Antimicrobial proteins and peptides in early life: ontogeny and translational opportunities

Anna J. Battersby1, 2*, Jasmeet Khara1, 3, Victoria Wright1, Ofer Levy4, 5, Beate Kampmann1, 2

1Academic Paediatrics, Imperial College London, United Kingdom, 2Vaccines and Immunity Theme, Medical Research Council (MRC) Unit - The Gambia, Fajara, The Gambia, Gambia, 3Department of Pharmacy, National University of Singapore, Singapore, 4Precision Vaccines Program, Division of Infectious Diseases, Department of Medicine, Boston Children’s Hospital, USA, 5Harvard Medical School, USA

Submitted to Journal: Frontiers in Immunology
Specialty Section: Immunotherapies and Vaccines
Article type: Review Article
Manuscript ID: 212138
Received on: 30 May 2016
Revised on: 18 Jul 2016
Frontiers website link: www.frontiersin.org
Conflict of interest statement

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest

Author contribution statement

AB, OL and BK contributed to the conception of the review article. AB, JK and VW undertook the literature review and identified key papers for inclusion. AB and JK drafted the initial article, and OL, VW and BK contributed to all revisions and subsequent drafts. All authors have given final approval for the version submitted for publication.

Keywords

antimicrobial peptides, Infant, Newborn, Sepsis, Infection, Immunity, Innate, antimicrobial protein, Pneumonia, Bloodstream infection, Bacteremia

Abstract

Word count: 188

Whilst developing adaptive immune responses, young infants are especially vulnerable to serious infections including sepsis, meningitis and pneumonia. Antimicrobial proteins and peptides (APPs) are key effectors that function as broad-spectrum anti-infectives. This review seeks to summarise the clinically relevant functional qualities of APPs and the increasing clinical trial evidence for their use to combat serious infections in infancy. Levels of APPs are relatively low in early life, especially in infants born preterm or with low birth weight (LBW). There are several rationales for the potential clinical utility of APPs in the prevention and treatment of infections in infants: (a) APPs may be most helpful in those with reduced levels; (b) during sepsis microbial products signal via pattern recognition receptors (PRRs) causing potentially harmful inflammation which APPs may counteract; and (c) in the era of antibiotic resistance, development of new anti-infective strategies is essential. Evidence supports the potential clinical utility of exogenous APPs to reduce infection-related morbidity in infancy. Further studies should characterize the ontogeny of antimicrobial activity in mucosal and systemic compartments, and examine the efficacy of exogenous-APP formulations to inform translational development of APPs for infant groups.

Funding statement

Anna J Battersby is supported by a Wellcome Trust clinical research training fellowship. Beate Kampmann is supported by funding from the Medical Research Council (MC_UP_A900/1122) and the NIHR based at Imperial College Healthcare NHS Trust and Imperial College London. Jasmeet S Khara is supported by the President’s Graduate Fellowship from the National University of Singapore. Victoria J Wright is supported by Great Ormond Street Hospital Charity [v1401]. Ofer Levy’s laboratory is supported by a Boston Children’s Hospital Department of Medicine award to the Precision Vaccines Program and by NIH Infant Immunity grant (1R01AI100135-01) and its Administrative Supplements.
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Introduction
During early life, the immune system of the newborn (first 28 days of life) and young infant (up to 3 months of age) undergoes remarkable functional change. Historically, the newborn immune system was thought to be an immature version of the adult. However, contemporary evidence suggests that neonatal responses are not simply “immature” but wholly unique, reflecting the distinct immunological needs of foetal versus newborn life (1). Antenatally the fetus experiences a normally sterile environment until delivery, when the newborn infant is rapidly colonized and challenged with a broad array of microbes (2).

The challenge of immune adaption to this rapid environmental change from immune seclusion to immune challenge may contribute to the propensity of neonates to succumb to overwhelming infection (3). Unique newborn innate and adaptive immunity, reflecting the constraints and needs of the perinatal transition, may also contribute to this susceptibility. Distinct aspects include Th2 polarized responses of monocyte and dendritic cells via pattern recognition receptors, T cell hyporesponsiveness to many stimuli (4) and a limited assortment of infant B-cells capable of producing high affinity antibodies (5). These distinct features of newborn immunity may help prevent overwhelming, and potentially tissue-damaging pro-inflammatory responses and/or potential cross-reactive auto-immune responses to newly encountered microbes. During this immunological transitional period, certain “bridging” mechanisms help provide immune protection for the newborn. This includes “passive immunity” from the transplacental transfer of maternal antibodies to the fetus during pregnancy and postnatal transfer to the newborn primarily through breastfeeding. However, the neonate remains inadequately protected from infection, with
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over one third of deaths during the neonatal period directly attributable to perinatal infections including sepsis, meningitis, pneumonia and diarrheal disease(6,7).

In the absence of developed adaptive immunity, infants may particularly depend upon innate immune mechanisms to combat infections. Indeed, primary immune deficiencies, such as MyD88 and IRAK4 defects in the Toll-like receptor (TLR) pathways, present in early life, and survival past the neonatal phase is associated with much lower risk of infection(8,9). Antimicrobial proteins and peptides (APPs) are a key effector arm of innate immunity that function as broad-spectrum anti-infectives against a wide array of Gram-negative and Gram-positive bacteria, mycobacteria, fungi, and enveloped viruses(10)(11)(12). In this review we discuss the capacity of the newborn and infant to express and deploy APPs; how this may affect early life responses to infection; and how exogenous APPs or agents that induce APP expression may have clinical utility in this age group (Figure 1.), based on systematically collected data using the methods described in tables 1 and 2.

Relative to older infants and adults, newborns (particularly those born preterm) demonstrate lower levels of circulating APPs and reduced cellular release of APPs at sites of infection. This relative deficiency of APPs may contribute to the high risk of invasive infections in early life(13,14). Factors such as age, including gestational age at birth, may influence the physiological levels of APPs in infancy. Table 3 depicts APP levels in preterm and term neonates according to anatomical site. Newborns are at increased risk of infection by microbes including fungi(15), Gram-negative bacteria such as Escherichia coli (E. coli) and Klebsiella pneumoniae (K. pneumoniae), and Gram-positive bacteria such as Staphylococcus aureus (S. aureus), Streptococcus pneumoniae (S. pneumoniae) and Group B Streptococcus (GBS)(15).
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What are antimicrobial peptides and proteins (APPs)?

