, while the inhibitors of NO synthesis block PG production during chronic and acute inflammation (Salvemini et al., 1995). On the other hand, ET after binding to ETB receptors was shown to be a potent stimulus of NO release from the vascular endothelium, suggesting the existence of a feedback mechanism between these two molecules of opposing functions (Takayanagi et al., 1991). Since the endometrium is a well-known source of PG, and ETB receptors are expressed in the glandular epithelium (Collet et al., 1996), interaction between NO, PG and ET may well be of physiological importance. NO is also involved in angiogenesis...
by modulating VEGF expression. It has recently been demonstrated that a VEGF increase in response to endothelial injury is inhibited by NO (Tsurumi et al., 1997), a mechanism which may represent a negative feed-back loop between NO and VEGF during angiogenesis. On the other hand, VEGF stimulates NO release from endothelial cells, a mechanism contributing to the vascular effects of VEGF (Papapetropoulos et al., 1997). In the endometrium, NO may also interact with PAF, a potent inflammatory lipid mediator. PAF is known to increase vascular permeability and vasodilatation in various tissues — effects which may be, at least in part, mediated by NO. PAF receptor (PAF-R) immunoreactivity and mRNA were detected in proliferative and secretory endometrium (Ahmed et al., 1998). This study also demonstrates that endometrial explants release NO in response to physiological concentrations of PAF. Interestingly, the maximum NO release was observed in endometrial tissues obtained during the late luteal phase.

Finally, at high concentrations NO plays a role in apoptotic cell death. An increased apoptosis following exogenous application of NO donors or iNOS induction has been described in different cell types, such as macrophages and mesangial cells (Brüne et al., 1998). NO-induced apoptosis was accompanied by the accumulation of the tumour suppressor protein p53 and activation of caspases (Meßmer and Brüne, 1996).

In summary, low eNOS- and nNOS-produced concentrations of NO are involved in maintaining basic physiological functions such as vascular homeostasis and neurotransmission, and generally exhibit anti-inflammatory effects. Conversely, high concentrations of NO, i.e. iNOS-derived, mediate various pro-inflammatory responses, including extracellular matrix remodelling, apoptotic cell death and tissue destruction.

**NOS regulation by steroid hormones**

It has been postulated that oestrogen is the chief hormonal factor regulating NO production in the vasculature and reproductive tract. Indeed, numerous experimental and clinical studies indicate that oestrogens stimulate vascular NO production by up-regulating eNOS and/or inhibiting superoxide anion production (Van Buren et al., 1992; Weiner et al., 1994; Hishikawa et al., 1995). In fact, the protective effects of oestrogen replacement therapy on cardiovascular disease are attributed to the up-regulation of NO production in the endothelial cells (Collins, 1996). On the other hand, oestrogen was shown to inhibit iNOS synthesis in rat vascular smooth muscle cells via oestrogen receptor activation (Zancan et al., 1999). This finding may indicate a novel anti-inflammatory mechanism of a protective oestrogen effect on cardiovascular disease by preventing excessive NO production during atherosclerosis. Oestrogen treatment is also thought to elevate NO production rapidly in various tissues of the female reproductive tract, such as the uterus (Van Buren et al., 1992; Weiner et al., 1994). In the latter, the oestrogen effects on NOS synthesis seem to be tissue-specific. Oestrogen administered to ovariectomized sheep up-regulated eNOS in the myometrium, but not in the endometrium (Figueroa and Massman, 1995). In addition NO mediates, at least in part, the oestrogen-induced uterine oedema—an acute reaction to oestrogen treatment in rodents (Chaves et al., 1993).

Previous experimental and clinical studies of myometrial, cervical and endometrial NOS expression, as well as our own functional studies with antiprogestins, clearly indicate however that progesterone also regulates NO production and NOS expression. During pregnancy, when both oestrogen and progesterone blood concentrations are elevated, progesterone may in fact be the chief hormonal factor regulating NO production in the female reproductive tract. Our previous studies in rats have shown that iNOS is the dominant NOS isoform in the pregnant uterus, cervix and placenta (Buhimschi et al., 1996; Ali et al., 1997; Purcell et al., 1997). In pregnant rats, uterine, cervical and placental iNOS expression is gestationally regulated at protein and mRNA levels, with progesterone as the key physiological regulating agent. These results are consistent with studies in mice. In this species combined oestrogen and progesterone treatment has elevated both eNOS myometrial expression and iNOS expression in the endometrial glands, the stroma and myometrium compared to treatment with oestrogen alone (Huang et al., 1995b). The effects of progesterone on uterine and...
cervical iNOS expression are, however, tissue-
dependent. Experimental studies with antiproges-
tins in rats indicate that in the uterus and placenta
progesterone up-regulates iNOS expression and
NO production, while exerting opposite effects in
the cervix (Buhimschi et al., 1996; Chwalisz et al.,

