Vaccinia virus immune evasion: mechanisms, virulence and immunogenicity

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Virus infection of mammalian cells is sensed by pattern recognition receptors and leads to an innate immune response that restricts virus replication and induces adaptive immunity. In response, viruses have evolved many countermeasures that enable them to replicate and be transmitted to new hosts, despite the host innate immune response. Poxviruses, such as vaccinia virus (VACV), have large DNA genomes and encode many proteins that are dedicated to host immune evasion. Some of these proteins are secreted from the infected cell, where they bind and neutralize complement factors, interferons, cytokines and chemokines. Other VACV proteins function inside cells to inhibit apoptosis or signalling pathways that lead to the production of interferons and pro-inflammatory cytokines and chemokines. In this review, these VACV immunomodulatory proteins are described and the potential to create more immunogenic VACV strains by manipulation of the gene encoding these proteins is discussed.

Introduction

Vaccinia virus (VACV) is the live vaccine used to immunize against smallpox (Fenner et al., 1988) and, whilst it remains the only vaccine to have eradicated a human disease, its origin and natural host are unknown (Baxby, 1981). VACV is the most intensively studied member of the genus Orthopoxvirus of the family Poxviridae (Moss, 2007). It is distinct from cowpox virus (CPXV), the virus presumed to have been used by Edward Jenner in 1796 when he introduced vaccination against smallpox. Properties of orthopoxviruses include a dsDNA genome of approximately 200 kb, a cytoplasmic replication cycle, the production of two distinct forms of infectious virus particle called intracellular mature virus (IMV) and extracellular enveloped virus (EEV), virus-encoded enzymes for transcription and DNA replication, and many virulence factors that modulate the innate immune response to infection.

Although smallpox was declared eradicated in 1980, interest in VACV has continued because of the development of VACV as a vector for the expression of foreign genes, and because VACV represents an excellent model for studying virus–host interactions. In the early 1980s, recombinant VACV strains expressing foreign genes were constructed (Mackett et al., 1982; Panicali & Paoletti, 1982) and shown to have potential application as new live vaccines (Panicali et al., 1983; Smith et al., 1983a, b; Paoletti et al., 1984) that could induce both antibody and T-cell responses to the foreign antigen (Bennink et al., 1984). The capacity of VACV for foreign DNA is at least 25 kb (Smith & Moss, 1983) and therefore multiple foreign genes can be expressed simultaneously to create a polyclonal vaccine (Perkus et al., 1985). Apart from the use of recombinant VACVs as live vaccines, these viruses are valuable research tools that have been used, for instance, to identify which virus antigens are recognized by CTLs (Yewdell et al., 1985; Bennink et al., 1986, 1987; McMichael et al., 1986; Osman et al., 1999) and to identify the human immunodeficiency virus (HIV) co-receptor fusin (CXCR4) (Feng et al., 1996). Whilst the concept of reusing VACV as a vaccine for other infectious diseases was attractive, the imperfect safety record associated with its use (Lane et al., 1969) necessitated improvements in safety before its reuse in man. To this end, researchers sought to identify VACV virulence genes and then remove these from the genome to create stably attenuated vaccines. This search and other approaches led to the discovery of the many VACV proteins that inhibit the innate response to infection, the subject of this review. For earlier reviews of this topic, see Smith (1994), Smith et al. (1997b), Moss & Shisler (2001), Alcamì (2003) and Seet et al. (2003).

The linear dsDNA genome of VACV and other orthopoxviruses may be divided into a conserved central region of about 100 kb that encodes proteins that are mostly...
essential for virus replication, and more variable terminal regions, which encode non-essential factors affecting virulence, host range and immunomodulation and represent about half the virus genes (Gubser et al., 2004). The proteins encoded by these terminal genes have diverse functions, but many target the innate immune system and can be grouped according to which component they target. The function of some of these proteins was inferred from amino acid similarity with cellular proteins of known function. For instance, the VACV complement protein (VCP) (Kotwal & Moss, 1988), the soluble IL-1 receptor (Smith & Chan, 1991; Alcamí & Smith, 1992) and the 3β-hydroxysteroid dehydrogenase (3β-HSD) enzyme (Moore & Smith, 1992). In other cases, however, the protein function was deduced by experimentation or determination of its three-dimensional structure, comparison with protein structure databases and experimentation. The study of these proteins has established some general principles. First, these immunomodulatory proteins are very numerous and VACV devotes between one-third and one-half of its genetic coding capacity to them. Secondly, VACV has many gene families that indicate duplication and diversification of an ancestral gene (Goebel et al., 1990; Smith et al., 1991). Thirdly, the great majority of these proteins are expressed early during infection to combat the innate immune system rapidly, although a notable exception is the soluble IL-1 receptor (IL-1R), which is expressed late during infection (Alcamí & Smith, 1992). Fourthly, there are several examples where multiple proteins apparently target the same cellular pathway and yet loss of each protein individually alters the virus phenotype in vivo, indicating that the proteins have non-redundant functions. Lastly, a protein may have multiple immunomodulatory functions.

This review focuses largely on proteins from VACV rather than poxviruses in general and this is dictated by length restrictions. Thus, we regret it has not been possible to cite all articles on this topic; however, many of the principles learnt by VACV are applicable to these other viruses, and in some cases reference is made to other orthopoxviruses. Different aspects of the innate immune system, and how VACV interferes with these, are described in turn, and the review concludes with a consideration of the influence of virus immunomodulators on virus virulence and immunogenicity, and future prospects for development of therapeutics and vaccines.

**Complement**

The complement system represents an important host defence that can destroy viruses or virus-infected cells and promote the phagocytosis of virions that have been opsonized by antibody via recognition of the Fc region of bound immunoglobulin. To counteract complement, VACV expresses an abundant, 35 kDa protein called VCP that is secreted from infected cells and contains four short consensus repeats that are characteristic of the family of complement control proteins (Kotwal & Moss, 1988). VCP binds to complement components C3b and C4b and functions as a co-factor with factor I in promoting cleavage of C3b and C4b and thereby blocks activation of the complement cascade by either the classical or alternative pathway (McKenzie et al., 1992). VCP contributes to virus virulence because a VACV strain engineered to lack the VCP gene is attenuated in vivo (Isaacs et al., 1992a). More recently, it was reported that VCP binds to the A56 protein (also called the haemagglutinin), which is present on the surface of infected cells and EEV particles (DeHaven et al., 2010). This interaction helps defend cells and EEV particles against complement. A second VACV protein, B5, is also a member of the complement protein family and has four short consensus repeats (Takahashi-Nishimaki et al., 1991). B5 is a type I integral membrane glycoprotein and is present in the EEV outer envelope (Engelstad et al., 1992; Isaacs et al., 1992b), but no role in protection against complement has been described. Instead, B5 is needed for the formation of EEV and thereby promotes virus dissemination (Engelstad & Smith, 1993; Wolff et al., 1993; reviewed by Smith et al., 2002; Roberts & Smith, 2008). VACV has another defense against complement that is mediated by acquisition of host complement control proteins CD46, CD55 and CD59 in the EEV envelope (Vanderplasschen et al., 1998). The presence of CD55, in particular, helps the EEV particle escape destruction by complement and explains the greater resistance of EEV to complement compared with IMV particles, which lack these host complement proteins and are very sensitive to destruction by complement.

These virus defences against complement are beneficial but not absolute. For instance, it is known that, whilst the EEV particle is more resistant to complement than IMV in the absence of specific antibody (Vanderplasschen et al., 1998), the EEV particle can be neutralized by antibody directed against the A33 protein if complement is present (Lustig et al., 2004), and neutralization via antibodies to B5 is enhanced by, or dependent on, complement (Benhnia et al., 2009). Furthermore, the protective efficacy of antibody to EEV is mediated by complement and Fc receptors (Cohen et al., 2011).