APPs are fascinating cationic molecules that are released primarily by neutrophils, monocytes and macrophages by secretion or during degranulation. APPs are also produced within the skin and at mucosal surfaces by epithelial cells in the respiratory, gastrointestinal and urinary tract, and thus are present within bodily fluids including saliva, tears, nasal secretion, gastric juice, sweat, semen, airway surface liquid and breast milk.(16). Clinically important APPs in early life include defensins, cathelicidins, protegrins, bactericidal/permeability-increasing protein (BPI), S100 proteins (e.g. calprotectin), lactoferrin, lysozyme and RNAses (e.g. 4,5 and 7)(13).

Defensins are disulphide-rich cationic peptides expressed in plants, insects, fungi, and mammals, including humans(17). Humans express α-defensins (human neutrophil peptides HNP-1, HNP-2, HNP-3, HNP-4 and human defensins HD-5 and -6) and human β-defensins (HBDs including HBD-1, HBD-2 and HBD-3(18,19)). Cathelicidins are multifunctional bactericidal peptides with N-terminal fragments bearing a structural similarity to the protease inhibitor cathelin(20), and include human cathelicidin (LL-37), bovine indolicidin and ranalexin(21). Protegrins are porcine APPs, structurally similar to catherlins, and have served as templates for development of congeners for therapeutic use in humans(22). BPI is a 456 residue LPS-neutralizing anti-infective protein stored within primary granules of human polymorphic neutrophils (PMNs), and has been developed as a synthetic therapeutic (rBPI21)(23,24). Calprotectin is a predominantly neutrophil-derived metal-chelating protein of the S100 protein family(25), which is gaining recognition as a potential diagnostic marker for necrotising enterocolitis (NEC). Lactoferrin is a neutrophil and mammalian-milk derived protein based on one polypeptide chain that contains around 700 amino acids and forms two homologous globular domains (N-and C-lobes)(26,27).
APPs can be constitutively expressed, and/or inducible in response to proinflammatory stimuli. Cathelicidins and HNPs 1-4 are both constitutively expressed and inducible. Lysozyme, lactoferrin, HD5-6 and HBD1 are only constitutively expressed, and HBDs 2-4 are only detectable in response to stimuli(28). APPs facilitate effective pathogen clearance by both direct antimicrobial action and immunomodulatory functions(11,16,29), inducing angiogenesis, promoting wound healing(10), inhibiting LPS-induced proinflammatory responses(10,30), modulating adaptive cellular immune responses(13,31) mediating immune cell ontogeny in the lung and gut and acting as chemoattractants for other immune cells. Chemokines and cytokines regulate the release of APPs but can also display direct antimicrobial activity themselves: indeed, up to two-thirds of human chemokines have been shown to have some direct antibacterial action(28).

APPs target invading bacteria via initial electrostatic contact at the anionic bacterial surface. The specific mode of action differs between APP families but permeabilisation of target cytoplasmic membranes is a common crucial step in APP-mediated antimicrobial activity and cytotoxicity(29). The concept of extracellular entrapment of bacteria, and the contribution of APPs to this process, has advanced in recent years, both in relation to antibacterial activity at epithelial surfaces and within the bloodstream. Yost et al describe neutrophil extracellular traps (NETs), which are lattices of extracellular DNA, chromatin, and APPs that mediate extracellular killing of bacteria(32). A similar process occurs at the intestinal mucosal surface whereby defensins form nanonets to trap bacteria and combat invasion across the intestinal barrier into deeper tissues(33).

In addition APPs could be used as adjunctive agents, to reduce either length of antibiotic treatment and/or inflammation induced by killed microbes/microbial products(34). Important APPs that have undergone clinical trials include rBPI21, Pexiganan, an analogue
of Magainin (MSI-78) (35), Iseganan (IB-367) a protegrin mimetic, Omiganan pentahydrochloride (CLS001) an Indolicidin analogue, Brilacidin a defensin mimetic, LTX-109, a short lactoferricin-based peptide (36) and Talactoferrin (37, 38). The terms analogue and mimetic are used respectively to describe synthetic compounds with closely similar molecular structure versus those with a closely similar functional capacity to that of an endogenous APP.

**APPs and the skin: at the frontline of immune defenses**

Many APPs exert their main effects at the frontlines of the body’s immune defences - the skin and mucosal surfaces. The skin acts as both a physical and a chemical barrier to potential pathogenic organisms and is a source for many APPs, which can be found on the mammalian skin surfaces. HBD-2 is particularly effective against both Gram-negative and Gram-positive bacteria such as *E. coli* and *S. aureus* respectively (22). Amphibian skin has proven to be a promising source of new APPs (39), which can be chemically synthesized for human use. For example, pexiganan (an analogue of magainin - isolated from the skin of the African clawed frog) shows promise for use in the treatment of localized skin infections in humans (35). *Staphylococcus epidermidis* (*S. epidermidis*) is commonly found on the skin, and is responsible for clinically significant infection in preterm and LBW infants (40). LL-37 significantly inhibits growth of *S. epidermidis* isolated from the skin of newborn infants (41), and the reduced levels of LL-37 in preterms (6) may contribute to their susceptibility to *S. epidermidis* infection. In fact, in newborn infants, the lesions of a commonly encountered harmless rash only seen in the neonatal period, termed as “erythema toxicum”, are densely filled with LL-37 expressing neutrophils and eosinophils. While the exact trigger for the erythema toxicum rash remains unclear, it appears that activation of
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innate immune cells to express APPs occurs, and thus colonization of the skin with microbial flora may initiate this process(42).

