The role of nuclear factor kappa B in human labour

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Abstract

Preterm birth remains the leading cause of perinatal mortality and morbidity, largely as a result of a poor understanding of the precise mechanisms controlling labour onset in humans. Inflammation has long been recognised as a key feature of both preterm and term labour, with an influx of inflammatory cells into the uterus and elevated levels of pro-inflammatory cytokines observed during parturition. Nuclear factor kappa B (NF-κB) is a transcription factor family classically associated with inflammation. Accumulating evidence points to a role for NF-κB in the physiology and pathophysiology of labour. NF-κB activity increases with labour onset and is central to multiple pro-labour pathways. Premature or aberrant activation of NF-κB may thus contribute to preterm labour. The current understanding of NF-κB in the context of human labour is discussed here.

Introduction

Human labour is the culmination of fetal maturation, fetal membrane rupture, placental separation, cervical ripening and dilatation, and coordinated uterine contractions. The precise mechanisms controlling the onset of labour in humans remains one of the fundamental unsolved questions in reproductive biology. Understanding this process is of great importance given that premature delivery complicates up to 10% of pregnancies and is associated with up to 70% of neonatal morbidity and mortality. Inflammation is now widely accepted to be a key feature of human labour. Microarray and suppression subtractive hybridization studies have demonstrated the up-regulation of a large panel of pro-inflammatory genes in both fetal membranes (Marvin et al. 2002, Bethin et al. 2003) and myometrium (Chan et al. 2002, Charpigny et al. 2003) with labour onset. Extensive work over the last two decades has implicated cytokines and prostaglandins in the parturition process. Parturition is characterised by an influx of inflammatory cells into the uterus (Young et al. 2002) and increased expression of pro-inflammatory cytokines in both preterm and term labour: elevated levels of interleukin-1β (IL-1β), IL-6 and tumour necrosis factor-α (TNF-α) are detected in amniotic fluid (Romero et al. 1992, Opsjøn et al. 1993, Romero et al. 1993, Maymon et al. 1999), while IL-1β and IL-6 expression is also increased in amnion (Dudley et al. 1996, Keelan et al. 1999), myometrium and choriodendua (Keelan et al. 1999, Osman et al. 2003) and cervicovaginal secretions (Steinborn et al. 1996, Tanaka et al. 1998). These pro-inflammatory cytokines are thought to contribute to labour onset by stimulating the production of IL-8 and prostaglandins. Prostaglandins, in turn, induce uterine contractions and act in concert with IL-8 to cause cervical ripening and fetal membrane remodelling (Olson 2003).

Nuclear factor-kappa B (NF-κB) is a transcription factor family classically associated with inflammation, which is activated in response to infection and pro-inflammatory cytokines, such as those prevalent during labour. Importantly, many pro-inflammatory and labour-associated genes are regulated by NF-κB, and aberrant NF-κB activity underlies a number of inflammation-related disorders. Thus, this transcription factor may play a pivotal role in parturition. NF-κB has been the focus of intense investigation in recent years. Numerous articles have summarized the considerable progress that has been made in elucidating the complexities of NF-κB function and regulation (Hayden & Ghosh 2004, Schmitz et al. 2004). This review will briefly outline the regulation of NF-κB and focus on the current understanding of NF-κB activity in the context of human labour.

The NF-κB and IκB proteins

The mammalian NF-κB/Rel family comprises five members: NF-κB1 (p105/p50), NF-κB2 (p100/p52), p65 (RelA), c-rel and RelB (Fig. 1). These proteins share a structurally conserved N-terminal region termed the Rel homology domain (RHD). The RHD mediates dimerization, DNA binding, nuclear localization and interaction with the
inhibitors of kappa B (IkB) proteins. In the active form NF-κB consists of heterogeneous dimers of various combinations of subunits: each member of the NF-κB family, except for RelB, can form homodimers, as well as heterodimers with one another. RelB forms heterodimers with p100, p52 and p50. The p65, c-Rel and RelB proteins contain C-terminal non-homologous transactivation domains (TADs), which are required for transactivation by these proteins. The p50 and p52 proteins are generated by proteolytic processing of their precursors, p105 and p100, respectively. The p105 and p100 precursor proteins are constitutively processed through a cotranslational mechanism, but processing of p105 is much more efficient, so that most cells exhibit constitutively high levels of p50, whereas steady-state levels of p52 are low and tightly regulated (Lin et al. 1998, Heusch et al. 1999). The p50 and p52 subunits lack TADs, hence homodimers of these proteins have no intrinsic ability to drive transcription and may bind DNA to repress gene expression in resting cells. The prototypical and most prevalent activated form of NF-κB is the p50/p65 heterodimer.