**Interferons**

Interferons (IFNs) are species-specific, secreted glycoproteins with potent antiviral effects. They were discovered in 1957 (Isaacs & Lindenmann, 1957; Isaacs et al., 1957) and are grouped into three classes. Type I IFNs include IFN-α and IFN-β, and others such as IFN-κ, IFN-δ and IFN-ω, and all exert their effects via the type I IFN receptor, which is expressed ubiquitously. Type II IFN (IFN-γ) is secreted by activated immune cells [principally natural killer (NK) and T-cells], and activates macrophages and promotes a cell-mediated [T-helper 1 (Th1)] adaptive immune response. Type III IFNs (IFN-λs) are also secreted in response to virus infection, but the type III IFN receptor
has a more limited tissue distribution. Type I, II and III IFNs each play important roles in anti-VACV defence, as illustrated by the different in vivo responses to infection when these IFNs, or their receptors (IFNRs), are either absent from the host or expressed by the virus (Kohonen-Corish et al., 1990; van den Broek et al., 1995; Bartlett et al., 2005).

The IFN response is initiated upon sensing of viral pathogen-associated molecular patterns (PAMPs) by host cell pattern recognition receptors (PRRs) (Fig. 1). These include membrane-associated Toll-like receptors (TLRs), retinoic acid inducible gene I (RIG-I)-like receptors (RLRs), such as RIG-I and melanoma differentiation antigen 5 (MDA5) that detect foreign cytoplasmic RNA, and putative cytosolic dsDNA sensors, such as absent in melanoma 2 (AIM2), RNA polymerase III, DNA-RNA, and putative cytosolic dsDNA sensors, such as absent from the host or expressed by the virus (Kohonen-Corish et al., 1990; van den Broek et al., 1995; Bartlett et al., 2005).

*IPS-1* and *IPS-2* induce signalling cascades that culminate in the activation of transcription factors, such as IRF3 and IRF7, NF-kB activation of transcription factors, such as IFN-regulatory factors 3 and 7, DNA protein kinase dependent activator of IFN-regulatory factors (DAI), IFN-inducible factor 16 (IFI16), DNA protein kinase (DNA-PK) and cyclic GMP-AMP synthase (cGAS) (reviewed by Paludan & Bowie, 2013). Engagement of PRRs induces signalling cascades that culminate in the activation of transcription factors, such as IFN-regulatory factors (IRF) 3 and IRF7, NF-kB and activator protein 1 (AP-1), their translocation into the nucleus and transcription of genes encoding type I IFNs (notably IFN-β), cytokines and chemokines. IRF3, NF-kB and AP-1 together form a complex called the enhancerosome that binds to the IFN-β promoter and stimulates transcription (Warth et al., 1998). IRF7 induces the transcription of IFN-α genes as well as the IFN-β gene (Marie et al., 1998), and is responsible for the high levels of IFN-α released by specialized plasmacytoid dendritic cells (Kato et al., 2005).

IFNs are secreted from the cell and then engage their cognate receptor on the same cell (autocrine signalling) or neighbouring cells (paracrine signalling), and thereby induce the Janus kinase (JAK)/signal transducer and activator of transcription (STAT) signalling cascades. Type I and III IFNs activate signalling pathways that lead to the formation of a complex called IFN-stimulated gene factor 3 (ISGF3) (comprising STAT1, STAT2 and IRF9) (Fig. 1). ISGF3 activates transcription of IFN-stimulated genes (ISGs) by binding to IFN-stimulated response elements (ISREs) present in the promoters of these genes. Type II IFN (IFN-γ) signals via STAT1 homodimers that activate transcription by binding to γ-activated sequences (GAS) in a subset of ISG promoters. For a review of JAK/STAT signalling, see Stark & Darnell (2010). Thus, IFN induces the co-ordinated expression of several hundred ISGs [including protein kinase R (PKR), 2′-5′-oligoadenylate synthase (OAS), ISG15 and Mx proteins] that together confer an antiviral state. PKR is activated by dsRNA and then phosphorylates the eukaryotic translation initiation factor 2α (eIF2α), thereby causing inhibition of protein synthesis. OAS synthesizes 2′-5′-oligoadenylates upon its activation by dsRNA, and these activate RNase L, which degrades viral and cellular mRNAs (Silverman, 2007). The ubiquitin-like protein ISG15 becomes conjugated to a range of proteins, including IRF3, RIG-I, human MxA and PKR, and stabilizes these targets against degradation (Zhao et al., 2005; Lu et al., 2006; Kim et al., 2008), thus modulating the IFN-stimulated antiviral response. ISG15 may also be secreted from cells and contribute to defence against microbial infection (Bogunovic et al., 2012). For a review of IFNs, their antiviral activity and virus evasion strategies see Randall & Goodbourn (2008).

Early studies indicated that VACV was able to interfere with IFNs or their mechanism(s) of action. Forty years ago, it was noted that vesicular stomatitis virus (VSV) replication was inhibited by prior treatment of susceptible cells with IFN. However, if the cells were treated with IFN and then co-infected with VSV and VACV, VSV replication was restored (Thacore & Youngner, 1973). This implied that VACV was providing some factor(s) in trans that overcame the IFN-mediated blockade of VSV replication. Later, it was demonstrated that this factor prevented PKR and OAS activation (Whitaker-Dowling & Youngner, 1983; Paez & Esteban, 1984), bound dsRNA and was encoded by the E3L gene (Chang et al., 1992). Other early studies revealed that VACV mutants with large deletions in the terminal regions of the virus genome had increased sensitivity to IFN, and that the presence of IFN would prevent formation of such deletion mutant viruses (Paez & Esteban, 1985), suggesting that these regions encode proteins that antagonize the antiviral action of IFNs.

It is now known that viruses inhibit the IFN response at multiple levels, and many of these are illustrated by VACV (Fig. 1). First, VACV restricts IFN production by minimizing the production or recognition of PAMPs, expressing proteins that block the PRR-induced signalling pathways that activate transcription factors leading to IFN induction, and by inhibiting host protein synthesis. Secondly, VACV secretes proteins from the infected cell to capture IFNs in solution or on the cell surface, and prevent engagement of IFN receptors by IFNs. Thirdly, VACV blocks signal transduction induced by IFNs binding to their receptors. Finally, additional VACV proteins act within the infected cell to inhibit the antiviral action of IFN-induced proteins. Individual VACV proteins can possess multiple anti-IFN activities, as exemplified by the E3 protein, which inhibits B-DNA-stimulated IFN-β transcription in mouse embryonic fibroblasts (Wang et al., 2008), sensing of RNAs produced by DNA-dependent RNA polymerase transcription of AT-rich DNA (Marq et al., 2009; Valentine & Smith, 2010) and the antiviral action of ISG15 in mouse embryonic fibroblasts (Guerra et al., 2008).

**Blocking induction of IFNs**

The simplest way of avoiding the antiviral activity of IFNs is to prevent their production, and VACV utilizes several mechanisms to accomplish this. The first is to minimize the production of dsRNA, an important PAMP leading to IFN production. To do this, the VACV genome is arranged with...
genes located at the left or right terminal region of the genome being transcribed predominantly outward towards the genomic terminus. With transcription from only one DNA strand in these regions, dsRNA formation is prevented. In the central region of the genome, although genes are transcribed equally from both strands, genes are generally arranged in blocks with leftward and rightward transcribed blocks of genes alternating. Where there is convergent transcription, especially early during infection, there are multiple intergenic transcriptional termination sequences to prevent the formation of overlapping transcripts and so diminish dsRNA formation (Smith et al., 1998).