APPs in the lungs and during pneumonia

Airborne organisms can gain entry to the human host through the airways, but the lung tissue is well protected from invasion by epithelial lining fluid which is rich in APPs(43); including LL-37, defensins and lysozyme(44). Resident mucosal immune cells (e.g. alveolar macrophages), epithelial cells and systemic immune cells (recruited to the lung epithelium at times of microbial challenge) all contribute to the secretion of APPs into epithelial lining fluid(45). During an episode of pneumonia, increased levels of APPs are detectable in bronchoalveolar lavage (BAL) fluid(46). It is clear that HBD-2 is the predominant defensin in neonatal lung, and whether defensin levels are lower in preterm or term infants is yet to be established(47). However, there appear to be reduced levels of BPI in the lungs of preterm infants compared to term infants, which may contribute to the higher risk of pneumonia in this age group; with lower lung APPs, preterm infants are thus unable to clear pathogenic organisms effectively(45,47,48).

APPs in the intestine in health and disease

The human intestine harbors a broad array of micro-organisms (the intestinal microbiome), which are increasingly understood to interact dynamically with the host immune system potentially leading to long term effects on health. APPs are believed to significantly alter environmental microbiota and influence expression of pattern-recognition receptors at the intestinal epithelial surface(49). Indeed, mouse models have helped describe the homeostatic role of α-defensins in regulating the makeup of the commensal microbiota in the neonatal intestine(50). However, whilst hosting beneficial bacteria, the intestinal
mucosa must also protect itself from dangerous invasive organisms: Paneth cells contribute
to this protection by secreting defensins and other APPs into the intestinal fluid. The various
mechanisms by which gut defensins in particular are able to protect the intestinal mucosa
from microbial invasion continue to be elucidated. Recent work published in Science
describes eloquently how HD-6 released from Paneth cells undergoes a complex self-
assembly into nanonets and fibrils at the ostia of crypts, allowing highly effective
entrainment of bacteria and preventing damage to stem cells at the base of crypts (33).

There is a paucity of literature describing APP function in the healthy human newborn and
infant gut, but some inferences can be made from studies of animals, and of human fetal
tissue. Perhaps contrary to what we might expect, a recent study indicates that specific APP
levels are increased in the mouse intestine during the neonatal period. The intestinal
intraepithelial cell (IEC) mRNA expression levels of the mouse cathelicidin related
antimicrobial peptide (mCRAMP), the murine intestinal homologue of human LL-37, is
highly expressed in healthy term neonatal epithelium and becomes less abundant during the
postnatal period as IEC proliferation and differentiation occurs (51). Indeed, mCRAMP
expression has previously also been shown to be increased in embryonic and neonatal
mouse skin, when compared with adult skin (52). Further research is required to explore
whether this specific developmental phenomenon exists in the skin and intestinal mucosae
of human infants.

Studies of human fetal intestinal tissue support the premise that APP levels are relatively
diminished in early life: reduced mRNA expression levels of HD-5 and HD-6 have been
reported within terminal ileal tissue at 24-weeks gestation compared to full-term infants and
adults (53). Indeed, data suggests that low levels of defensins in preterm infants are
associated with increased incidence of intestinal pathology, in particular the devastating
illness, necrotizing enterocolitis (NEC)(54). NEC etiology is incompletely understood but
an interplay exists between host factors (prematurity, very low birth weight VLBW), the
intestinal microbiota and enteral feeds. APPs potentially contribute, as animal models have
shown that depletion of Paneth cells of α-defensins followed by enteric infection results in a
clinical picture akin to human neonatal NEC(55).

Ileal tissue from infants with NEC show elevated defensin levels compared to age-matched
controls, likely indicating that at some stage in the pathogenesis of the disease, Paneth cells
are induced to increase production of defensins(53). Higher HBD-2 concentrations appear
to have a protective effect once NEC pathology is established, in that they have been
associated with more moderate courses of the disease. Indeed, in severe NEC, low HBD-2
expression is accompanied by low TLR4/MD2 expression, suggesting an inadequate
response to luminal bacteria, possibly predisposing to the development of NEC(56).
Calprotectin levels have been extensively investigated in a neonatal stool samples, as a
potential screening marker for the detection of NEC. A recent systematic review of the
literature confirmed fecal calprotectin levels are elevated in NEC, but whether this is robust
enough to act as a diagnostic test early in the disease, and what relevance the levels have to
disease progression and severity remains unclear(25).

An important mode by which the infant intestinal mucosal surface is furnished with APPs,
is through ingestion of maternal breast milk. Indeed, APPs may contribute to the ability of
breast milk to protect the newborn from inflammatory and infectious diseases. Several
APPs have been identified in breast milk, including lactoferrin (LF)(57), lysozyme(58), LL-
37(59), α- and β-defensins(60)(61). Importantly, LF is abundant at concentrations
sufficient to inhibit bacterial growth(60,61). Given its multi-functional immuno-
modulatory, anti-inflammatory and antimicrobial properties, LF supplementation in VLBW
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has been increasingly studied for the prophylactic treatment of BSI and NEC(62). Evidence supports the notion that combinations of components working in synergy contribute to the antimicrobial activity of breast milk, as exemplified by the concomitant action of LF with bovine RNase 5 (angiogenin-1), RNase 4, and angiogenin-2(63). A strategy of mimicking the synergistic nature of breast milk derived APPs and associated molecules has potential for future therapeutics.

**APPs in the blood and bloodstream infection (BSI)**

APPs consistently circulate in the bloodstream, they are transported freely within the plasma, and provide an ongoing low-level non-specific immune defense against potential invasive pathogens. Expression and secretion of some APPs including defensins(64), LL-37(65) and BPI can be mediated by TLRs(6). In infants with BSI with bacterial etiology, plasma BPI concentrations are higher than in healthy infants, which indicates that BPI transcription and/or cellular secretion is up-regulated during infection(23,66). Additionally, healthy uninfected neonates born to mothers who have suffered from an amniotic infection demonstrate higher levels of LF, BPI, HNP-1, HNP-2 and HNP-3 in the cord plasma(67).

Maternal plasma LL-37 levels appear to be the most important predictor of infant plasma LL-37 levels, and although the source of these APPs in cord blood is not known, it is possible that these higher levels may not be a reflection of the functional status of the infant’s own immune system, but an example of maternally derived transplacentally transferred immune protection(68).