In resting cells, NF-κB is retained in the cytoplasm in an inactive form through association with the IkB proteins, the most prominent of which are IkBα, IkBβ and IkBε. The IkBs are characterized by the presence of multiple ankyrin repeats, which mediate binding to the RHD of NF-κB (ankyrin repeats; protein motifs containing a 33-amino acid long sequence that occur in tandem array and cooperatively fold into structures that mediate protein–protein interactions). The IkBα masks only the nuclear localization sequence (NLS) of the p65 subunit, leaving the p50 NLS exposed (Huxford et al. 1998). This exposed NLS, coupled with nuclear export sequences (NES) present on IkBα and p65, results in constant nuclear-cytoplasmic shuttling of the IkBα/p50/p65 complex. Since the export process is more potent than the import process, the steady-state localization of IkBα-bound NF-κB is in the cytosol (Harhaj & Sun, 1999, Huang et al. 2000). Similarly, IkBe also actively shuttles between the nucleus and cytoplasm (Lee & Hannink 2002). In contrast, IkBβ lacks a NES and masks both NF-κB NLSs and IkBβ-bound NF-κB is consequently sequestered in the cytoplasm of unstimulated cells (Malek et al. 2001). Two unusual IkB proteins are Bcl-3 and IkBζ. These contain ankyrin repeats but are constitutively nuclear and may act as trans-activating transcription factors (Fujita et al. 1993, Yamamoto et al. 2004).

**Figure 1** Schematic diagram of NF-κB and IkB family proteins. The NF-κB DNA-binding subunits share a conserved N-terminal rel homology domain (RHD). p65, c-Rel and RelB also have C-terminal transactivation domains (TADs). RelB contains an additional leucine-zipper motif (LZ). The glycine-rich region (GRR) is required for the proteolytic processing of the p105 and p100 precursor proteins, which contain multiple ankyrin repeats, in common with the IkB proteins.
NF-κB signalling pathways

Three distinct NF-κB signalling pathways have been delineated to date, all of which rely on sequentially activated kinases, the generation of DNA-binding NF-κB dimers, and enhancement of the transcriptional activity of NF-κB (Fig. 2).

The so-called canonical pathway is triggered by bacterial lipopolysaccharide (LPS) and pro-inflammatory cytokines, such as IL-1β and TNFα. Whilst many of the very early events following receptor engagement are specific for each stimulus (Hayden & Ghosh, 2004), the signalling converges on the IκB kinase (IKK) complex (Fig. 3). The IKK complex includes the regulatory scaffold protein NF-κB essential modulator (NEMO or IKKγ) and the IKKa and IKKB kinases. Once activated, IKK phosphorylates IκBα on Ser32 and Ser36 (Traenckner et al. 1995) and this phosphorylation targets IκBα for ubiquitination by the SCFβ-TrCP ubiquitin ligase at lysines 21 and 22 (SCFβ-TrCP; The SCF ligase is composed of Skp1, Cdc53/Cu11, and a specificity-conferring F-box protein, in this case beta-transducin repeat-containing protein; βTrCP) (Yaron et al. 1998). Ubiquitinated IκBα is subsequently degraded by the 26S proteasome, thereby releasing NF-κB dimers from the cytoplasmic IκBα/NF-κB complex, unmasking their NLSs and allowing them to translocate to the nucleus. Canonical NF-κB activation is usually transient as a result of a ‘postinduction repression’ mechanism. Due to the presence of NF-κB binding sites in the promoter of the IκBα gene, activation of NF-κB leads to the rapid resynthesis of IκBα, which accumulates in the nucleus and dissociates NF-κB from DNA-bound complexes (Brown et al. 1993). These newly formed IκBα/NF-κB complexes are then exported out to the cytoplasm, in a process mediated by the IκBα NES (Huang & Miyamoto, 2001), which restores the cytoplasmic pool of inactive NF-κB. IκB degradation by the canonical pathway requires the IKKB and NEMO components of the IKK.

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Figure 2 Three distinct NF-κB signalling pathways. The canonical pathway is activated when tumour necrosis factor-α (TNFα), interleukin-1β (IL-1β) or lipopolysaccharide (LPS) bind their respective receptors and involves IκB kinase (IKK)-mediated phosphorylation of IκBα. IκBα is subsequently degraded by the proteasome to release p50/p65 dimers. In the atypical pathway, DNA damage results in extensive phosphorylation of IκBα by p38-induced casein kinase-2 (CK-2). The noncanonical pathway is triggered by lymphotixin β (LTβ) or B-cell activating factor (BAFF) and involves the activation of IKKα by NF-κB inducing kinase (NIK). IKKα, in turn, phosphorylates p100, which then undergoes proteosomal processing to generate p52. RelB/p52 dimers are thus released and translocate to the nucleus to activate genes distinct from those regulated by the canonical pathway. 1. Extracellular stimulus 2. Kinase activation 3. Generation and translocation of active NF-κB dimers 4. DNA-binding and phosphorylation of NF-κB dimers and cofactor recruitment. P = phosphorylation; Ub = ubiquitination.
complex (Tanaka et al. 1999, Rudolph et al. 2000) and can involve the degradation of IκBα, IκBβ and IκBe. The p105 protein may also play a role in the canonical pathway. In addition to the constitutive, cotranslational processing of p105 (Lin et al. 1998), which provides the resting cell with the small amount of p50 required for its basal needs (e.g. low-level transcription or repression of transcription), IKK-dependent phosphorylation and ubiquitination of p105 may occur in response to pro-inflammatory cytokines and LPS (Heissmeyer et al. 1999, Heissmeyer et al. 2001). Such inductive targeting of the p105 precursor can result in two distinct processes, which employ distinct ubiquitin ligases: there may be either complete degradation or limited processing of the protein (Cohen et al. 2004). Presumably processing of p105 will provide solely p50 subunits whereas degradation may release a variety of NF-κB subunits bound to the p105 ankyrin repeats.