The role of progesterone in regulating NO pro-
duction in the primate uterus has been poorly
investigated to date. However, studies of eNOS
and iNOS expression in both the human and
baboon endometrium and decidua, discussed
below, suggest that progesterone may also up-
regulate uterine NO production in primates.

**NOS in the endometrium**

**Animal studies**

In the initial investigations, nicotinamide adenine
dinucleotide phosphate (NADPH)-diaphorase
activity was employed to study NOS localization
in the rat endometrium (Schmidt et al., 1992; Shew
et al., 1993). This method can, however, detect
other enzymes besides NOS. More recently, NOS
localization in the endometrium was examined via
both NADPH-diaphorase and immunohistochem-
istry. In rats, both diaphorase activity and nNOS-
like immunoreactivity was found in uterine nerves,
whereas iNOS staining was positive in macro-
phage-like cells in the vicinity of the uterine lumen
(Suburo et al., 1995). In the endometrium of
mice, iNOS immunoreactivity could be observed
in uterine epithelial cells, macrophage-like stromal
cells, mast cells and in myometrial cells (Huang
et al., 1995b). The latter study also indicates a
differential regulation of iNOS expression in uter-
ine mast and epithelial cells by ovarian steroids.
After progesterone treatment, iNOS staining was
found in endometrial epithelial cells but not in
mast cells, whereas the reverse occurred after oestro-
adiol treatment. In mice and baboons, dramatic
changes in the pattern of eNOS and iNOS expres-
sion were observed at peri-implantation. These
studies are discussed below.

**Human endometrium**

A number of recent studies have identified both
eNOS and iNOS in the human endometrium (Telfer
et al., 1995, 1997; Tseng et al., 1996; Ota et al.,
1998; Tschugguel et al., 1998, 1999; Khorram
et al., 1999; Taguchi et al., 2000). The results of
these investigations—particularly those address-
ing steroid hormone regulation—are somewhat
divergent, perhaps due to various techniques of
different sensitivities used in these studies.

Initial studies of NOS activity were carried out
in premenopausal women via NADPH-diaphorase
and Northern blot analysis (Tseng et al., 1996).
There was an increased NADPH-diaphorase activ-
ity in epithelial cells and blood vessels during the
secretory phase of the menstrual cycle. Northern
blot analysis revealed the presence of both eNOS
and iNOS mRNA in epithelial cells. In Tseng’s
study an increased expression of eNOS mRNA
was found in glandular epithelial cells obtained
from the late secretory phase, whereas iNOS
mRNA was only observed in the glandular epithe-
lium obtained during menstruation. Subsequently,
the presence of iNOS and eNOS was confirmed in
endometrial glandular epithelial cells by applying
immunohistochemistry and reverse transcriptase-
polymerase chain reaction (RT–PCR) (Telfer et al.,
1997). However, contrary to the observations by
Tseng et al., the study of Telfer and colleagues did
not reveal any cycle-dependent NOS variations,
nor any correlation between NOS expression and
menstrual blood loss. In addition, in this study
neither eNOS nor iNOS immunostaining could be
detected in stromal cells during the menstrual cycle
of non-pregnant women. Further studies employing
NADPH-diaphorase and iNOS and eNOS immuno-
histochemistry (Tschugguel et al., 1998) reported
the presence of iNOS immunoreactivity exclusively
in the secretory endometrium, whereas eNOS
immunoreactivity could be detected only in endo-
thelial cells.