However, generally, intracellular levels of APPs are lower in neonates than in later life: LL-37 and BPI levels are reduced in neonatal whole blood and neutrophils when compared with adults(44,69-71), and BPI deficiency of neutrophils in neonates is associated with reduced bacterial-killing capacity(23). However, it is yet to be established whether an infant’s
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intrinsic intracellular or plasma levels of APPs influence an individual’s risk of developing
a BSI, or indeed the clinical outcome following BSI. Measuring serum, plasma or even
resting-state intracellular levels of APPs have obvious limitations in understanding the
importance of differences between neonates and adults. Indeed, more relevant perhaps is
identification of functional impairments of the innate immune response in neonates, such as
defective neutrophil external trap (NET) formation resulting in impaired bacterial killing in
vitro(72). Further characterization of the functional capacities of peripheral blood
neutrophils in term and preterm infants will undoubtedly yield insights into understanding
neonatal BSI and developing strategies for its prevention and cure.

The premature infant: a special case

Premature birth significantly increases susceptibility to serious infections including BSI,
meningitis and pneumonia(73,74). APP levels are generally lower in preterm than in full-
term infants, including within the bloodstream(75) (both in the circulating plasma and
intracellularly within immune cells), at epithelial surfaces and within bodily fluids and
feces(56) (6,47) (Table 3). This relative deficiency in APPs may contribute to the preterm
infant’s increased risk for invasive bacterial infection(13). Importantly, higher levels of
APPs (including HBD-1, HBD-2 and LL-37) are seen in the blood and body fluids of those
with acute infections such as BSI(76) and respiratory infection(46). Increased levels of
APPs in cord blood of infants born to mothers with a history of BSI or chorioamnionitis(67)
is important in the context of premature infants, as preterm delivery is often triggered by
amniotic infection which may therefore act as a significant confounder when assessing for
effect of gestational age on APP levels. Studies not taking a history of chorioamnionitis into
account should therefore be interpreted with caution(18,46).

Clinical application of APPs: Promising evidence from clinical trials in adults?
While the number of APPs undergoing pre-clinical development has been increasing, the majority of clinical trials have focused on topical formulations with few trials in the pediatric population (Table 4). Several lead compounds including Pexiganan, Iseganan and Omiganan have failed to achieve late stage development due to their failure to meet primary trial endpoints, or disappointingly insurmountable regulatory hurdles (38). Currently, Dipexium Pharmaceutical’s Locilex (Pexiganan cream 0.8%) is the only APP undergoing a phase III clinical trial, for the treatment of mild wound infections (NCT01594762). Cellceutix Corporation recently completed phase II trials of Brilacidin in acute bacterial skin infections (NCT02052388) and have begun preclinical studies in otitis media and ocular infections. Cutanea Life Sciences has identified new indications (including skin infections) for Omiganan (CLS001) which was previously not approved for urinary tract infections (NCT02456480). Lytix Biopharma has completed phase II trials of LTX-109 in impetigo (a problematic condition primarily affecting young children). Several pharmaceutical companies are developing APPs for systemic administration, such as Agennix AG who is pursuing the development of oral Talactoferrin in severe sepsis (NCT00630656). Results from their phase II RCT showed a significant reduction in all-cause mortality at 28 days and 6 months in the treatment group (77) yet, the recent follow on phase II/III RCT (OASIS trial) was terminated prematurely over concerns of safety and efficacy (37). Interestingly the APP that has undergone most advanced clinical testing using the intravenous (IV) route is rBPI21, which was assessed for its efficacy in meningococcemia in children (24). Other AMPs such as lactoferrin 1-11 (hLF1-11) are undergoing safety and tolerability testing for delivery via the IV route in healthy volunteers (78).

Clinical applications of APPs in infants
Evidence supports the use of recombinant congeners of APPs to improve circulating levels and potentially reduce the incidence of, and/or improve outcomes from bacterial infection in infants. APPs have been used to prevent infections and aberrant inflammation in high-risk infants such as premature and LBW infants. A large, multicentre, double-blind, randomized controlled trial (RCT) comparing LF supplementation alone or in combination with probiotics demonstrated a significant reduction in late onset sepsis (LOS) in VLBW infants in both treatment groups as compared to placebo controls(79). Secondary analysis of data from the same RCT showed significant reductions in incidence rates of invasive fungal infection in both treatment groups as compared to placebo controls(80). A third LF study demonstrated that the same treatment interventions significantly diminished incidence of NEC in VLBW infants(81). These findings were reiterated in a smaller RCT which found that LF-treated infants experienced fewer primary but also secondary episodes of sepsis as compared to placebo(82). A recent Peruvian study also reported that infants receiving LF were less likely to develop sepsis than placebo controls(83). Taken together, these findings highlight the feasibility of supplemental LF, either alone or in combination with probiotics, as a promising approach to protect VBLW infants from neonatal infections.

Invasive meningococcal disease is a rare but devastating disease, associated with high morbidity and mortality in the young. Promising preclinical data supported the antibacterial and anti-endotoxin properties rBPI21, while phase I/II trials demonstrated the safety of rBPI21 in adults and suggested beneficial effect on inflammatory biomarkers in children with severe meningococcal sepsis, thus prompting a phase III RCT for this indication(84). The study, whose youngest participant was ~2 weeks old, suggested that rBPI21 conferred benefit with respect to mortality and morbidity. By intention to treat analysis, mortality was lower in the rBPI group, though not significantly. A sub-group analysis of those who survived to complete the first infusion of rBPI or placebo demonstrated nearly a 50%
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reduction in mortality in the rBPI_{21} group. Although the study was underpowered to detect
significant changes in mortality by intention to treat analysis, rBPI_{21}-treated study
participants had a substantial reduction in severe limb amputations, shorter ICU stay, and
better return to baseline function. These results suggest the potential utility of rBPI_{21} in
reducing meningococcal-associated complications and, if approved such that it could be
given even sooner in the sepsis cascade, would likely confer even greater benefit. Notably,
when administered to total body irradiated mice, rBPI_{21} demonstrated benefit in conjunction
with conventional fluoroquinolone antibiotic, including more rapid recovery of the
hematopoietic compartment and improved survival suggesting that it may be a useful
adjunct in those deficient in BPI due to chemoradiotherapy(85). These results raise the
possibility to extend the beneficial effects of rBPI_{21} to other populations that are relatively
deficient in functional BPI activity, including the preterm infant group.