A second strategy is to inhibit host protein synthesis, so that production of host IFNs and other pro-inflammatory molecules is diminished shortly after infection. VACV inhibits host protein synthesis within a few hours of infection (Moss & Salzman, 1968). A contributory factor is the increased degradation of host mRNAs (Rice & Roberts, 1983) mediated by the D9 and D10 proteins, which recognize mRNAs and cleave off their 5’ methylated caps (Parrish & Moss, 2006, 2007; Parrish et al., 2007). These proteins also cause turnover of VACV mRNAs, thereby promoting a switch from early to intermediate and late protein synthesis. Although most host mRNAs are downregulated during infection (Brum et al., 2003; Guerra et al., 2004), VACV can preserve or increase some cellular functions by activating host gene expression, for instance, genes controlled by the transcription factor hypoxia-inducing factor (HIF)-1α. Early after infection, VACV strain Western Reserve (WR) protein C16 binds and inhibits prolyl hydroxylase domain-containing protein 2 (PHD2) (Mazzon et al., 2013). PHD2 is an oxygen sensor and under normoxic conditions can hydroxylate and induce proteosomal degradation of HIF-1α. However, once PHD2 is inhibited by C16, HIF-1α remains stable and moves into the nucleus to activate genes containing a HIF-responsive element, so mimicking a hypoxic response under normoxic conditions (Mazzon et al., 2013).

A third strategy is to prevent binding of PAMPs by PRRs. The VACV E3 protein sequesters dsRNA via a C-terminal dsRNA-binding domain and thereby prevents activation of dsRNA-binding PRRs (Chang et al., 1992). E3 also blocks the production of IFN following sensing of AT-rich dsDNA by RNA polymerase III, because this leads to RNA formation, which is bound by E3 (Marq et al., 2009; Valentine & Smith, 2010). E3 has an N-terminal Z-DNA-binding domain of unknown function, and both this and the C-terminal RNA-binding domain contribute to virulence (Brandt & Jacobs, 2001; Kim et al., 2003). VACV also encodes a protein to block the recognition of...
cytosolic DNA by DNA-PK, which was shown recently to be a PRR for IRF3-dependent innate immunity (Ferguson et al., 2012). The C-terminal region of VACV strain WR protein C16 binds the Ku complex (part of DNA-PK) and thereby blocks the recruitment of DNA-PK to DNA and inhibits the induction of IRF3-dependent chemokines, cytokines and IFN (Peters et al., 2013).

A fourth strategy is to express proteins that act downstream of PRR binding to PAMPs to block the intracellular signalling pathways leading to IRF3 or NF-κB activation that are required for IFN induction (see Figs 2 and 3, discussed below). There are many such proteins and they are grouped according to the pathway they target.

**Inhibitors of NF-κB activation**

VACV intracellular proteins that inhibit NF-κB activation are numerous and include A46, A49, A52, B14, C4, E3, K1, K7, M2 and N1. These proteins are all expressed early during infection but inhibit NF-κB activation at differing stages in the signalling pathway (Fig. 2). Protein A46 binds to several Toll/IL-1R (TIR) domain-containing adaptor molecules [myeloid differentiation primary response gene 88 (MyD88), Myd88 adaptor-like (MAL), TIR-domain-containing adaptor-inducing interferon-β (TRIF) and TRIF-related adaptor molecule (TRAM)] that associate with the cytoplasmic tails of TLRs (Bowie et al., 2000; Stack et al., 2005). Binding to these multiple ligands enables A46...
to inhibit activation of mitogen-activated protein (MAP) kinases, NF-κB and IRF3 and, therefore, the induction of IFN-β. Interactions with TRIF and TRAM also enable A46 to block TLR3/4-mediated activation of IRF3 (Fig. 3). The A52 protein also acts early in the activation pathway and inhibits IL-1 and TLR-induced activation of NF-κB by binding to IL-1R-associated kinase 2 (IRAK2) and tumour necrosis factor (TNF) receptor-associated factor 6 (TRAF6) (Bowie et al., 2000; Harte et al., 2003). The structure of protein A52 has been solved and revealed a B-cell lymphoma-2 (Bcl-2) fold (Graham et al., 2008) that is conserved in several other VACV proteins that function as inhibitors of innate immune signalling pathways (see below). Protein K7 is also a member of the Bcl-2 family (Kalverda et al., 2009) and binds to IRAK2 and TRAF6 and suppresses TLR-dependent NF-κB activation (Schröder et al., 2008; Oda et al., 2009). K7 also binds the DEAD-box RNA helicase 3 (DDX3) and inhibits PRR-induced IFN-β induction by preventing IRF3 activation (Schröder et al., 2008). These three proteins (A46, A52 and K7) inhibit TLR- and IL-1β-mediated NF-κB activation, but not NF-κB activation mediated by TNF (Fig. 2). In contrast, all the other VACV proteins targeting NF-κB activation act at, or downstream of, the convergence of IL-1- and TNF-mediated signalling and so inhibit both pathways.

Protein N1 inhibits NF-κB activation (DiPerna et al., 2004), but the report that it binds to the inhibitor of κB

Fig. 3. IRF3 signalling pathway and its antagonism by VACV. RNA sensing by RIG-I or MDA5, and DNA sensing by RNA polymerase III induces signalling via the mitochondrial-associated adaptor MAVS (also known as IPS-1, CARDIF and VISA). Signalling from other cytoplasmic DNA sensors such as DNA-PK and IFI16 involves the adaptor protein STING. Signalling from TLR3 (that is endosomal) and TLR4 (found at the plasma membrane and in endosomes) requires the adaptor TRIF, whilst TRAM acts as a bridging adaptor between TRIF and TLR4. The IRF3 kinases, TBK1 and IKKe, are activated subsequent to activation of TRAF3, and form complexes with the proteins NAP1, SINTBAD, TANK and DDX3. Upon phosphorylation, IRF3 undergoes dimerization and nuclear translocation. Within the nucleus, activated IRF3 binds to IRF3-binding sites within the promoters of IFN-β and other IRF3-dependent genes. The sites of action of VACV proteins E3, C16, A46, K7, C6 and N2, which inhibit the IRF3 pathway, are shown and are described further in the text.
kinase (IKK) complex has been disputed (Chen et al., 2008) and its mechanism of action remains uncertain. N1 is dimeric (Bartlett et al., 2002) and has a Bcl-2 fold (Aoyagi et al., 2007; Cooray et al., 2007), and mutagenesis of the N1 dimer surface inhibits both dimerization and the ability to block NF-κB activation, suggesting that either N1 acts as a dimer or it uses the dimer interface to block NF-κB (Maluquer de Motes et al., 2011).

Protein B14 binds to IKKβ and prevents its phosphorylation and activation by upstream kinases, thereby blocking IKKβ-mediated phosphorylation of the inhibitor of κB (IκBz) (Chen et al., 2008). The structure of B14 also revealed a Bcl-2 fold (Graham et al., 2008), and targeted mutation of an exposed hydrophobic surface eliminated binding of IKKβ and inhibition of NF-κB activation (Benfield et al., 2011). Protein C4 inhibits activation of NF-κB at, or downstream of, the IKK complex by an unknown mechanism (Ember et al., 2012). Protein E3 inhibits NF-κB activation in both PKR-dependent and -independent manners (Myskiw et al., 2009) and also by antagonizing the RNA polymerase III–dsDNA sensing pathway (Marq et al., 2009; Valentine & Smith, 2010).

Recently, protein A49 was shown to stabilize phosphorylated IκBz by molecular mimicry (Mansur et al., 2013). Near the N terminus of A49, there is a short sequence containing conserved serine residues that are present in IκBz and that, in IκBz, are phosphorylated by IKKβ. Normally, once IκBz is phosphorylated by IKKβ, p-IκBz is recognized and ubiquitinated by the E3 ubiquitin ligase β-transducing repeat-containing protein (β-TrCP) leading to p-IκBz degradation by the proteasome. A49 functions by binding to β-TrCP so that, even if IκBz is phosphorylated, it is not recognized and ubiquitinated by β-TrCP, and p-IκBz remains bound to NF-κB in the cytoplasm (Mansur et al., 2013). Protein K1 was also reported to inhibit NF-κB signalling in rabbit kidney epithelial cells by preventing the degradation of IκBz, but the mechanism remains unclear (Shisler & Jin, 2004). Finally, protein M2 reduces extracellular signal-regulated kinase 2 (ERK2) phosphorylation induced by phorbol myristate acetate and prevents p65 nuclear translocation (Gedey et al., 2006).