The results of more recent studies provide further
evidence suggesting that eNOS may be a dominant
isoform in the non-pregnant human endometrium.
Both iNOS and eNOS expression were studied
(Western blot analysis and immunohistochemistry)
in the endometrium and myometrium of premeno-
pausal and postmenopausal women undergoing
hysterectomy for benign gynaecological reasons
(Khorram et al., 1999). This study clearly revealed
eNOS to be predominant in the human uterus.
eNOS immunostaining was localized primarily in
Nitric oxide in implantation and menstruation

the glandular epithelium and endometrial microvascular endothelium, whereas iNOS labelling was detectable only in occasional specimens obtained during the secretory phase. Western immunoblot analysis, however, showed a differential menstrual cycle-dependent eNOS expression in the endometrium and myometrium. The secretory endometrium revealed a greater eNOS expression then the proliferative endometrium. The eNOS expression pattern in the myometrium was reversed, with the up-regulation of eNOS during the proliferative phase. In postmenopausal women, hormone replacement therapy (HRT) produced an increased expression of eNOS in both the endometrium and myometrium. Similar results were obtained later when cycle-dependent eNOS immunostaining on cryostat endometrial sections was studied (Taguchi et al., 2000). Immunoreactivity for eNOS was clearly localized in various types of arterial and endothelial cells, as well as in the capillaries. Furthermore, in some samples there was positive eNOS staining in endometrial glandular epithelium. Interestingly, the number of vessels which were positively stained for eNOS increased gradually during the proliferative phase — indeed, most of the vessels were positive in the early secretory phase.

There is growing evidence, however, indicating that iNOS turns into a dominant NOS isoform at peri-menstruation and during early pregnancy. A very elegant study recently showed a six-fold increase of iNOS activity in endometrial samples obtained during menstruation compared with those from the proliferative or secretory phases, whereas the constitutive NOS enzymes remained unchanged (Tschugguel et al., 1999). In this study, a cRT-PCR reaction revealed an increase in endometrial iNOS mRNA expression during the secretory phase and during menstruation, contrary to the proliferative phase. Immunohistochemistry demonstrated intense iNOS immunostaining in epithelial cells during menstruation. The authors concluded that iNOS is highly elevated in the human endometrium during menstruation and plays a role in the signal transduction mechanisms, leading to endometrial breakdown and apoptosis. An increased iNOS immunoreactivity was previously found in decidual cells obtained from early pregnant women and those exposed to synthetic progestagen treatment (Telfer et al., 1997). This observation, which is consistent with our morphological and functional studies in mice and rats (Chwalisz et al., 1999a; Purcell et al., 1999a), suggests that decidualization may generally be accompanied by the up-regulation of iNOS. Furthermore, increased activity in superoxide dismutase (SOD), an enzyme enhancing NO actions by reducing superoxide-mediated NO inactivation, could be detected in decidual cells (Sugino et al., 1996).

In conclusion, both eNOS and iNOS have been identified in the human endometrium. Although some of the results of the studies reviewed above tend to be rather divergent, the majority of them demonstrate the presence of eNOS in the glandular and epithelial endometrium and in the endometrial microvasculature, accompanied by greater eNOS expression during the secretory phase which suggests progesterone regulation of this particular isoform. The menstrual cycle-dependent regulation of endometrial eNOS indicates that this isoform is not strictly constitutive. It may indeed be regulated by steroid hormones and may regulate endometrial glandular function and blood flow during endometrial receptivity. iNOS seems to be present in various immunocompetent endometrial cells, in decidualized stromal cells, as well as in epithelial cells during menstruation. Unfortunately, systematic studies of NOS activity and expression in women exhibiting abnormal uterine bleeding are presently not available.

**NO and the uterine immune system**

The regulation of leukocyte migration to specific targets of the female reproductive tract in response to the local production of chemokines, subsequent to the leukocyte secretion of specific paracrine factors, may be one of the ways in which key events of female reproduction such as ovulation, menstruation, implantation, cervical ripening and labour are controlled. Since NO is a major product of activated macrophages and other bone marrow-derived cells, it may mediate the pro-inflammatory effects of these cells. We suggested that infiltrating leukocytes might be the major source of NO during cervical ripening during both term and preterm labour (Chwalisz et al., 1997; Chwalisz and Garfield, 1998).
Compared with other tissues of the female reproductive tract, the endometrium is unique in this respect. It contains a large number of bone marrow-derived cells, leukocytes, which may play a pivotal role during menstruation, endometrial proliferation and differentiation, neovascularization and implantation. Normal human endometrium contains numerous leukocytes in both stromal and intra-epithelial sites, the quantity of which changes during both the menstrual cycle and pregnancy. During the follicular phase they account for approximately 5–10% of the total stromal cell population, whereas in the late luteal phase leukocytes make up 20–25% of stromal cells (Bulmer et al., 1991; Jones et al., 1998). This large increase in the endometrial leukocyte population is due to the mucosal infiltration of phenotypically unusual uterus-specific natural killer (NK) cells also called endometrial large granular lymphocytes (LGL; reviewed by King et al., 1998; see also Jones et al., 1998). Both leukocyte subtypes persist in early pregnant decidua (Loke and King, 1995). In addition, except immediately before and during menstruation, only a small number of polymorphonuclear leukocytes are present in the endometrium during the proliferative and secretory phases (Poropatich et al., 1987). Mast cells do not change in number throughout the menstrual cycle, but a dramatic mast cell activation occurs immediately before and during menstruation (Jeziorska et al., 1995). The exact function of the endometrial population of leukocytes is still unknown, although a role in the regulation of key endometrial functions, including implantation and menstruation has been previously suggested (Bulmer et al., 1991; King et al., 1998).