Future potential of APPs in diseases of infancy

Circulating and intracellular levels of APPs are relatively low in early life, especially in
those born preterm or with LBW, potentially contributing to susceptibility to infection.
There are several rationales for the potential clinical utility of APPs in the prevention and
treatment of infections in infants: (a) APPs may be most helpful in those with reduced
levels; (b) during sepsis microbial products signal via PRRs causing potentially harmful
inflammation which APPs may counteract; and (c) in the era of antibiotic resistance,
development of new anti-infective strategies is essential.

Clinical trials of oral LF and IV rBPI_{21} have suggested significant clinical benefit lending
support to the hypothesis that APPs, either induced endogenously or as exogenously
administered congeners, may help prevent and treat infections in highly susceptible infants
in early life: particularly premature or VLBW infants. Future strategies should identify and
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develop APPs with potential for prevention and treatment of the most devastating diseases: BSI, pneumonia, CNS infection, diarrheal disease and NEC. There are a number of strategies that have as yet made little progress in clinical trials: such as inhaled TLR ligands that can stimulate production of APPs at the lung surface. The company Pulmotech have developed “PUL-042”; a novel combination of two synthetic TLR agonists (Pam2 and ODN)(86) which will begin Phase 1b/2a clinical studies this year in immunosuppressed adults at high risk of developing pneumonia. PUL-042 or similar compounds could be considered for use to reduce pneumonia in at risk infants, such as ventilated premature or VLBW infants.

APPs in the era of antibiotic resistance

In the era of antibiotic resistance individual APPs, combinations of APPs, or agents that induce their expression (e.g. TLR agonists), may serve as novel alternatives antibiotics. It has been proposed that bacterial resistance to APPs is much less likely to evolve than to conventional antibiotics, owing to their broad, non-specific antibacterial mechanism of action(87). The in-vivo response to infection involves the action of multiple endogenous APPs, and thus a combination therapy of multiple synthetic APPs may be a better therapeutic option than an individual agent.

As long-term survival rates of preterm and VLBW infants in neonatal intensive care units (NICUs) increase, so does morbidity associated with catheter-associated blood-stream infections (CA-BSIs). Neonates are at particular risk of exposure to antibiotic resistant bacterial BSIs: specifically, from, methicillin-resistant Staphylococcus aureus (MRSA), vancomycin resistant enterococci (VRE) and extended spectrum beta-lactamase producing Gram-negative bacteria (ESBL)(88). New strategies are needed to eradicate antibiotic-resistant bacterial strains, including those colonizing or infecting the skin and mucosal
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surfaces, before the organisms gain entry to the bloodstream. Experimental data is emerging on the potential of APPs as single or synergistic agents to existing therapies in this regard.

In the case of staphylococcal resistant organisms, a recent study using a skin explant model to assess the efficacy of ranalexin with an endopeptidase (lysostaphin) found that the combination was able to rapidly and specifically kill resistant staphylococcal species without adversely affecting normal skin microflora(89). Additionally, a group from Singapore have designed 4 hybrid peptides (based on indolicidin and ranalexin) which display strong antibacterial activity against MRSA in vitro(90), and another in vitro study identified indolicidin (and a number of other APPs) alone and in combination with antibiotics, as potential candidates for future therapeutics against MRSA biofilms(91). The underlying mechanisms explaining these synergistic effects against MRSA remain to be completely elucidated. An in vitro and in vivo study of nafcillin (an anti-staphylococcal β-lactam) identified that it enhances killing of MRSA by increasing the binding of LL-37 to the MRSA membrane.

Infection with penicillin-resistant strains of S. pneumonia can be a serious therapeutic challenge in the young infant. Recently, a Malaysian research group designed a novel hybrid peptide “DM3” which has shown synergistic therapeutic efficacy in combination with penicillin in a mouse model of systemic infection with a strain of penicillin-resistant S.pneumoniae(92). Design and testing of APPs to ensure maximal efficacy whilst limiting toxicity is of paramount importance for the vulnerable infant age group.

A broad-based approach to future research

Newborn infants and in particular those born prematurely are highly susceptible to invasive and often overwhelming sepsis. Data from the World Health Organization suggests that
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worldwide every year 1.1 million neonates die from infection(3). Evidence is growing for
the potential of APPs to be useful in the reduction of morbidity and mortality from infection
in infancy in both resource-rich and resource-poor countries. Further research is needed,
including in vitro and in vivo studies characterizing the ontogeny of global cellular and
soluble antimicrobial and anti-infective (e.g. endotoxin-neutralizing) activity within
systemic compartments and at epithelial surfaces. This basal survey will then need to be
systematically compared in relation to induced and exogenous-APP supplemented fluids to
inform translational development of APPs in high-risk populations, including newborn and
infant groups.
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Acknowledgements

The authors would like to acknowledge the contributions of Jankey Ya Jagne and Hadi Sallah to the early drafts of the manuscript. Conflict-of-interest disclosure: The authors declare no competing financial interests. All authors have read and acknowledge the journal’s authorship agreement.
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547 Minami J, Odamaki T, Hashikura N, Abe F, Xiao JZ. Lysozyme in breast milk is a
548 selection factor for bifidobacterial colonisation in the infant intestine. Benef Microbes

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552 of cathelicidin antimicrobial peptides in murine mammary glands and human milk.