The non-canonical pathway is activated in response to a subset of NF-κB inducers, such as lymphotixin β, B-cell activating factor, or the CD40 ligand, although these can also trigger the canonical pathway. In the non-canonical pathway, which is NEMO- and IKKb-independent (Claudio et al. 2002, Dejardin et al. 2002), IKKa homodimers phosphorylate p100 associated with RelB. This elicits the processing of p100 to p52 and releases transcriptionally active p50 homodimers.
active RelB/p52 dimers (Dejardin et al. 2002, Xiao et al. 2004). The third pathway is triggered by DNA damage and is considered atypical because it does not involve an initiating receptor ligation event and is independent of the IKK complex. NF-κB activation by UV irradiation, for instance, involves the multiple phosphorylation of IκBα on C terminus residues by the p38-activated casein kinase 2 (Kato et al. 2003). Whilst all the aforementioned signalling pathways have a requirement for proteasomal degradation of one or more IκB proteins, a novel pathway involving proteasome inhibitor-resistant (PIR) degradation has recently been described (O’Connor et al. 2004). PIR is IκK-dependent and targets IκBα, but not IκBβ, resulting in constitutive p50/c-rel activity in B cells.

**Multiple levels of NF-κB regulation**

NF-κB is a ubiquitous transcription factor that regulates numerous genes involved in a diverse array of cellular processes. Hence the specificity and temporal control of the NF-κB response is crucial and multiple levels of control are in place to ensure its tight regulation. As discussed, different stimuli activate distinct kinases, which differentially target IκB degradation. Since the various IκB proteins exhibit distinct preferences for association with particular NF-κB dimers (e.g. IκBα predominantly binds p50/p65, IκBε binds p65/c-rel, p100 binds RelB), such selective IκB degradation can determine whether transcriptionally active or repressive NF-κB dimers are released. Furthermore, target genes require specific NF-κB family members for their activation and this varies from gene to gene (Hoffmann et al. 2003). Whilst different stimuli can activate distinct NF-κB dimer combinations, the same stimulus can also elicit distinct waves and subsets of gene activation due to the differential dynamics of IκB degradation and resynthesis coupled with target gene requirements (Hoffmann et al. 2002). Finally, the transcriptional activity of the NF-κB subunits themselves is also regulated by a variety of post-translational modifications, such as phosphorylation, acetylation, ubiquitination and prolyl isomerization (Schmitz et al. 2004). Regulation of NF-κB signalling is thus complex and cell-type differences in NF-κB signalling may depend on which kinases are expressed, which subunits of NF-κB are expressed, in what ratios and on the NF-κB-activating signals to which a given cell responds.

**Insights from mice**

A major obstacle in understanding the onset of human labour is the limited ability to extrapolate findings from animal models since there are intrinsic differences between humans and other species in the parturition process, e.g. discordance in the sites and patterns of steroid production. Nevertheless, whilst the role of the corpus luteum and progesterone withdrawal differs between mice and humans, a number of fundamental similarities are apparent. For instance, both mouse and human exhibit an increase in myometrial cell gap junctions and increased uterine sensitivity to oxytocin at term, as well as similar patterns of cytokine expression during infection-related preterm labour. The primary advantage of using the mouse as a model system is the ability to maintain tight experimental control in an *in vivo* context and to manipulate the mouse genome or proteome in ways that are precluded in human studies due to ethical and practical considerations.

Although genetic disruption of *NF-κB* genes has not been informative in terms of their contribution to labour onset, studies using mice deficient in p65 (Alcamo et al. 2001), p50 (Sha et al. 1995) or c-rel (Donovan et al. 1999) have confirmed the requirement of these proteins for the mounting of inflammatory sequelae and the response to infection, both of which impinge on the labour process. The establishment of mouse models of parturition is now beginning to yield interesting findings. A crucial role for NF-κB in murine parturition was recently demonstrated in a mouse model of term labour (Condon et al. 2004). Nuclear translocation of the p50 and p65 subunits in the pregnant mouse uterus increased as term approached. Mice injected intra-amniotically with the NF-κB inhibitor peptide SN50 displayed a delay in the onset of labour, whereas control mice injected with the inactive SN50mut peptide delivered at term. Furthermore, surfactant protein-A (SP-A), a protein secreted by the fetal lung that reaches maximal levels at term, was shown to increase p65 nuclear levels in the mouse uterus and induce labour. The authors proposed a model wherein SP-A secreted by the maturing fetal lung acts as a trigger for the onset of parturition at term by inducing the migration of macrophages to the maternal uterus, where they activate NF-κB, resulting in the stimulation of uterine contractility. It is not currently clear to what extent these findings can be extrapolated to the human, although the pattern of SP-A synthesis is similar and a ‘fetal signal’ to parturition is an attractive hypothesis.