Moreover, the non-pregnant endometrium is also the synthesis site of multiple cytokines and chemokines, including TNF-α, IL-1 and IL-8 (Tabibzadeh, 1996), which are very potent inducers of iNOS in macrophages and other leukocytes. It is also well known that the pro-inflammatory cytokines are up-regulated in the uterus during implantation (Simón et al., 1993; Chard, 1995; Tazuke and Giudice, 1996). In the endometrium and decidua the leukocytes may in fact represent the most important source of NO during menstruation, implantation and early pregnancy. In mice, a strong iNOS expression was found in the uterine leukocytes, including mast cells, macrophage-like cells, and uterine natural killer cells during early and mid-pregnancy (Hunt et al., 1997). Similar findings were reported in rats (Sladek et al., 1998). Furthermore, progesterone is most likely an important endocrine factor controlling directly or indirectly both leukocyte infiltration and NO production in macrophages and other leukocytes. Experimental studies in mice and in-vitro studies employing RAW264.7 mouse macrophages clearly indicate that, despite the absence of detectable PR mRNA, progesterone down-regulates NO production and iNOS mRNA expression in uterine macrophages (Miller and Hunt, 1996; Hunt et al., 1998). Recently, in an in-vivo model of progesterone withdrawal and maintenance in women, there was evidence indicating that progesterone withdrawal is a signal for an influx of macrophages and LGL into the endometrium (Critchley et al., 1999). This study also showed an up-regulation of various pro-inflammatory mediators, including IL-8 and COX-2 in the endometrium in response to progesterone withdrawal.

Role of NO during implantation

In all mammals, the endometrium is receptive to blastocyst implantation only during a specific period after ovulation. This stage of the luteal phase is called ‘implantation window’ (Chang, 1950; McLaren, 1973; Psychoyos, 1973). During early pregnancy under the influence of progesterone (humans) and both progesterone and embryonic signals (rodents), the endometrial strata undergoes a dramatic differentiation into the decidua, a specialized, well-vascularized tissue that encapsulates the developing embryo (Schlafke and Enders, 1975). Decidual cells are believed to play a key role in providing nutrients to the embryo, and in controlling the trophoblast invasion (Parr and Parr, 1989; Loke and King, 1995). A localized increase in endometrial vascular permeability seems to be the first sign of impending implantation in all mammals studied to date, including humans (reviewed by Rogers, 1996). In rodents, the decidual cell reaction occurs in response to either blastocysts or artificial stimuli, and is always preceded by an increase in endometrial vascular
Nitric oxide in implantation and menstruation

permeability which is normally initiated at the antimesometrial sites where blastocysts implant (Psychoyos, 1973). Similarly, in humans an adequate uterine blood supply is essential for embryo development, and an impaired blood flow to the uterus can jeopardize the establishment of pregnancy (Edwards, 1995). Furthermore, uterine blood flow, as measured by colour Doppler, was proposed as the physiological parameter to assess endometrial receptivity to blastocyst implantation following assisted reproduction treatments (Achiron et al., 1995; Friedler et al., 1996).

The exact mechanism of the vascular reaction at peri-implantation is unclear. There is ample evidence indicating that prostaglandins mediate, at least in part, the changes in endometrial vascular permeability and subsequent decidualization in pregnant as well as in pseudopregnant animals (Evans and Kennedy, 1978; Kennedy, 1977, 1980). However, there is growing evidence that NO may play an important role in implantation and decidualization. In guinea pigs, dilatation of uteroplacental arteries was observed when invading trophoblast cells co-expressing eNOS and iNOS were present in the extravillous trophoblast (Nanaev et al., 1995), suggesting that NO mediates spiral arterial changes occurring during pregnancy. We also found an intense iNOS and eNOS labelling in the connective tissue surrounding spiral arterioles in the baboon endometrium during implantation (Purcell et al., 1999b). This study also revealed a very prominent iNOS immunostaining in the cytotrophoblasts during early pregnancy, while eNOS labelling was mainly associated with the glandular endometrium and decidua. In both studies the pattern of NOS localization suggests the involvement of NO in vasodilatation during the initial stages of trophoblast migration.