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563 Murata M, Wakabayashi H, Yamauchi K, Abe F. Identification of milk proteins
enhancing the antimicrobial activity of lactoferrin and lactoferricin. J Dairy Sci

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K, Meinken C, et al. Toll-like receptor triggering of a vitamin D-mediated human
Antimicrobial proteins and peptides in early life: ontogeny and translational opportunities
Battersby AJ, Khara J, Wright VJ, Levy O, Kampmann B

doi:10.1126/science.1123933


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Battersby AJ, Khara J, Wright VJ, Levy O, Kampmann B


87. Perron GG, Zasloff M, Bell G. Experimental evolution of resistance to an
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25
Figure 1. Antimicrobial proteins and peptides as protective antimicrobial molecules in the newborn bloodstream and at barrier surfaces. Depicts the site of action of naturally occurring as well as exogenous therapeutic and prophylactic antimicrobial peptides and proteins. (APP; antimicrobial peptide, BPI; bactericidal/permeability-Increasing protein, LL-37; human cathelicidin, PMNs; polymorphic neutrophils, TLR; toll-like receptor, rBPI21; opebacan, BSI; bloodstream infection, CA-BSI; catheter-associated bloodstream infection).
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Tables

Table 1. Literature search strategy. A search for articles was performed using a “systematic review” based method: searching through the Pubmed database using a detailed search strategy with keywords and MeSH terms as listed above. Rapid assessment of the literature to identify the most relevant articles through a rapid screen of titles and abstracts by 1 reviewer. Article selection removed duplicates and the remainder were then screened based on inclusion criteria below.

<table>
<thead>
<tr>
<th>antimicrobial peptide</th>
<th>AND/OR</th>
<th>infant</th>
<th>AND/OR</th>
<th>sepsis</th>
</tr>
</thead>
<tbody>
<tr>
<td>antimicrobial protein</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>lactoferrin</td>
<td></td>
<td>neonat*</td>
<td></td>
<td>infection</td>
</tr>
<tr>
<td>cathelicidin</td>
<td></td>
<td>early life</td>
<td></td>
<td>pneumonia</td>
</tr>
<tr>
<td>LL-37</td>
<td></td>
<td>newborn</td>
<td></td>
<td>diarrhoea</td>
</tr>
<tr>
<td>BPI</td>
<td></td>
<td>birth</td>
<td></td>
<td>necrotizing enterocolitis</td>
</tr>
<tr>
<td>cathelin</td>
<td></td>
<td></td>
<td>BSI</td>
<td></td>
</tr>
<tr>
<td>HNP-1</td>
<td></td>
<td></td>
<td>meningitis</td>
<td></td>
</tr>
<tr>
<td>HNP-2</td>
<td></td>
<td></td>
<td>preterm</td>
<td></td>
</tr>
<tr>
<td>HNP-3</td>
<td></td>
<td></td>
<td>prematur*</td>
<td></td>
</tr>
<tr>
<td>HBD-1</td>
<td></td>
<td></td>
<td>low birth weight</td>
<td></td>
</tr>
<tr>
<td>HBD-2</td>
<td></td>
<td></td>
<td>skin</td>
<td></td>
</tr>
<tr>
<td>HBD-3</td>
<td></td>
<td></td>
<td>intestin*</td>
<td></td>
</tr>
<tr>
<td>protegrin</td>
<td></td>
<td></td>
<td>breast milk</td>
<td></td>
</tr>
<tr>
<td>protegrin</td>
<td></td>
<td></td>
<td>amnion*</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>blood</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>lung</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Immun*</td>
<td></td>
</tr>
</tbody>
</table>
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Table 2. Inclusion criteria for referenced studies. Description of the studies included in the structured review: topics covered and reasons for their inclusion.

<table>
<thead>
<tr>
<th>Inclusion criteria</th>
</tr>
</thead>
<tbody>
<tr>
<td>Language: English</td>
</tr>
<tr>
<td>Populations: All</td>
</tr>
<tr>
<td>Articles that include research on: Antimicrobial protein and peptide (APP) expression and secretion during the first year of life within the blood, mucosal surfaces and bodily fluids, including preterm, low birth weight and infected human infants. Clinical trials of APPs as therapeutics that show promise for use in the treatment or prevention of neonatal infections and inflammatory conditions. Where relevant reference animal studies that support clinical studies or hypotheses relating to human infants</td>
</tr>
</tbody>
</table>
Table 3. Differential levels of antimicrobial peptides and proteins (APPs) according to age and anatomical site. Summary of the results of published human studies assessing APP levels in preterm infants, term infants, their mothers and other adults. Study results are reported in the context of the anatomical site and sample type assessed, the methods used, and the age of the study participants.
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### Table 3.