Condon et al. (2004) suggest that SP-A signalling to NF-κB during murine parturition may occur via Toll-like receptors (TLRs). TLRs recognize pathogen-associated molecular patterns in specific classes of microbes and are key regulators of both innate and adaptive immune responses. They share considerable homology with the IL-1 receptors and also signal to NF-κB through the canonical pathway. Studies using *Tlr-4* -/- mutant mice suggest that this TLR is a critical factor in bacterially-induced preterm labour (Wang & Hirsch 2003). Furthermore, both maternal and fetal polymorphisms of the human *TLR-4* gene have been associated with spontaneous preterm labour (Varner & Esplin 2005). Since NF-κB is known to mediate TLR-4 signalling, these findings imply a role for NF-κB in both spontaneous preterm labour, infection-associated preterm labour and possibly normal labour at term.
Suppression of NF-κB during pregnancy – NF-κB/steroid antagonism

Suppression of NF-κB activity during pregnancy might be expected if NF-κB does play a role in the onset of labour. McCracken et al. (2004) reported that NF-κB down-regulation in T cells of pregnant women is essential for maintaining the cytokine profile necessary for pregnancy success. Suppression of NF-κB activation in first trimester decidua has also been suggested to contribute to the immunosuppressive mechanisms that prevail during pregnancy (King et al. 2001).

Steroids are present in the circulation at high concentrations throughout gestation and are known to have immunosuppressive effects. The steroid hormone progesterone maintains the uterus in a quiescent state for the majority of pregnancy. In most animal species, a withdrawal of this progesterone effect, manifest as a decline in maternal circulating progesterone levels, precedes the onset of labour at term. Although this does not occur in human pregnancy, the administration of antiprogestins to pregnant women induces labour and enhances sensitivity to oxytocin (Chwalisz 1994). Therefore, in theabsence of a demonstrable fall in maternal plasma or tissue progesterone concentrations, it has been postulated that alterations in the functions of the progesterone receptor (PR) may mediate functional or local progesterone antagonism.

In human amnion epithelial cells, a transient transfection system was used to demonstrate mutual antigenic antagonism between PR and NF-κB transcriptional activities (Allport et al. 2001). Progesterone itself will also repress IL1-β-induced expression of NF-κB-regulated genes in human amnion (Loudon et al. 2003). This suggests that progesterone may act via its receptor to suppress NF-κB signalling during pregnancy and that the converse, NF-κB mediated repression of PR, may occur in association with labour. A negative direct protein-protein interaction between p65 and PR has recently been reported in breast cancer cells (Kalkhoven et al. 1996), while, in a preliminary report, Condon et al. (2005) argue that increased p65 expression at term may promote a change in PR isoform predomiance, leading to alleviation of the progesterone effects. Progesterone can also bind directly to the oxytocin receptor (OTR) to inhibit its signalling (Grazzini et al. 1998). OTR is a regulator of uterine contractility and contains putative NF-κB binding sites in its gene promoter.

Placental production of glucocorticoids is also markedly increased during pregnancy. The placenta itself is a glucocorticoid-responsive organ and Rosen et al. (1998) demonstrated that NF-κB activity in cytotrophoblasts isolated from human term placenta is chronically suppressed by treatment with the glucocorticoid dexamethasone. Immunohistochemical analysis of cervical tissue from postpartum women compared to that from women at term revealed a decrease in glucocorticoid receptor (GR) levels and a concomitant increase in NF-κB nuclear localisation at parturition (Stjernholm-Vladic et al. 2004). Thus GR-mediated anti-inflammatory mechanisms may also be in place to suppress NF-κB activity and ensure pregnancy maintenance. Such inhibitory mechanisms can occur either through p65/GR protein interactions (Garside et al. 2004) or via the induction of IkBα synthesis (Auphan et al. 1995).

NF-κB activity in human labour

In the study of human labour, there have been no genomic or associative genetic reports directly linking NF-κB to labour onset. However, activation of NF-κB as a result of alterations in the mechanisms that regulate NF-κB may occur with labour and aberrant or premature NF-κB activation could contribute to preterm labour. Research in humans has focused on (i) determining whether the expression or activity of NF-κB expression is within the uterus in association with labour, (ii) investigating the activation of NF-κB by potential triggers of parturition and, (iii) assessing the requirement of pro-labour pathways for NF-κB-mediated transcription.

NF-κB activation in association with labour

The expression profile and activation of NF-κB family members in myometrial tissue from nonpregnant, term pregnant and spontaneously labouring women was recently reported (Chapman et al. 2004). p65, c-rel, p50, p100 and p105 proteins were detected in tissues from all three groups. Surprisingly, a decrease in p65 protein expression was observed in lower segment myometrium in association with labour, although there was no change in fundal myometrium, which is considered the principal contractile region of the myometrium during labour. This decrease was proposed to occur via the selective recruitment of the proteasome complex to a subset of p65-regulated (possibly quiescence-associated) promoters, although this remains to be demonstrated. Nevertheless, NF-κB is generally post-translationally regulated and a shift in subunit composition of the predominant DNA-binding complex was detected, such that binding of potentially repressive p50 homodimers prevailed in pregnant myometrium, whereas p50/p65 heterodimers were dominant in pregnant and labouring myometrium. However, there has recently been a preliminary report (currently in abstract form) of an increase in nuclear and cytosolic p65 expression in fundal uterine segment myometrium in association with human labour (Condon et al. 2005). Increased levels of nuclear NF-κB at parturition have been demonstrated in the cervix (Stjernholm-Vladic et al. 2004).