Recently, we performed immunohistochemical, molecular and functional studies in mice and rats to address the question of whether or not NO is involved in implantation (Chwalisz et al., 1999a; Purcell et al., 1999a). All three NOS isoforms were present within the mouse implantation site, with iNOS and eNOS being the most prominent within the ectoplacental cone as well as the layers of the myometrium and the primary decidual zone respectively (Purcell et al., 1999a). In this study, Western blot analysis of iNOS and eNOS in conjunction with trace optical density readings revealed a significant elevation of iNOS and eNOS expression in implantation sites versus intersite tissues on days 6, 7 and 8 of mouse pregnancy (Figures 1 and 2). This study also demonstrated...
an inhibitory effect of L-NAME (non-specific NOS inhibitor) on mice implantation after treatment during the peri-implantation phase. The results of our studies in rats clearly demonstrate that NO inhibition with aminoguanidine (iNOS inhibitor) and L-NAME markedly increases the inhibitory effects of the antiprogestin onapristone: (i) on the establishment of pregnancy after treatment during pre-implantation; (ii) on pregnancy and decidualization; and (iii) on successful pregnancy outcome during the peri-implantation phase (Chwalisz et al., 1999a). These effects were synergistic, as either treatment alone only marginally affected implantation and pregnancy outcome. Implantation is subject to the interaction of the trophoblast cells with the decidua. The results of this study also suggest that NO is involved in decidualization since NOS inhibitors, in particular L-NAME, reduced the extent of decidualization after treatment at peri-implantation even in the absence of onapristone.

Overall, our molecular and functional studies in mice and rats demonstrate that: (i) both iNOS and eNOS proteins are up-regulated in the implantation sites; (ii) NOS inhibitors block both decidualization and the establishment of pregnancy; and (iii) NOS inhibitors act synergistically with antiprogestins. The dramatic increase in iNOS and eNOS in the decidua at peri-implantation suggests, however, that besides progesterone, additional signals of embryonic origin are involved in NOS regulation during implantation. Since IL-1β, a very potent inducer of iNOS, is produced by the embryo (Simón et al., 1993; Krussel et al., 1997), this cytokine may also act as an embryonic signal promoting implantation. It could in fact, via iNOS and COX-2 induction, initiate the vascular reaction, decidualization, and the remodelling of the extracellular matrix during trophoblast invasion. Since NO may directly regulate the activity of MMP, it may play a role in extracellular matrix changes occurring during trophoblast invasion.

Role of NO during uterine bleeding

According to earlier classic experiments (Markee, 1940), in which the morphological changes of the autologous endometrial tissue transplanted to the anterior eye of the rhesus monkey were examined, initial changes that occurred after progesterone withdrawal were endometrial tissue regression followed by vasoconstriction of the spiral arterioles and vasodilatation. More recent studies have shown that the widespread degeneration accompanied by reduced cell-to-cell contacts occurs in endometrial stroma and in the lamina basalis before the onset of menstruation, but that the endothelial cells remain relatively intact during this time (Roberts et al., 1992). These changes, which are accompanied by leukocytic infiltration and MMP activation, suggest that the menstrual process is initiated by changes in the extracellular matrix and the stromal and epithelial cells, rather than in the vascular network (Osteen et al., 1994; Rogers, 1996; Salamonsen and Woolley, 1996). Since endometrial bleeding may last for several days, specific mechanisms have to operate to maintain blood flow. There are currently two hypotheses to explain the maintenance of uterine bleeding during menstruation: (i) an enhanced vasodilatation of endometrial arterioles and capillaries (Markee, 1940); and (ii) the coagulation theory based on increased fibrinolytic activity (Lockwood et al., 1994). The former hypothesis is supported by the finding of high tissue-type plasminogen activator (tPA) concentrations in the endometrium of menorrhagic women, and can be seen in the efficacy of anti-fibrinolytic drugs administered in this condition (Bonnar and Sheppard, 1996).