<table>
<thead>
<tr>
<th>Family/Peptide</th>
<th>Site</th>
<th>Sample type</th>
<th>Age groups</th>
<th>APP levels</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cathelicidin: LL37</td>
<td>Blood</td>
<td>Whole blood</td>
<td>Neonates and adults</td>
<td>Lower levels in preterm than term neonates and mothers (enzyme-linked immunosorbent - ELISA)(75). Lower levels in neonatal than in adult neutrophils (flow cytometry), but no difference in plasma levels (ELISA)(69).</td>
</tr>
<tr>
<td>Breast</td>
<td>Breast milk</td>
<td>Mothers</td>
<td>Present in expressed breast milk (EBM) of mothers of term &amp; preterm neonates (reverse-transcriptase PCR (RT-PCR) &amp; ELISA) and in EBM-derived cells (direct immunoprecipitation and western blot)(59),(61).</td>
<td></td>
</tr>
<tr>
<td>Gut</td>
<td>Faeces/meconium</td>
<td>Term neonates</td>
<td>Distinct inter-individual variation in faeces &amp; meconium (western blot)(93).</td>
<td></td>
</tr>
<tr>
<td>Lungs</td>
<td>Tracheal aspirates</td>
<td>Preterm/term neonates</td>
<td>Detected in bronchoalveolar lavage fluid (BALF) of mechanically ventilated neonates (antigen capture dot-blot assay), concentration did not vary with gestational age (46).</td>
<td></td>
</tr>
<tr>
<td>Lungs</td>
<td>Skin biopsies/vernix caseosa</td>
<td>Term neonates and adults</td>
<td>Site specific expression profile, with expression in human skin biopsies of newborns (immunohistochemistry)(42), higher levels within neonatal foreskin compared to adults (immune staining)(52), and dense expression in vernix of newborns (enhanced chemiluminescence western blot detection system(42) and reverse-phase chromatography-dot blot/western blot analyses)(94).</td>
<td></td>
</tr>
<tr>
<td>Blood</td>
<td>Whole blood</td>
<td>Preterm/term neonates and mothers</td>
<td>Significantly lower HNP-1, -2 and -3 levels in preterm and term neonates compared to mothers (ELISA)(75). Significantly higher HNP-1 and -3 levels in preterm infants delivered to mothers with amniotic infection, compared to normal deliveries (ELISA). Correlation between gestation and HNP levels in preterm infants(67).</td>
<td></td>
</tr>
<tr>
<td>Blood</td>
<td>Breast milk</td>
<td>Mothers</td>
<td>Significantly higher HD5 levels in breast milk from mothers at day 7 than at day 21, and no association between HD5 levels and risk of sepsis(61).</td>
<td></td>
</tr>
<tr>
<td>Gut</td>
<td>Faeces/meconium</td>
<td>Term neonates</td>
<td>HNP-1 and -2 in meconium and neonatal faeces (ELISA). HNP-3 in meconium (Matrix-assisted laser desorption/ionization-mass spectrometry (MALDI-MS)) (93). HD5 in meconium and faeces of neonates (weak cationic exchange chromatography and reversed-phase chromatography/MALDI-MS)(93).</td>
<td></td>
</tr>
<tr>
<td>Skin</td>
<td>Vernix caseosa</td>
<td>Term neonates</td>
<td>The main antimicrobial components in vernix (HPLC, dot blot analysis, mass spectrometry)(94), and western analysis(95)).</td>
<td></td>
</tr>
<tr>
<td>Blood</td>
<td>Whole blood</td>
<td>Mother-infant pairs</td>
<td>Significantly lower HBD-2 (ELISA) in serum of preterm compared to term infants. Low levels of HBD-2 may be associated with increased risk of late onset sepsis (LOS)(96).</td>
<td></td>
</tr>
<tr>
<td>Blood</td>
<td>Breast milk</td>
<td>Mothers</td>
<td>HBD-1 and HBD-2 levels (ELISA) significantly higher at day 7 than day 21, and displayed antimicrobial activity against neonatal pathogens. No difference between levels fed to infants with and without LOS(61).</td>
<td></td>
</tr>
<tr>
<td>Gut</td>
<td>Faeces/meconium</td>
<td>Preterm/term neonates</td>
<td>Similar levels of HBD-2 in preterm and term infants (ELISA), both of which are significantly higher than in children or adults(18). Significant lower levels in faeces compared to meconium (ELISA)(56).</td>
<td></td>
</tr>
<tr>
<td>Lungs</td>
<td>Tracheal aspirates/lung tissue</td>
<td>Preterm/term neonates</td>
<td>Present in tracheal aspirates (TA) (antigen capture dot-blot assay) with similar levels in preterm and term infants(46). HBD-2 is the predominant defense in neonatal lung, and levels (RT-PCR) appear to be developmentally regulated(47).</td>
<td></td>
</tr>
<tr>
<td>Skin</td>
<td>Skin biopsies</td>
<td>Term neonates/adults</td>
<td>HBD-1 is constitutively expressed in human skin, (42) and HBD-2 levels comparable between perinatal and adult skin (immunohistochemistry)(52).</td>
<td></td>
</tr>
<tr>
<td>Blood</td>
<td>Whole blood</td>
<td>Preterm/term neonates and adults</td>
<td>Three-fourfold lower cellular content of BPI in neonatal compared to adult neutrophils (western blot)(70). Lower plasma levels of BPI in preterm infants compared to mothers (ELISA)(75), and lower ability to release BPI from neutrophils in preterm than term infants and adults (ELISA)(44). Higher levels in infants delivered prematurely due to maternal amniotic infection (ELISA). No association between gestational age and BPI levels(67).</td>
<td></td>
</tr>
<tr>
<td>Lungs</td>
<td>Tracheal aspirates</td>
<td>Preterm/term neonates</td>
<td>Higher levels in term than preterm infants and significant increase in first postnatal week, as detected in acid extracts of neonatal TA polymorphic neutrophils (PMNs) (ELISA)(45).</td>
<td></td>
</tr>
<tr>
<td>Maternal</td>
<td>Breast milk</td>
<td>Mothers</td>
<td>Most abundant APP present within breast milk of mothers of preterm infants (ELISA) with significantly higher levels at day 7 than day 21(61).</td>
<td></td>
</tr>
<tr>
<td>Lactoferrin</td>
<td>Skin surface/vernix caseosa</td>
<td>Term neonates and adults</td>
<td>Enriched on neonatal skin surface compared to adults(97), and identified in vernix of full-term infants (western analysis)(95).</td>
<td></td>
</tr>
</tbody>
</table>
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**Table 4. Important synthetic antimicrobial peptides and proteins according to the endogenous compounds from which they are derived.** *Denotes promising compounds currently in pre-clinical experimental stages, all other synthetic forms are in clinical trial stages. ^Denotes compounds in the endogenous form that have undergone human clinical trial.

<table>
<thead>
<tr>
<th>Origin</th>
<th>Endogenous compounds</th>
<th>Exogenous synthetic compounds</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bovine</td>
<td>• Indolicidin</td>
<td>• Omiganan pentahydrochloride (CLS001)</td>
</tr>
<tr>
<td></td>
<td>• Bovine Lactoferrin (BLF)^</td>
<td>• LTX-109</td>
</tr>
<tr>
<td>Porcine</td>
<td>• Protegrin</td>
<td>• Iseganan (IB-367)</td>
</tr>
<tr>
<td></td>
<td>• β-defensin 2 (pBD-2)</td>
<td>• pBD-2* (REF TANG 2015)</td>
</tr>
<tr>
<td>Amphibian</td>
<td>• Ranalexin</td>
<td>• Polymixin</td>
</tr>
<tr>
<td></td>
<td>• Magainin</td>
<td>• Pexiganan (MSI-78)</td>
</tr>
<tr>
<td>Human</td>
<td>• Human defensins</td>
<td>• Brilacidin</td>
</tr>
<tr>
<td></td>
<td>• Cathelicidin</td>
<td>• N/A</td>
</tr>
<tr>
<td></td>
<td>• Bactericidal/permeability-increasing protein (BPI)</td>
<td>• rBPI21</td>
</tr>
<tr>
<td></td>
<td>• Lactoferrin (LF)</td>
<td>• Talactoferrin &amp; LTX-109</td>
</tr>
</tbody>
</table>