Despite inhibiting the NF-κB activation pathway at multiple places, these VACV proteins are non-redundant, because loss of any individual protein gives an in vivo phenotype (see below).

Inhibitors of IRF3 activation

The kinases TANK-binding kinase 1 (TBK1) and IKKε lie at the convergence of several pathways leading to IRF3 activation (Fig. 3), and thus provide an attractive target for viral antagonism of IFN production. For example, the VACV C6 protein interacts with the scaffold adaptor proteins for these kinases, NAK-associated protein 1 (NAP1), TRAF family member-associated NF-κB activator (TANK) and similar to NAP1 TBK1 adaptor (SINTBAD), and prevents TBK1/IKKε-dependent activation of IRF3 and IRF7 (Unterholzner et al., 2011). A related VACV protein, K7, binds to DDX3, and led to the discovery that DDX3 is an adaptor of TBK1/IKKε and can also directly bind the IFN-β promoter (Schröder et al., 2008; Soulat et al., 2008; Oda et al., 2009). Thus, K7 antagonizes both TLR-dependent and -independent IFN-β activation. As noted earlier, protein C16 inhibits IRF3 activation by disrupting recognition of dsDNA by DNA-PK (Peters et al., 2013). In addition, as mentioned above, protein A46 binds to TRIF, TRAM, MAL and Myd88 and so can also block IRF3 activation (Stack et al., 2005). Lastly, protein N2 inhibits IRF3 activation downstream of IRF3 phosphorylation and nuclear translocation via an unknown mechanism (Ferguson et al., 2013).

Collectively, this wide array of proteins that block IRF3 and NF-κB activation provides a profound block on IFN-β production from VACV-infected cells.

Blocking IFN reaching its receptors

The strategies outlined above are effective means by which VACV can restrict the production of IFN from infected cells. To combat IFNs produced from uninfected cells, VACV has another strategy, namely the release of decoy IFN receptors from the infected cells (Fig. 4).

VACV strain WR protein B18 is a type I IFN-binding protein and acts both in solution and when associated with the cell surface via glycosaminoglycans (GAGs) to sequester type I IFNs (Colamonici et al., 1995; Symons et al., 1995; Alcamí et al., 2000; Montanuy et al., 2011). B18 binds type I IFNs from a broad range of species (Symons et al., 1995); however, it only inhibits IFN-α efficiently and defence against IFN-β relies more on intracellular proteins (Waibler et al., 2009). This strategy is logical because IFN-α (leukocyte IFN) is produced largely, and in high levels, by activated dendritic cells that are recruited to sites of inflammation and so require neutralization outside the cell by a decoy receptor. In contrast, IFN-β (fibroblast IFN) is also produced by fibroblasts and epithelial cells before leukocytes are recruited to the site of infection and so can be targeted by inhibition of signalling pathways leading to IFN-β promoter activation. The ability of B18 to bind to the surface of cells enables it to prevent the IFN-mediated antiviral state in uninfected cells, which therefore remain susceptible to virus replication as it spreads.

Type II IFN is also neutralized via a VACV soluble decoy IFN receptor, protein B8, which binds IFN-γR outside cells and, unlike the cellular IFN-γR, can also dimerize in the absence of IFN-γ (Alcamí & Smith, 2002). The B8 protein shares amino acid similarity to the cellular IFN-γR but lacks the transmembrane and cytoplasmic domains found in the cellular IFN-γR (Upton et al., 1992; Alcamí & Smith, 1995; Mossman et al., 1995), and this enabled its function to be predicted. A structural study of the closely related IFN-γR-binding protein from ectromelia virus (ECTV, the causative agent of mousepox) showed that the complex of
the ECTV IFN-γ-binding protein and IFN-γ consisted of four molecules of the ECTV protein in complex with two IFN-γ dimers, and that tetramerization of the ECTV IFN-γ-binding protein is mediated by a C-terminal helix–turn–helix domain (Nuara et al., 2008).

The study of these decoy IFN receptors provided an opportunity to investigate the unknown origin of VACV because of the species-specific nature of IFNs and their receptors. It seemed logical that VACV would have evolved proteins to bind and neutralize IFNs from its natural host species, and therefore studying the binding of B18 and B8 to type I or type II IFNs from different species might indicate a natural host for VACV. However, both B18 and B8 bound type I or type II IFNs from many different species, although they bound less well to murine IFNs (Alcamí & Smith, 1995; Mossman et al., 1995; Symons et al., 1995). This broad IFN specificity did not reveal a likely host for VACV but did indicate that these proteins would be useful to help VACV combat IFNs in many hosts and thereby help facilitate a broad host range (Alcamí & Smith, 1996b). It has been established that both B18 (Symons et al., 1995) and B8 (Symons et al., 2002b) contribute to VACV virulence where the host IFN is bound by the virus protein. Interestingly, the yatapoxvirus, Yaba-like disease virus, encodes protein Y136, which is related to VACV WR B18 but can inhibit both type I and type III IFNs (Huang et al., 2007).

Inhibiting IFN-induced signal transduction

Another mechanism to block the action of IFNs is to inhibit signal transduction induced by IFN binding to IFN...
receptors. Signalling events within the JAK/STAT pathway that are elicited in response to the binding of type I, II or III IFNs are shown in Fig. 4.

The VACV protein VH1 is a virion-associated phosphatase that is brought into infected cells with the infecting virion and rapidly dephosphorylates STAT1 and STAT2, thereby inhibiting signalling from all IFN receptors (Najarro et al., 2001; Mann et al., 2008). Given the redundancy in inhibitors of the IRF3 and NF-κB activation pathways, it is quite possible that other VACV inhibitors of the JAK/STAT signalling pathway exist.

**Inhibiting IFN-induced antiviral proteins**

Finally, VACV also encodes proteins that counter the effects of proteins encoded by ISGs. The E3 dsRNA-binding protein sequesters dsRNA to prevent activation of PKR, OAS and other dsRNA sensors. E3 also binds ISG15 and prevents its antiviral action (Guerra et al., 2008). Another example is VACV protein K3, which has amino acid similarity to eIF2α, and acts as a non-phosphorylatable pseudo-substrate for PKR and thus competitively inhibits the phosphorylation of eIF2α by PKR (Beattie et al., 1991; Carroll et al., 1993). Lastly, the ability of the host-range genes C7 and K1 to support VACV replication in permissive cell lines is thought to be due to antagonism of currently undefined IFN-induced antiviral factor(s) (Meng et al., 2009).

**Cytokines**

Pro-inflammatory cytokines such as TNF, IL-1 and IL-18 amplify the innate immune response to virus infection and shape the adaptive immune response to follow. TNF also has direct antiviral activity by the induction of apoptosis of infected cells (see below). VACV has evolved strategies to block these cytokines at multiple levels in a manner analogous to the inhibition of IFN. These include the inhibition of proteolytic maturation of specific cytokines, expression of soluble decoy receptors and inhibition of cytokine-induced signal transduction. These principles are illustrated with proteins targeting IL-1, IL-18 and TNF.