In amnion, basal and IL-1β-induced NF-κB DNA binding activity involves the p50/p65 heterodimer, as well as p65 and p50 homodimers (Lee et al. 2003). Allport et al. (2001) demonstrated that baseline NF-κB DNA binding and transcriptional activity of a NF-κB reporter are
increased in amnion cells following spontaneous labour relative to amnion cells at term, suggesting that NF-κB plays a role in labour in the amnion. Constitutive NF-κB activity in many cancer cell types is maintained through continuous IkBα turnover, as a result of unrelenting IKK activity (Geleziunas et al. 1998, Carter et al. 2001). However, the increased constitutive NF-κB activity seen in post-labour amnion cells was paralleled by an increase in IkBα expression, suggesting that IkBα is responding to, but not regulating, NF-κB activation (Allport et al. 2001). This apparent paradox is not unprecedented and has been explained by a chaperone-like function of IkBβ. Following stimulus-induced degradation, newly synthesized IkBβ accumulates in the nucleus in a hypophosphorylated form, which can bind NF-κB without masking its NLS (Suyang et al. 1996). Hypophosphorylated IkBβ may thus maintain persistent NF-κB activity by preventing its sequestration by IkBα and export to the cytoplasm (Thompson et al. 1995, DeLuca et al. 1999). Such an IkBβ-mediated mechanism of sustained NF-κB activity may be responsible for the labour-associated constitutive NF-κB activity observed in the amnion, since IkBβ expression increases with gestational age and labour onset and there is an increase in nuclear localisation of IkBβ in post-labour cells (Lee et al. 2003). However, the phosphorylation status of this nuclear IkBβ, as well as its possible participation in a ternary complex with NF-κB/DNA, remains to be assessed.

Findings contradictory to the study by Allport et al. (2001) were reported by Yan et al. (2002a) who showed, by immunohistochemical analysis, that p65 is localised principally in the cytoplasm of amnion and chorion at term, regardless of labour status. However, this study did not examine potential changes in posttranslational modifications of p65 (e.g. phosphorylations, acetylations), which are important for its transactivation potential (Schmitz et al. 2004). It is possible that, while a significant increase in nuclear protein levels may not be detectable, labour-associated modifications of pre-existing low-level nuclear p65 could enhance its transcriptional activity. An increase in nuclear localisation of p65 in the decidua was observed with advancing gestation, which was unaffected by labour onset (Yan et al. 2002a).

A number of confounding factors may complicate studies of this nature. Challis and colleagues have proposed that functional regionalization of both chorion and myometrium occurs at term, as a result of progesterone action (Challis et al. 2000). Thus in the cervical, but not the fundal, region of the chorion there is increased production of prostaglandin E2 and matrix remodelling. In the myometrium, functional progesterone withdrawal in the fundus induces the expression of contraction-associated proteins (CAPs) and myometrial activation, whereas maintained progesterone signalling in the lower segment myometrium drives the expression of genes that promote relaxation. There may also be inner/outer polarity of the myometrium (Brosens et al. 2002). Discrepancies between studies may therefore reflect the different regions of tissue sampled. Furthermore, Challis et al. (2002) have proposed the existence of four phases of uterine activity during pregnancy and labour: a relatively quiescent phase of pregnancy, an initial ‘activation’ phase of parturition in which mechanical stretch and uterotrophins lead to up-regulation of CAPs and agonist receptors, followed by a ‘stimulation’ phase in which the uterus responds to uterotrophins such as prostaglandins and oxytocin, and a final phase corresponding to postpartum involution. Differences in proximity to labour of the patients classified as not in labour may thus impact on the findings in different studies. The point at which NF-κB is activated in the parturition cascade remains to be elucidated.

**Uterine distension**

Stretch is imposed on the myometrium and fetal membranes by the growing fetus throughout pregnancy and more acutely at the time of labour. Studies using unilaterally pregnant rats (Ou et al. 1997) suggest that uterine distension is a major regulator of smooth muscle contractility, which may explain the high rate of preterm labour in conditions such as polyhydramnios and multiple pregnancies. Stretch is also likely to contribute to labour at term: decline in uterine growth relative to fetal growth near the end of pregnancy would increase uterine wall stretch and hence promote myometrial activation (Lye et al. 2001). The OTR plays an important role in uterine contractions during labour (Romero et al. 2000), and OTR mRNA expression is up-regulated by mechanical stretch in pregnant uterine myocytes in vitro (Terzidou et al. 2005). The OTR promoter contains three putative NF-κB binding sites. However, although NF-κB proteins do bind to the OTR promoter and may synergise with the transcription factor CCAAT/enhancer binding protein β to induce OTR transcription in myometrium (Terzidou et al. 2003), Johnson and colleagues demonstrated that myometrial NF-κB DNA binding activity is not stimulated by stretch and therefore does not mediate stretch-induced up-regulation of OTR expression (Terzidou et al. 2005). In amnion cells, however, stretch does activate NF-κB, which in turn induces expression of cyclo-oxygenase-2 (COX-2), an enzyme important in the production of prostaglandins, see below (Mohan et al. 2005).