Although the precise role of NO during menstruation is still unclear and studies of NOS inhibitors on uterine bleeding are not yet available, the existing data on endometrial NOS expression and NO production during the menstrual cycle strongly suggest that NO plays a central role in controlling both the initiation and maintenance of uterine bleeding (Figure 3). Since NO is both a powerful inhibitor of platelet aggregation and a potent vasodilator, the concept of endometrial iNOS induction during menstruation bridges somewhat the vascular and coagulation theories of menstruation. In addition, iNOS-derived NO can promote tissue destruction by activating MMP and inducing apoptosis.

It is still unclear which mechanisms are responsible for the initial vasoconstriction of spiral arterioles in response to progesterone withdrawal. It is likely that an up-regulation of the ET system (increase in ET synthesis and decrease in degrada-
Nitric oxide in implantation and menstruation

During the luteal phase, under the influence of both progesterone and oestrogen, there is an up-regulation of eNOS in endometrial glands and blood vessels, thus precipitating a moderate local elevation in NO. An increased NO production may play a role in both the dilatation of endometrial blood vessels and receptivity. Luteal phase progesterone also down-regulates the endometrial endothelin (ET) system. Progesterone withdrawal at the end of the luteal phase leads to an elevation in endometrial ET expression while simultaneously inhibiting its major inactivator, enkephalinase. These effects may induce vasoconstriction of spiral arterioles. At peri-menstruation there is also an increased endometrial expression of pro-inflammatory cytokines, including IL-1 and TNF-α, which in turn induce iNOS and cyclooxygenase-2 (COX-2) in uterine leukocytes and epithelial and stromal cells. High concentrations of iNOS-derived NO may contribute to the maintenance of uterine bleeding during menstruation. Furthermore, it may activate endometrial metalloproteinases (MMPs) which play a key role during tissue destruction at peri-menstruation. In addition, high NO concentrations can induce endometrial apoptosis, an effect which can be observed during menstruation. The effects of NO on the endometrial arterioles and platelets may be enhanced by COX-2-derived vasodilatory prostaglandins (PGs), such as prostacyclin (PGI2) and PGE2.

![Figure 3. Proposed model of nitric oxide (NO) action during the peri-menstrual phase of the cycle and during menstruation.](image)

During the luteal phase, under the influence of both progesterone and oestrogen, there is an up-regulation of eNOS in endometrial glands and blood vessels, thus precipitating a moderate local elevation in NO. An increased NO production may play a role in both the dilatation of endometrial blood vessels and receptivity. Luteal phase progesterone also down-regulates the endometrial endothelin (ET) system. Progesterone withdrawal at the end of the luteal phase leads to an elevation in endometrial ET expression while simultaneously inhibiting its major inactivator, enkephalinase. These effects may induce vasoconstriction of spiral arterioles. At peri-menstruation there is also an increased endometrial expression of pro-inflammatory cytokines, including IL-1 and TNF-α, which in turn induce iNOS and cyclooxygenase-2 (COX-2) in uterine leukocytes and epithelial and stromal cells. High concentrations of iNOS-derived NO may contribute to the maintenance of uterine bleeding during menstruation. Furthermore, it may activate endometrial metalloproteinases (MMPs) which play a key role during tissue destruction at peri-menstruation. In addition, high NO concentrations can induce endometrial apoptosis, an effect which can be observed during menstruation. The effects of NO on the endometrial arterioles and platelets may be enhanced by COX-2-derived vasodilatory prostaglandins (PGs), such as prostacyclin (PGI2) and PGE2.
Slayden, 1994; Williams et al., 1994; Zelinski-Wooten et al., 1998). More recent studies in rhesus monkeys (Slayden et al., 1998) and cynomolgous monkeys (Chwalisz et al., 1999b) strongly suggest that vasoconstriction of spiral arterioles and/or inhibition of endometrial angiogenesis is a primary event of treatment with antiprogestins (RU 486, ZK 137 316) and the progesterone receptor modulator J1042, leading to amenorrhoea and endometrial atrophy.