**Targeting IL-1**

IL-1 is a pro-inflammatory cytokine that activates NF-κB and leads to induction of inflammatory mediators such as cyclo-oxygenase-2 (COX-2) and inducible nitric oxide synthase (iNOS). It exists in three forms, IL-1α and IL-1β, which can both activate IL-1R-mediated signalling, and the IL-1R antagonist protein, which binds to the IL-1R without signalling (reviewed by Dinarello, 2006). The production and secretion of IL-1β usually requires two signals; a first signal, often NF-κB activity, induces the transcription and synthesis of an inactive intracellular form, pro-IL-1β. VACV can therefore inhibit the synthesis of pro-IL-1β by inhibiting NF-κB (see above). The second signal is required to activate caspase-1; this can cleave pro-IL-1β to form IL-1β, which is then secreted from the cell. In response to virus infection, this second signal is provided by the activation of inflammasomes, large protein complexes containing PRRs, which activate caspase-1. Various inflammasomes, which are activated by different molecular stimuli, can detect VACV infection and contribute to IL-1β production (Hornung et al., 2009; Gerlic et al., 2013), and VACV has evolved mechanisms to inhibit this process. The F1 protein can bind directly to the nucleotide-binding domain, leucine-rich repeat and pyrin domain containing protein 1 (NLRP1) inflammasome and reduce the amount of active caspase-1 and IL-1β secretion (Gerlic et al., 2013). In addition, to prevent pro-IL-1β cleavage within infected cells, the VACV strain WR protein B13 [also called serine protease inhibitor 2 (SPI-2) and cytokine response modifier A (CrmA) in CPXV] binds caspase-1 and blocks pro-IL-1β cleavage (Ray et al., 1992; Dobbelstein & Shenk, 1996; Kettle et al., 1997). This has the additional function of preventing caspase-1-induced cell death. Not all VACV strains have a functional B13R gene, and in several strains, including Copenhagen and Lister, the B13 protein is not produced (Kettle et al., 1995).

The strategy of preventing IL-1β formation is restricted to infected cells, and so uninfected cells recruited to infected tissue can produce IL-1β freely. To combat IL-1β from this source and any IL-1β that escapes blocking strategies from infected cells, VACV strain WR expresses a soluble IL-1R that is released from infected cells to capture IL-1β in solution (Alcamí & Smith, 1992; Spriggs et al., 1992). Protein B15 shows amino acid similarity to the extracellular ligand-binding domain of the cellular IL-1R (Smith & Chan, 1991) and binds IL-1β with high affinity, preventing IL-1β from binding its natural receptor (Alcamí & Smith, 1992; Spriggs et al., 1992). A study of the contribution of the B13 and B15 proteins to virus virulence showed that loss of the B13 protein did not alter virulence in the murine intranasal model (Kettle et al., 1995) but caused an increase in lesion sizes after intradermal infection (Tscharke et al., 2002). In contrast, a virus lacking the B15R gene had reduced virulence after intracranial infection (Spriggs et al., 1992) and caused an accelerated weight loss and the induction of fever after intranasal infection (Alcamí & Smith, 1996a). B15 only bound IL-1β, and not IL-1α, TNF or IFNs, and therefore the ability to block fever was due to inhibition of IL-1β only. This finding contributed to the conclusion that IL-1β is the principal endogenous pyrogen (Alcamí & Smith, 1996a).

In addition to preventing the production of IL-1β from infected cells and the capturing of IL-1β in solution, VACV expresses multiple proteins that can block IL-1-induced activation of NF-κB. These have been described already under IFNs. A remarkable feature of the multiple inhibitors of NF-κB activation is that the removal of A46, A49, A52, B14, C4 and N1 separately causes an in vivo phenotype (Bartlett et al., 2002; Harte et al., 2003; Stack et al., 2005; Chen et al., 2006; Ember et al., 2012; Mansur et al., 2013),
indicating that these proteins have non-redundant functions. This may be due to a protein having multiple functions (for instance, N1 can block apoptosis and NF-κB activation; Maluquer de Motes et al., 2011), multiple binding partners (e.g. A46; Stack et al., 2005) or being able to inhibit the pathway at different stages. In the latter case, cross-talk between signalling pathways can lead to other signalling pathways being inhibited, or remaining unaffected, depending upon where inhibition of NF-κB activation is mediated.

**Targeting IL-18**

IL-18 (originally termed IFN-γ-inducing factor) is also a member of the IL-1 family and is a pleiotropic, pro-inflammatory cytokine (Gracie et al., 2003). Like IL-1β, IL-18 is synthesized as an inactive precursor that requires cleavage by caspase-1, and the intracellular signalling pathway induced by binding of IL-18 to the IL-18R has similarity with IL-1β-induced signalling. IL-18 facilitates clearance of virus-infected cells by inducing IFN-γ synthesis and activating NK and CD8^+^ T-cells (Gracie et al., 2003), and its importance for defence against viruses is illustrated by IL-18 administration enabling recovery from infection with VACV or herpes simplex virus type 1 (Fujioka et al., 1999; Tanaka-Kataoka et al., 1999). VACV has been predicted, or shown, to inhibit IL-18 action in three ways. First, the formation of mature IL-18 is predicted to be inhibited by B13, which inhibits caspase-1. Secondly, VACV and several other orthopoxviruses secrete a soluble IL-18-binding protein (IL-18BP), called protein C12, that binds IL-18 in solution and thereby stops IL-18 reaching the IL-18R on cells (Born et al., 2000; Smith et al., 2000; Calderara et al., 2001; Symons et al., 2002a). Unlike protein B15, which is related to the IL-1R, the VACV IL-18BP is unrelated to the cellular IL-18R but shows amino acid similarity to the host IL-18BP, a negative regulator of IL-18 action. Protein C12 enhances VACV virulence by diminishing the production of IFN-γ, leading to reduced NK cell and VACV-specific CD8^+^ T-cell responses (Reading & Smith, 2003). Thirdly, VACV inhibits IL-18-induced signal transduction by expressing intracellular proteins that block NF-κB or IRF activation (see above).

**Targeting TNF**

TNF-α and TNF-β, also called lymphotoxin α (LT-α), are related cytokines that have pro-inflammatory activity and also can cause cell death. TNF-α is the most studied member, and has been implicated in tumour regression, rheumatoid arthritis, septic shock and cachexia (Locksley et al., 2001). The predominant source of TNF-α is thought to be macrophages and activated T-cells, and its pleiotropic activity is attributed to the promotion of an antiviral state in uninfected neighbouring cells, selective cytosis of virus-infected cells, apoptosis and recruitment of lymphocytes to foci of infection (Smith et al., 1994). Therefore, it is unsurprising that viruses have evolved anti-TNF strategies. These include the secretion of VACV proteins that serve as decoy TNF receptors (vTNFRs) to sequester extracellular TNF and preclude cellular receptor binding (reviewed by Alcamí, 2003), and also proteins that interfere with intracellular signalling downstream of host-cell TNFRs (described above). In addition, TNF is itself an NF-κB target gene and thus intracellular VACV inhibitors of NF-κB also affect TNF production.

The majority of VACV strains, including Copenhagen and WR, encode gene fragments related to vTNFR genes but do not encode functional TNF-binding proteins (Goebel et al., 1990; Howard et al., 1991; Smith et al., 1991). However, VACV strains USSR, Lister and Evans express soluble and cell-surface vTNFRs encoded by the CrmC (A53R) and CrmE genes (Alcamí et al., 1999). These decoy vTNFRs exhibit amino acid similarity to the extracellular domains of cellular TNFRs but lack a membrane anchor and the C-terminal cytoplasmic domain necessary for signal transduction (Alcamí et al., 1999). The crystal structure of CrmE confirmed that it has the canonical TNFR fold but showed that it is closer to the type II TNFR (p75) rather than type I TNFR (p55) and contains only one of the two ligand-binding loops of TNFRSF1A, suggesting an explanation for the higher affinity of poxvirus TNFRs for TNF-α than LT-α (Graham et al., 2007). Furthermore, VACV CrmE is a virulence factor, because VACV strain USSR mutants lacking CrmE were attenuated in a mouse model of infection, and a recombinant strain of VACV WR expressing CrmE had increased virulence in the same model (Reading et al., 2002). Although the expression of vTNFRs is restricted to a few strains of VACV, CPXV strains express multiple TNFRs, some of which have additional properties (see below) (Hu et al., 1994; Smith et al., 1996).