**Corticotrophin-releasing hormone**

Corticotrophin-releasing hormone (CRH) is a peptide hormone that functions in the hypothalamic–pituitary–adrenal axis to co-ordinate the neuroendocrine response to stress. CRH is also produced by a number of tissues outside the central nervous system. During pregnancy, the placenta and fetal membranes produce large amounts of CRH, whose levels in maternal and fetal blood and in amniotic fluid peak at term (McLean & Smith 2001). Placent al production of CRH has been linked with the
timing of birth and Roger Smith’s group have proposed a ‘placental clock’ hypothesis, in which the rate of increase of maternal plasma CRH throughout pregnancy influences the timing of labour (McLean et al. 1995).

Thus, in addition to fetal lung SP-A (Condon et al. 2004) and bacterial infection (Romero et al. 2002), CRH is also considered a possible trigger for the onset of labour. Whereas numerous studies demonstrate a link between CRH and NF-κB, CRH may exert paracrine or autocrine actions in uterine tissues, in addition to its endocrine effects. Pro-inflammatory local effects of CRH have been demonstrated in a model of aseptic inflammation in rats (Karalis et al. 1991), and NF-κB was recently shown to mediate the pro-inflammatory effects of CRH in mouse thymocytes (Zhao & Karalis, 2002). The identification of CRH and its receptors in myometrium (Clifton et al. 1998, Stevens et al. 1998) suggested that CRH may have a direct effect on this tissue. In a study using myometrial explants, CRH was unable to stimulate pro-inflammatory cytokine production (Sehringer et al. 2003). However, only lower segment myometrium was examined and CRH is thought to promote relaxation in the lower segment but stimulate myometrial activity in the fundus (Stevens et al. 1998).

CRH is also expressed in fetal membranes, where it may stimulate prostaglandin production (Jones & Challis, 1999; Young et al. 2003). NF-κB is an important regulator of prostaglandin production – as discussed below – but a potential link between CRH and NF-κB activation in fetal membranes has not been addressed.

NF-κB is activated by and regulates pro-inflammatory cytokines

The importance of pro-inflammatory cytokines in parturition has long been appreciated. A polymorphism in the TNF-α promoter that increases TNF-α gene transcription is associated with preterm birth in black women, whilst an IL-6 gene promoter polymorphism that results in reduced IL-6 production is associated with a decreased risk of preterm birth in Caucasian women (Varner & Esplin 2005). Concentrations of IL-1β, IL-8, IL-6 and TNF-α are elevated in amniotic fluid and uterine tissues in association with preterm and term labour (Keelan et al. 2003) and mediate infection-induced preterm labour (Romero et al. 2002). Furthermore, systemic administration of IL-1β can induce preterm parturition in pregnant mice (Romero et al. 1991). The high levels of pro-inflammatory cytokines detected in uterine tissues may derive, in part, from infiltrating leukocytes (Young et al. 2002, Osman et al. 2003), but decidual, myometrial, amnion and placental cells can themselves all produce pro-inflammatory cytokines. NF-κB is highly inducible by pro-inflammatory stimuli. LPS (Lappas et al. 2002), IL-1β (Belt et al. 1999) and TNF-α (Knis et al. 2001) have all been shown to stimulate NF-κB activity in uterine tissues. In addition, many genes encoding pro-inflammatory cytokines, such as TNF-α, IL-1β, IL-8 and IL-6, contain NF-κB recognition elements within their promoters and NF-κB is known to promote the formation of cytokines in many cell types. Cytokine-induced NF-κB can therefore precipitate a positive feed-forward loop resulting in amplification of cytokine production and further NF-κB activation.

Uterine NF-κB expression and activity is reduced in IL-1β-deficient pregnant mice compared to pregnant wild-type mice. This is associated with a decrease in cytokine production in response to LPS (Reznikov et al. 2000), indicating an important role for NF-κB in the inflammatory response in uterine tissues. Repression of NF-κB DNA-binding by the anti-inflammatory agent sulforaphane (SASP) or the anti-oxidant N-acetyl-cysteine (NAC) inhibits the release of IL-6, IL-8 and TNF-α from LPS-treated placental, choriodedidual and amnion explants (Lappas et al. 2002, Lappas et al. 2003). Soloff et al. (2004) recently reported the in situ binding of the p65 NF-κB subunit to the endogenous IL-8 promoter in IL-1β-stimulated myometrial cells. Reporter studies in amnion and cervical cells demonstrated that the NF-κB response element is required for transcription of the IL-8 gene in these cells (Elliott et al. 2001).