After the onset of uterine bleeding in response to progesterone withdrawal, an increased iNOS activity (Tschugguel et al., 1999) may lead to a local release of NO at high concentrations. It is likely that during this phase iNOS is induced by pro-inflammatory cytokines which are elevated at peri-menstruation (Figure 3). An increased endometrial production of IL-1 and TNF-α, during the late luteal phase and during menstruation has been previously reported (Tabibzadeh, 1996). As a result, elevated local NO production may on the one hand induce vasodilatation of endometrial arterioles, and on the other hand contribute to the reduction of platelet fibrin plug formation. Since NO can activate MMP and enhance COX-2 activity leading to an increase in PGE₂ and PGI₂, both of these actions would be expected to promote both extracellular matrix remodelling and vasodilatation. Finally, NO may play a role in endometrial apoptosis which is increased in various components of the functional layer during the late secretory phase and menstruation (Kokawa et al., 1996).

The role of NO in menorrhagia and other uterine bleeding disorders remains poorly understood. Unfortunately, systematic studies on NO production and NOS expression in menorrhagic women are not available to date. We believe that the possibility of increased local NO production in this condition merits consideration. In fact, a recently published study (Hurskainen et al., 1999) clearly showed an association between uterine artery blood flow (measured by transvaginal colour Doppler) and menstrual blood loss. A significant inverse correlation was found between uterine pulsatility index and the amount of blood loss. This study suggests that local concentrations of vasoactive agent(s) simultaneously decrease uterine blood flow resistance as well as promoting uterine bleeding. Hence, NO could be a good candidate to exert both effects, since it is well-known that NO donors can increase uterine blood flow in humans (Ramsay et al., 1994).

In this context, endometrium-derived NO can also play a role in the pathogenesis of dysmenorrhea (Pittrof et al., 1996). There is meanwhile ample evidence that NO relaxes uterine smooth muscle under both in-vitro and in-vivo conditions (reviewed by Chwalisz et al., 1996). On the other hand, local effects of NO on spiral arterioles during menstruation may be beneficial in preventing pain due to anoxia. Hence, NO under physiological conditions may exhibit a dual action — a paracrine tocolytic effect on the myometrium, and a direct action on the endometrial blood vessels.

**Therapeutic perspectives**

The data reviewed above indicate that NOS, in particular iNOS, may represent a new target for novel therapeutic agents capable of both promoting and inhibiting implantation. NO donors or NO substrates may also have implications for the management of early pregnancy disorders, including recurrent abortions, treatment of dysmenorrhea and chronic pelvic pain. On the other hand, iNOS inhibitors may find application in the treatment of uterine bleeding disorders.

Up-regulating uterine NO production with either the NO substrate l-arginine or NO donors alone or in combination with progesterone may have beneficial effects on pregnancy outcome during assisted conception. In fact, it has been shown recently (by Doppler measurement) that administration of l-arginine improved uterine and follicular flow in poor responder patients during in-vitro fertilization (Battaglia et al., 1999). However, larger clinical studies are needed to address the question of whether the up-regulation of NO will improve the pregnancy rate during assisted reproduction. On the other hand, the effects of NOS inhibitors in combination with antiprogestins point to a novel method for controlling fertility, particularly by enhancing the efficacy of antiprogestins used for endometrial contraception, menstrual induction and postcoital contraception.

Abnormal uterine bleeding is a common gynaecological problem which has an enormous impact
on the lives of many women. Furthermore, unscheduled bleeding, which is frequently associated with chronic progestin administration or continuous HRT regimens, represents one of the major problems leading to the discontinuance of medication. The role of NO in this respect is likely to be of considerable interest for the understanding of the mechanisms of uterine bleeding under normal and pathological conditions. Both experimental and clinical evidence is emerging pointing to cross-talk between progesterone and NO in the endometrium. Further clinical studies are clearly needed to explore the potential of antiprogestins, other progesterone receptor modulators, and NOS inhibitors for the treatment of abnormal uterine bleeding.

Finally, NO donors may find application in the treatment of dysmenorrhea. In fact, preliminary studies employing transdermal nitroglycerine suggest its efficacy in severe dysmenorrhea (Pittrof et al., 1996). However, larger, controlled studies are needed to establish the potential of NO donors for the treatment of dysmenorrhea.

References


K.Chwalisz and R.E.Garfield


Kruessel, J.K., Huang, H.Y., Wen, Y. et al. (1997) Different pattern of interleukin-1β-(IL-1β), interleukin-1 receptor antagonist-(IL-1ra) and interleukin-1 receptor type I-(IL-1R I) mRNA-expression in single preimplantation mouse embryos.
Nitric oxide in implantation and menstruation

at various developmental stages. J. Reprod. Immunol., 34, 103–120.