**Chemokines**

Chemokines are small chemoattractant cytokines that recruit leukocytes to the site of infection or inflammation (Rot & von Andrian, 2004; Charo & Ransohoff, 2006). Chemokines are produced in response to infection or inflammation and bind to GAGs on the surface of adjacent endothelial cell walls, where a concentration gradient is established. Circulating leukocytes express chemokine receptors on their cell surface that bind to chemokines via their chemokine receptor-binding site, and thereby recruit leukocytes to sites of infection (Fig. 5). There are many different chemokines, which are grouped according to the position of conserved cysteine residues (C, CC or CXC, where X is another amino acid), and also many chemokine receptors. A single chemokine may bind to several different chemokine receptors and, equally, a single chemokine receptor may bind several different chemokines. Chemokine production from the first cells infected by an invading virus is important for induction of the host response to infection, and without chemokine-mediated recruitment of leukocytes, the ability of a host to fight infection is diminished.
VACV has several ways to inhibit the production or function of chemokines. After infection, PRR engagement leads to IRF3 and NF-κB activation and the transcription of many chemokine genes driven by these transcription factors. For instance, whilst infection with VACV strain MVA induces the expression of several chemokines (Lehmann et al., 2009), infection with VACV strains WR, Wyeth and Lister (Elstree) does not (Lehmann et al., 2009), owing to their expression of immunomodulatory proteins that block intracellular signalling (see above) leading to chemokine production, such as of CXCL10 (Ferguson et al., 2012).

Secondly, VACV expresses chemokine-binding proteins. The first to be identified, called VACV chemokine-binding protein (vCKBP) or VACV CC chemokine inhibitor (vCCI), binds CC chemokines and is secreted from infected cells early during infection (Graham et al., 1997; Smith et al., 1997a; Alcamí et al., 1998). vCCI is made by some but not all VACV strains and binds a range of CC chemokines with pM affinity, such that it is able to prevent these chemokines binding to their receptors (Alcamí et al., 1998). The structures of the orthologue of vCCI from CPXV (Carfì et al., 1999) and from VACV strain rabbitpox in complex with CCL4 (macrophage inflammatory protein 1β) have been solved (Zhang et al., 2006). The latter study provided insight into how vCCI binds CC chemokines with high affinity and broad specificity. A second protein, A41, shows amino acid similarity to vCCI and is also secreted from infected cells early during infection (Ng et al., 2001). A41 binds chemokines (CCL21, CCL25, CCL26 and CCL28) with lower affinity (between 8 and 118 nM) and is unable to prevent chemokines binding to chemokine

Fig. 5. Mechanisms of chemokine inhibition by VACV. Chemokines are released from sites of infection and establish concentration gradients on the endothelial cell wall by binding to GAGs. The chemokines then bind to and activate circulating leukocytes, which are recruited to the site of infection. VACV protein vCCI prevents binding of CC chemokines to chemokine receptors on leukocytes (top), whereas protein A41 prevents the establishment of the chemokine concentration gradient (bottom). See text for details.
receptors due to this low affinity (Bahar et al., 2008). A41 has a similar structure to vCCI, but there are surface charge differences and an extended acidic loop that may contribute to chemokine-binding specificity (Bahar et al., 2008). A41 binding to chemokines was inhibited by heparin, indicating that the heparin and chemokine-binding sites overlap and suggesting that the mechanism of action of A41 is via the disruption of chemokine concentration gradients on endothelial cells (Bahar et al., 2008) (Fig. 5). A parallel study with the closely related ECTV protein E163 came to broadly similar conclusions (Ruiz-Arguello et al., 2008).

The role of A41 and vCCI in vivo is to diminish inflammation by preventing recruitment of leukocytes to the site of infection. Thus, when vCCI is expressed from VACV strain WR, which lacks this protein normally (Alcamí et al., 1998), the recombinant virus is less virulent in a murine intranasal model in which pathology is associated with excessive inflammation (Reading et al., 2003b). For A41, a VACV WR strain lacking this gene produced larger lesion sizes than controls in a murine intradermal model, but the infectious virus was cleared more rapidly due to greater recruitment of leukocytes (Ng et al., 2001).

VACV strain WR proteins B7 and B23 were predicted to have chemokine-binding activity because they share sequence similarity with protein E184 from ECTV, protein V216 from CPXV and the C-terminal domain from TNFRs CrmB and CrmD from CPXV and variola virus, which have been demonstrated to bind chemokines (Alejo et al., 2006). Interestingly, the structure of the chemokine-binding domain of CrmD from ECTV in complex with CX3CL1 showed that this domain shares structural similarity with the vCCI and A41 proteins (Xue et al., 2011).

Apoptosis

Apoptosis is an irreversible cascade of biochemical events orchestrated by caspase proteases that culminates in cell death and represents a powerful mechanism to eliminate virus-infected cells (Tait & Green, 2010). Activation of apoptosis by the intrinsic pathway is controlled by a complex network of protein–protein interactions between pro-apoptotic and anti-apoptotic members of the Bcl-2 family of proteins. In response to apoptotic signals, pro-apoptotic proteins such as Bad or Bid bind the effector proteins Bax and Bak, which oligomerize in the outer mitochondrial membrane inducing release of cytochrome c into the cytoplasm and formation of the caspase activation platform or apoptosome (Fig. 6). VACV directly subverts the intrinsic pathway by expressing proteins F1 and N1. Protein F1 adopts a Bcl-2-like fold (Kvansakul et al., 2008) and binds Bak at the mitochondrion (Wasilenko et al., 2003, 2005; Postigo et al., 2006; Kvansakul et al., 2008). F1 also reduces the inflammatory response by binding NLRP-1, an upstream activator of caspase-1 (Gerlic et al., 2013). Protein N1 also has a Bcl-2 fold (Aoyagi et al., 2007; Cooray et al., 2007) and contains a surface groove that enables it to bind pro-apoptotic Bcl-2 proteins Bid and Bad and to inhibit apoptosis (Cooray et al., 2007; Maluquer de Motes et al., 2011). N1 was also reported to bind peptides containing Bcl-2 homology domain 3 (BH3) domains of pro-apoptotic Bcl-2 proteins Bid, Bim and Bak in vitro (Aoyagi et al., 2007). Other studies found no interaction between N1 and Bax or N1-mediated inhibition of apoptosis (Banadyga et al., 2009; Postigo & Way, 2012). Nonetheless, mutagenesis of N1 showed that loss of binding to Bid and Bad correlated with loss of anti-apoptotic activity whilst retaining anti-NF-κB activity (Maluquer de Motes et al., 2011). Interestingly, for both F1 and N1, inhibition of innate immune signalling was more important for virus virulence than inhibition of apoptosis (Maluquer de Motes et al., 2011; Gerlic et al., 2013).

In addition to these viral Bcl-2-like proteins, VACV strain WR B13 (SPI-2) (Smith et al., 1989; Kettle et al., 1995) inhibits caspase-1 activity as well as extrinsic apoptosis triggered by TNF-α or Fas ligand (Dobbelstein & Shenk, 1996; Kettle et al., 1997). The CPXV orthologue of B13 (CrnA) inhibits caspases from group I (caspase-1, -4 and -5) and group III (caspase-8, -9 and -10) (Ray et al., 1992; Zhou et al., 1997; García-Calvo et al., 1998), and similar specificity is expected for VACV protein B13 due to conservation of the reactive site. This may explain how B13 inhibits both extrinsic apoptosis and the host inflammatory response. Furthermore, VACV inhibitors such as the dsRNA-binding protein E3 can show protective effects on cells when neutralizing pro-apoptotic effects of external stimuli like dsRNA (Kibler et al., 1997; García et al., 2002). Lastly, a few VACV strains, such as Evans, and also camelpox virus (Gubser & Smith, 2002) express a protein called viral Golgi anti-apoptotic protein (vGAAP) that is closely related (73% amino acid identity) to a human orthologue, hGAAP (Gubser et al., 2007). GAAPs are highly conserved throughout evolution, being present in all eukaryote genomes examined, and are part of the transmembrane Bax inhibitor-containing motif (TMBIM) family, which includes other anti-apoptotic and Ca²⁺-modulating membrane proteins such as Bax inhibitor 1. vGAAP and hGAAP have a six-membrane topology (Carrara et al., 2012), form oligomers (Saraiva et al., 2013a) and modulate calcium in intracellular stores (deMattia et al., 2009). hGAAP also promotes cell adhesion and migration via the stimulation of store-operated Ca²⁺ entry and calpain 2 (Saraiva et al., 2013b). hGAAP and vGAAP can protect cells from apoptosis deriving from both intrinsic and extrinsic pathways (Gubser et al., 2007). vGAAP and B13 are only expressed by the minority of VACV strains, whereas proteins F1 and N1 are more widely conserved. Nonetheless, deletion of any of these proteins gives an in vivo phenotype (Bartlett et al., 2002; Tscharke et al., 2002; Gubser et al., 2007; Gerlic et al., 2013).