NF-κB is required for prostaglandin synthesis

Prostaglandins (PGs) are pivotal to the parturition process, mediating cervical ripening and dilatation and stimulating myometrial contractions (Olson 2003). An increase in PG output precedes the onset of clinical labour (Romero et al. 1996, Brown et al. 1998) and, importantly, drugs that inhibit PG production have been used clinically to attenuate the progression of labour (Besinger et al. 1991), whilst the administration of exogenous PGs induces labour and delivery (Ray & Garite 1992). The rate-limiting and committing step of PG synthesis is catalysed by the cyclooxygenase (COX) enzymes. The COX enzymes exist as two main isoforms, the constitutively expressed COX-1 and the inducible COX-2 isozyme (a third isoform, COX-3 has recently been described; Berenbaum 2004). Studies in Cox-1 -/- knockout mice show that maternal Cox-1 is necessary and sufficient for murine labour at term (Gross et al. 1998). Cox-2 knockout mice exhibit impaired ovulation and blastocyst implantation, which limits the information that can be gained about the role of COX-2 in murine parturition (Lim et al. 1997). However, Gross et al. (2000) demonstrated that COX-2 but not COX-1 is induced during LPS-mediated preterm labour, and that administration of a COX-2 selective inhibitor was able to prevent preterm delivery. It has been proposed that COX-1-derived prostaglandins are responsible for the induction of luteolysis, while COX-2 may be important in the final pathway of parturition (Tsuboi et al. 2000).

In human labour, which does not involve PG-mediated luteolysis, there is substantial evidence for the importance
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of the inducible COX-2. Amnion is a major source of PGs and displays a marked increase in synthesis of PGE₂ with labour onset (Bennett et al. 1993). This is associated with the selective induction of the COX-2 gene (Slater et al. 1995). Similarly, chorio-decidual cells exhibit labour-associated upregulation of COX-2, but not COX-1, expression (Slater et al. 1998). Furthermore, COX-2-selective inhibitors may delay premature delivery in women (Mitchell & Olson 2004).

COX-2 expression in uterine tissues is transcriptionally induced by pro-inflammatory cytokines, such as IL-1β and TNFα (Belt et al. 1999, Kniss et al. 2001). The promoter region of the human COX-2 gene contains two NF-κB response elements and site-directed mutation of either of these elements represses the activity of a COX-2 promoter reporter construct in amnion epithelial cells (Allport et al. 2001). Blocking the nuclear translocation of NF-κB with the SN50 inhibitor peptide results in inhibition of IL-1β-induced COX-2 protein synthesis in amnion mesenchymal cells (Yan et al. 2002b). NF-κB is also required for TNFα-induced COX-2 expression in trophoblast cells (Kniss et al. 2001). Conversely, Lappas et al. (2004) reported that inhibition of NF-κB DNA binding by SASP did not affect COX-2 expression in LPS-stimulated amnion, placenta or choriodecidua. However, SASP is not a specific NF-κB inhibitor and the authors suggest that SASP could potentially extend the half-life of COX-2. NF-κB inhibition by SASP does, however, repress secretory type II phospholipase A₂ (an enzyme upstream of COX-2 in the PG biosynthetic pathway) in gestational tissues (Lappas et al. 2004), as does NF-κB inhibition by NAC (Lappas et al. 2003). The in situ binding of the p65 NF-κB subunit to the COX-2 promoter has been demonstrated in IL-1β-stimulated myometrial cells by chromatin immunoprecipitation (Soloff et al. 2004). Treatment of myometrial cells with proteasome inhibitors, a COX-2-derived PG metabolite, or a more selective IKKβ inhibitor, all of which block NF-κB activity, inhibits IL-1β-induced COX-2 expression and PG synthesis (Belt et al. 1999, Lindstrom & Bennett 2005).

NF-κB regulates matrix metalloproteinase expression

Extensive remodelling of the extracellular matrix (ECM) occurs in several processes during parturition, including fetal membrane rupture (Bryant-Greenwood & Yamamoto 1995), cervical ripening (Kelly 2002) and placental detachment from the decidua (Tsatas et al. 1999). Fetal membranes consist of amnion and chorion layers connected by ECM, which forms the structural framework of the amnion-chorion. ECM collagens provide the main tensile strength of the fetal membranes. As gestation progresses, programmed collagenolysis takes place, which is mediated by matrix metalloproteinase (MMP) enzymes. A decrease in the collagen content of the membranes and activation of MMPs occurs during labour (Hampson et al. 1997, Goldman et al. 2003), and inappropriate or premature MMP expression and activity is proposed to contribute to the pathological preterm premature rupture of membranes (PPROM) (Vadillo-Ortega & Estrada-Gutierrez 2005). ECM collagen degradation during cervical ripening occurs in order to allow the cervix to become soft and distensible, thereby accommodating the passage of the fetus during labour. Increases in MMP activity parallel the increase in cervical dilatation (Winkler et al. 1999) and, as with PPROM, premature cervical ripening is a feature of preterm labour (Schmitz 2004).