In review
Table 5. Antimicrobial peptides and proteins evaluated in clinical trials for the treatment of infections in children. 1. BLF; bovine lactoferrin, LGG; probiotic Lactobacillus rhamnosus GG, GOS; galacto-oligosaccharides. Sample size (n) is absent for trials either in progress or completed but unpublished. 2. NS; ‘not stated’. 3. Reference or registration numbers are obtained from http://clinicaltrials.gov, http://www.isrctn.com, and http://www.anzctr.org.au
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Table 5.

<table>
<thead>
<tr>
<th>Peptide</th>
<th>Clinical application</th>
<th>Treatment arms (n)</th>
<th>Phase</th>
<th>Status</th>
<th>Company</th>
<th>Outcome</th>
<th>Ref/Reg no.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Opebacan (rBPI21):</td>
<td>Severe meningococcal sepsis</td>
<td>rBPI21 (190)</td>
<td>III</td>
<td>Complete</td>
<td>Xoma</td>
<td>The trial was underpowered to detect significant differences in mortality. However, patients receiving rBPI21 had a trend towards improved outcome in all primary outcome variables, and the study authors concluded that rBPI21 is beneficial in decreasing complications of meningococcal disease.</td>
<td>Levin 2000(24)</td>
</tr>
<tr>
<td>Recombinant 21-kDa modified fragment of human bactericidal/permeability-increasing protein (BPI)</td>
<td>Placebo (203)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Late-onset sepsis</td>
<td>BLF (153)</td>
<td></td>
<td></td>
<td>NS</td>
<td>Saint Anna Foundation and Dicofarm</td>
<td>Compared with placebo, BLF supplementation alone or in combination with LGG (lactobacillus rhamnosus GG) reduced the incidence of a first episode of late-onset sepsis in VLBW neonates(79). Prophylactic oral administration of BLF also reduces the incidence of invasive fungal infection in preterm VLBW neonates. Compared with placebo, BLF supplementation alone or in combination with LGG reduced the incidence of ≥ stage 2 NEC and of death-and/or ≥ stage 2 NEC in VLBW neonates(81).</td>
<td>ISRCTN53107700 Manzoni 2009(79) Manzoni 2012(80) Manzoni 2014(81)</td>
</tr>
<tr>
<td>Invasive fungal infections</td>
<td>BLF plus LGG (151)</td>
<td></td>
<td></td>
<td>Complete</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Placebo (168)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Necrotizing enterocolitis</td>
<td>BLF (247)</td>
<td></td>
<td>NS</td>
<td>Complete</td>
<td></td>
<td></td>
<td></td>
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<tr>
<td></td>
<td>BLF plus LGG (238)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Placebo (258)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Late-onset sepsis</td>
<td>BLF (22)</td>
<td></td>
<td>NS</td>
<td>Complete</td>
<td>Ankara University</td>
<td>Fewer sepsis episodes were observed in LF-treated infants with none developing NEC, without statistical significance(82).</td>
<td>NCT01287507 Akin 2014(82)</td>
</tr>
<tr>
<td>Necrotizing enterocolitis</td>
<td>BLF (95)</td>
<td></td>
<td>II</td>
<td>Complete</td>
<td>Universidad Peruana Cayetano Heredia</td>
<td>Overall sepsis occurred less frequently in the LF group than in the control group. Although the primary outcome did not reach statistical significance(83)</td>
<td>NCT01264536(83)</td>
</tr>
<tr>
<td></td>
<td>Placebo (95)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Late-onset sepsis</td>
<td>BLF (22)</td>
<td></td>
<td>III</td>
<td>Ongoing</td>
<td></td>
<td></td>
<td>NCT01525316</td>
</tr>
<tr>
<td></td>
<td>Placebo</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Healthcare-associated infections Necrotizing enterocolitis</td>
<td>BLF</td>
<td>NS</td>
<td>Complete</td>
<td>Research Center of Sainte Justine, Canada</td>
<td>Results awaited</td>
<td>ISRCTN66482337</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Placebo</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Late-onset sepsis</td>
<td>BLF (25)</td>
<td></td>
<td>III</td>
<td>Ongoing</td>
<td>National Health and Medical Research Council, Australia</td>
<td>Results awaited</td>
<td>ACTRN12611000 247976</td>
</tr>
<tr>
<td></td>
<td>Placebo</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Late-onset sepsis</td>
<td>BLF (95)</td>
<td></td>
<td>III</td>
<td>Ongoing</td>
<td>The National Institute for Health Research, UK</td>
<td>Results awaited</td>
<td>ISRCTN88261002</td>
</tr>
<tr>
<td></td>
<td>Placebo</td>
<td></td>
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</tr>
</tbody>
</table>

737
Naturally occurring APPs in the infant immune system

↓ BPI in tracheal aspirates of preterm vs. term infants

↓ LL-37 and BPI in PMNs of term newborn infants vs. adults

↓ LL-37, BPI, α- and β-defensins in serum of preterm vs. term infants/adults

↓ Defensins in gut of preterm and VLBW infants vs. healthy term infants

↑ LL-37 in vernix caseosa of newborn infants vs. adults

APPs (and their stimulants) with future potential to prevent or treat infection/inflammation in infants

Inhaled TLR ligands to stimulate APP secretion in the lungs for treatment or prevention of pneumonia in ventilated infants?

Intravenous rBPI23 as an adjunctive therapy for the treatment of serious BSI in preterm or high risk infants?

Oral lactoferrin for treatment or prevention of BSI and NEC in at risk infants

Ranalexin (synthetic cathelicidin) with lysostaphin against antibiotic-resistant staphylococci colonising the skin of infants at risk CA-BSI