NK cells

NK cells are a specialized population of granular lymphocytes displaying high cytolytic activity against virus-infected and tumour cells. They serve as a first line of defence against
viral infections before the development of a virus-specific antibody and CTL response. NK cell activation depends on cytokines such as IFN-γ, IFN-β, IL-12 and IL-18 but is mostly regulated by a repertoire of activating and inhibitory receptors that integrate signals emanating from the surface of target cells (Lanier, 2005). Most NK inhibitory receptors recognize MHC class I molecules, and this ensures tolerance against self-antigens. In contrast, CD16, NKG2D and the natural cytotoxicity receptors NKP46, NKP44 and NKP30 are mostly involved in the activation of NK cells (Lanier, 2005).

It is well known that NK cells play an important role against poxvirus infections; for instance, the resistance of B6 mice to ECTV maps to genes involved in activation and regulation of NK cell responses (Delano & Brownstein, 1995), and depletion of NK cells with anti-asialo GM1 or anti-NK1.1 antibodies increases susceptibility to VACV (Bukowski et al., 1983; Martinez et al., 2010). In addition, VACV infection induces proliferation and accumulation of NK cells at the site of infection (Natuk & Welsh, 1987; Dokun et al., 2001; Jacobs et al., 2006), and VACV can modulate NK cell activation by modulating production of...
cytokines and IFN (see above). VACV infection increases cell susceptibility to NK lysis (Brutkiewicz et al., 1992; Baraz et al., 1999; Chisholm & Reyburn, 2006), and in specific cases this has been attributed to selective downregulation of HLA-E or C-type lectin related protein b (Clr-b) (Brooks et al., 2006; Williams et al., 2012). Protection against VACV challenge can also be mediated by passive transfer of NK cells from VACV-infected mice lacking classical adaptive T- and B-lymphocytes (Gillard et al., 2011).

Susceptibility to NK cells occurs after virus-mediated downregulation of MHC class I, a process employed by viruses to escape recognition by CTLs. Whereas VACV is known to modestly decrease MHC class I expression (Brutkiewicz et al., 1992; Kirwan et al., 2006), it seems that only downregulation of HLA-E is sufficient to induce lysis by NK cells (Brooks et al., 2006). Studies in vitro have shown that NK cell recognition of VACV-infected cells depends on the natural cytotoxicity receptor (Chisholm & Reyburn, 2006). Recently, the VACV haemaggglutinin (protein A56) was identified as a novel viral ligand for the activating receptors NKP30 and NKP46 (Jarahian et al., 2011). Upon binding to A56, NKP46 triggered NK cytotoxicity, but NKP30 activity was neutralized, which exemplifies the delicate interplay between VACV and its host. The same study revealed minimal alteration of NKG2D ligands after VACV infection of human cells. This is in contrast to other studies demonstrating a key role for NKG2D in the control of VACV (Martinez et al., 2010) or ECTV (Fang et al., 2008, 2011) infection in vivo. This indicates that different NK receptors are responsible for the control of genetically similar poxvirus species and strains in different hosts. To date, A56 is the only described VACV direct modulator of NK cell activity, although removal of several VACV proteins, including N1, F3, C12 and K7, altered the NK response to infection and this is probably due to their ability to block intracellular signalling cascades leading to production of cytokines or chemokines (Reading & Smith, 2003; Foggatt et al., 2007; Jacobs et al., 2008; Benfield et al., 2013). Other VACV mechanisms to evade NK recognition may exist.

The influence of VACV immunomodulators on virulence and immunogenicity

Virulence

Many of the VACV immunomodulatory genes described above are non-essential for virus replication in cell culture but affect virulence in vivo, where the innate immune response plays an important role in determining the outcome of infection. Two murine models of infection are used routinely to study VACV virulence: the intradermal model where inoculation of the ear pinnae causes a localized infection resulting in the formation of a lesion (Tscharke & Smith, 1999), and the intranasal infection route, which results in a systemic infection causing mice to lose weight (Williamson et al., 1990). In addition, virulence has also been investigated using intracranial and intraperitoneal injection, dermal scarification to the base of the tail, or by using rabbits and guinea pigs. The removal or inactivation of most immunomodulatory genes leads to reduced virus virulence in either the intranasal or intradermal infection model (Table 1). In many instances, attenuation is accompanied by increased immune cell infiltrates to the site of infection and/or decreased viral titres after the initial virus replication (see Table 1 for references). In some cases deletion of immunomodulatory genes leads to attenuation in more than one model of infection (Tscharke et al., 2002). Further work is required to understand why these differences exist. In certain instances, the removal of an immunomodulatory gene can lead to an increase in virulence; for example, VACV strain WR viruses engineered to lack the A41 (Ng et al., 2001; Clark et al., 2006) or B15 (Alcami & Smith, 1992; 1996a) proteins, or to express vCCI/ vCKBP (Reading et al., 2003b), produce immune pathology.

Immunogenicity

The adaptive immune system includes antibody (‘humoral’) and cell-mediated responses that are mediated by antibody-secreting B-lymphocytes and cytotoxic (CD8⁺) and Th1 (CD4⁺) T-lymphocytes, respectively. Adaptive immunity is characterized by its delayed onset, targeting of pathogen-specific antigens and immunological memory, and is the basis for vaccination. Both humoral and CD4⁺ and CD8⁺ T-cell responses are induced by VACV infection in mice (Xu et al., 2004) and humans (Ennis et al., 2002; Crotty et al., 2003; Hammarlund et al., 2003; Kennedy et al., 2004; Pütz et al., 2005, 2006; Moutaftsi et al., 2010). Efforts to dissect the relative roles of these responses in the mouse model using antibody depletion and gene knockout showed that the CD4⁺ T-cell-dependent antibody response is more important for viral clearance, whilst CD8⁺ T-cells limit disease severity and mediate protective memory upon reinfection (Xu et al., 2004). T-cell responses are evidently important for the response to infection with VACV because individuals with defects in cellular immunity are at risk of serious complications from vaccination (Lane et al., 1969). For a review of the response to smallpox vaccination, see Moss (2011).

VACV is being studied intensely as a vaccine vector and, in particular, the highly attenuated VACV strains MVA and NYVAC (Tartaglia et al., 1992) are being tested as vaccines for several diseases including AIDS, malaria, tuberculosis and some cancers (Gomez et al., 2008; Walsh & Dolin, 2011). MVA is a promising vaccine vector due to its safety record, efficient expression of foreign antigens and ability to induce a robust immune response (Sutter & Moss, 1992). MVA does not replicate fully in most mammalian cell lines (Sutter & Moss, 1992; Blanchard et al., 1998; Okeke et al., 2006) and is a safe vaccine even in immunocompromised mammals (Wyatt et al., 2004).