The onset of labour is associated with an influx of inflammatory cells into the membranes, decidua and cervix (Osman et al. 2003), and MMPs found within the uterus may derive from these infiltrating leukocytes (Vadillo-Ortega & Estrada-Gutierrez 2005). The chemokine IL-8 is largely responsible for the influx of leukocytes into uterine tissues, where it induces their degranulation and release of MMPs (Osmers et al. 1995). MMPs are also produced by the cervix itself (Stygar et al. 2002), as well as the placenta and fetal membranes (Xu et al. 2002). The production of MMP-9 (Yoo et al. 2002), MMP-1 and MMP-3 (Chase et al. 2002), and MMP-2 (Yoshida et al. 2001) by inflammatory cells requires the activation of NF-κB. Lappas et al (Lappas et al. 2003) have shown that inhibition of NF-κB DNA binding by NAC results in the repression of LPS-stimulated MMP-9 activity in amnion and choriodecidual explants.

NF-κB – a therapeutic target in preterm labour?

Preterm labour constitutes a syndrome, in that it is the outcome of multiple aetiologies. However, uterine inflammation may represent a final common pathway, mediating labour onset resulting from bacterial infections (Romero et al. 2002), SP-A secretion from the fetal lung (Condon et al. 2004), mechanical stretch (Mohan et al. 2005), or genetic predisposition (Varner & Esplin 2005). NF-κB has long been recognised as a key player in the inflammatory response and work over the last six years has revealed a role for NF-κB in labour-associated inflammation: NF-κB is activated by stimuli that induce labour and in turn regulates the expression of molecules involved in the parturition process. Aside from inflammation, a decline in responsiveness to progesterone is also crucial to labour onset in the human, and NF-κB may antagonise PR to bring about a ‘functional’ progesterone withdrawal. NF-κB is thus central to multiple pathways involved in the onset of labour (Fig. 4) and as such constitutes a potential therapeutic target in the management of preterm labour. Treatment directed against NF-κB has the potential to be more effective than current treatments, which do not cast a sufficiently wide therapeutic net and may also have the added advantage of preventing detrimental effects to the fetus that may result from infection/inflammation (Cornette 2004). However, because of its widespread physiological role, the identification of labour-specific NF-κB signalling...
components and selective targeting of the NF-κB pathway will be crucial in minimising the systemic toxicity of potential new therapies for preterm labour. The effectiveness of such a strategy may, in part, depend on how early in the parturition process NF-κB is activated and on the development of improved diagnostic indicators of preterm labour, so that intervention can arrive before a branching cascade has taken hold.

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References
Molecular Human Reproduction
Nuclear factor-kappa B is essential for up-regulation of interleukin-
motion-mediated preterm labor in the mouse. ENDO 2005 Program & Abstracts The Endo-
crine Society’s 87th Annual Meeting OR13–14, p. 90.
Cortone L 2004 Fetal and neonatal inflammatory response and adverse outcome. Outlines in Fetal & Neonatal Medicine 9
459–470.
Dejardin E, Droin NM, Delhase M, Haes E, Cao Y, Makris C, Li ZW, Karin M, Ware CF & Green DR 2002 The lymphoxygen-beta receptor
induces different patterns of gene expression via two NF-kapp-
aB-p50 homodimers. Immunity 17 525–535.
Deluca C, Petropoulos L, Zmeureanu L & Hiscott J 1999 Nuclear IkappaBbeta maintains persistent NF-kappaB activation in HIV-1-
Donovan CE, Mark DA, He HZ, Liu HC, Kobzik L, Wang Y, De Sanctis GT, Perkins DL & Finn PW 1999 NF-kappa B/Rel transcrip-
tion factors: c-Rel promotes airway hyperresponsiveness and aller-
Dudley DJ, Collmer D, Mitchell MD & Trautman MS 1996 Inflam-
Elliot CL, Allport VC, Loudon JA, Wu GD & Bennett PR 2001 Nuclear factor-kappa B is essential for up-regulation of interleukin-
Fujita T, Nolan GP, Liu HC, Scott ML & Baltimore D 1993 The can-
didate proto-oncogene bcl-3 encodes a transcriptional coactivator that activates through NF-kappa B p50 homodimers. Genes & Devel-
opment 7 1354–1363.
lating factor alpha mediates the inflammatory response to endo-
metrial implantation. Journal of Immunology 156 1802–1809.
Gelezunus R, Ferrell S, Lin X, Mu Y, Cunningham ET Jr, Grant M, Connelly MA & Hambor JE 2000 Inhibition of cyclooxygenase-2 prevents inflam-


Feigenbaum J, Fathallah J, Vinogradov A & Abulafia D 2005 15-Deoxy-Δ12,14-Prosta- 


Olson DM 2003 The role of prostaglandins in the initiation of parturi 


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Terzidou V, Lee YS, Thornton S & Bennett PR 2003 Identification of the response region on the oxytocin receptor (OTR) promoter which is important for the synergistic transactivation of OTR by CEBPBeta and NF-kappab3 transcription factors. Journal of the Society for Gynecologic Investigation 10: 190A.


Yan X, Sun M & Gubb W 2002a Localization of nuclear factor-kappa B (NF kappa B) and inhibitory factor-kappa B (I kappa B) in human fetal membranes and decidua at term and preterm delivery. Placenta 23: 288–293.


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