MVA was generated by the passage of chorioallantois VACV Ankara more than 500 times in chicken embryo fibroblasts, resulting in the loss of large portions of the
Vaccinia virus immune evasion

genome and substantial attenuation of the virus (Meyer et al., 1991; Antoine et al., 1998). Despite these deletions, a significant number of immunomodulatory genes remain in the MVA genome (Antoine et al., 1998; Blanchard et al., 1998). However, retention of an ORF does not ensure that the function of the encoded protein is retained, as illustrated with protein 183 (equivalent to VACV WR protein B14), which is rendered unstable by an internal deletion of 5 aa (McCoey et al., 2010). Removal of the chemokine-binding protein encoded by A41L (Clark et al., 2006) or the IL-1β-binding protein encoded by B15R (WR) (Staib et al., 2005) led to enhanced VACV-specific total CD8+ T-cell responses and enhanced protection against a challenge with virulent VACV WR. The deletion of A35R, encoding an inhibitor of MHC class II antigen presentation, from MVA also resulted in enhanced immunogenicity, with increased numbers of VACV-specific IFN-γ-secreting splenocytes, enhanced immunoglobulin production and class switching to IgG isotypes (Rehm & Roper, 2011). Deletion of the IL-18-binding protein, C12L (also from MVA), led to increased CD8+ and CD4+ T-cell responses to various VACV epitopes and provided enhanced protection against WR challenge (Falivene et al., 2012). Furthermore, a deletion mutant of C6L from the WR strain of VACV led to enhanced VACV-specific cytotoxicity of T-cells and provided better protection against challenge with a lethal dose of WR (Sumner et al., 2013).

Recently, several VACV vectors have been generated for immunization trials against HIV infection and their immunogenicity has been investigated. These include MVA-B, a vector expressing four HIV antigens and engineered to lack either both A41L and B15R (Garcia-Arriaza et al., 2010) or the IRF3 inhibitor C6L (Garcia-Arriaza et al., 2011). These viruses induced HIV-1-specific CD4+ and CD8+ T-cell immune responses of enhanced magnitude and polyfunctionality. For the C6L deletion mutant, enhanced levels of antibodies against the HIV Env protein were also observed. Furthermore, individual and double deletion mutants of the type I (B18) and type II (B8) IFN-binding proteins from NYVAC-C (which expresses the HIV-1 Env, Gag, Pol, and Nef antigens) improved HIV-1-specific CD8+ T-cell responses (Gomez et al., 2012). Finally, an MVA vector expressing codon-optimized HIV subtype C Env and Gag antigens and lacking four or five viral immunomodulators, including C12, B15, a dominant negative Toll/IL-1 signalling adaptor, a CC chemokine-binding protein and a gene encoding uracil-DNA glycosylase, elicited higher frequencies of HIV-specific CD8+ and CD4+ T-cells and higher titres of Env-specific antibodies in immunized rhesus macaques (Garber et al., 2012). Whether these VACV-based HIV vaccine vectors provide enhanced protection against infection remains to be determined.

Despite promising data with the recombinant VACVs described above, deletion of immunomodulatory genes does not always enhance immunogenicity. For instance, a VACV WR lacking C16L (Fahy et al., 2008) or N2L (Ferguson et al., 2013) and a VACV Wyeth lacking regions encoding the B5R, B8R, B12R, B13R, B14R, B16R, B18R and B19R genes, a number of which are immunomodulators (Jackson et al., 2005), showed unaltered immunogenicity under the conditions tested. It is likely that immunogenicity will reflect a balance between efficient recognition of virus antigens and the level of antigens expressed during infection (Wyatt et al., 2008). Understanding why the removal of certain immunomodulators enhances immunogenicity, whilst that of others does not, remains a goal of future research and will aid in the rational design of more efficacious vaccine vectors.

Future prospects
Therapeutics
As well as having applications for the development of vaccines, progress towards understanding how VACV evades and disrupts the immune system has important implications for the design and production of novel therapeutics. These can be split into three categories: (i) using modified forms of the virus; (ii) using recombinant viral proteins; and (iii) designing compounds that mimic the specific activity of viral proteins. The first two categories have examples that are now in clinical trials, whilst the third category is at a less advanced stage.

Other than as a vaccine, the therapeutic use of VACV as an oncolytic agent shows promise. Oncolytic viruses are those that can selectively, or preferentially, replicate in and kill tumour cells (Thorne, 2011). VACV has several advantages for this type of therapy, such as its broad tissue tropism, its ability to spread rapidly, the considerable experience with its use clinically during the eradication of smallpox, and the fact that it does not integrate its DNA into the host genome (Kirk & Thorne, 2009). Use of unmodified strains of VACV, such as WR and Lister, has proved less effective than other species of oncolytic viruses due to their lack of tumour specificity (Kirk & Thorne, 2009). However, a greater understanding of VACV immunogenicity and immune evasion mechanisms is enabling the design of modified viruses that have greater efficacy against cancer (Kirk & Thorne, 2009; Schmidt, 2011; Thorne, 2011). For example, the JX-594 virus, which is a thymidine kinase-negative VACV engineered to express granulocyte–macrophage colony stimulating fctor (GM-CSF), specifically lyses neoplastic cells and has undergone phase II clinical trials for the treatment of solid tumours such as advanced hepatocellular carcinoma (Breitbach et al., 2011; Heo et al., 2013). Furthermore, the removal of certain VACV immune evasion genes, such as B18, which inhibits type I IFN, improved its oncolytic potential, suggesting that immune modulation plays an important part in the activity of these viruses when attacking tumours (Kirk et al., 2007; Thorne, 2011). It is probable, therefore, that this promising approach will be improved by further modifications of VACV. For example, deletion of additional immune
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<th>Strain</th>
<th>Protein</th>
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<td>WR</td>
<td>A35</td>
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<td>Roper (2006)</td>
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<td>WR</td>
<td>A39</td>
<td>Secreted glycoprotein, aa similar to semaphorins</td>
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<td>Smaller lesion</td>
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<td>Gardner et al. (2001)</td>
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<td>A40</td>
<td>Surface glycoprotein. Immune modulator</td>
<td>No phenotype</td>
<td>Smaller lesion</td>
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<td>Wilcock et al. (1999); Tzarke et al. (2002)</td>
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<td>WR</td>
<td>A41</td>
<td>Secreted chemokine-binding protein</td>
<td>Increased virulence</td>
<td>Larger lesion, more rapid virus clearance</td>
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<td>Ng et al. (2001); Clark et al. (2006)</td>
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<td>WR</td>
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<td>3β-Hydroxysteroid dehydrogenase</td>
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<td>Smaller lesion</td>
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<td>A46</td>
<td>NF-κB/IRF3 inhibitor</td>
<td>Attenuated</td>
<td></td>
<td></td>
<td>Stack et al. (2005)</td>
</tr>
<tr>
<td>WR</td>
<td>A49</td>
<td>NF-κB inhibitor</td>
<td>Attenuated</td>
<td>No phenotype</td>
<td></td>
<td>Mansur et al. (2013)</td>
</tr>
<tr>
<td>WR</td>
<td>A52</td>
<td>NF-κB inhibitor</td>
<td>Attenuated</td>
<td></td>
<td></td>
<td>Harte et al. (2003)</td>
</tr>
<tr>
<td>WR</td>
<td>A53</td>
<td>Soluble TNF receptor (CrmC)</td>
<td>Attenuated</td>
<td>No phenotype (rabbit)</td>
<td>Attenuated</td>
<td>Dai et al. (2008)</td>
</tr>
<tr>
<td>WR</td>
<td>A55</td>
<td>Intracellular kelch protein immunomodulator</td>
<td>No phenotype</td>
<td>Larger lesion</td>
<td></td>
<td>Beard et al. (2006)</td>
</tr>
<tr>
<td>WR</td>
<td>A56</td>
<td>NK cell agonist/antagonist</td>
<td>No phenotype</td>
<td></td>
<td>Attenuated</td>
<td>Flexner et al. (1987); Smith et al. (2002)</td>
</tr>
<tr>
<td>WR</td>
<td>B7</td>
<td>ER protein, putative chemokine-binding protein</td>
<td>No phenotype</td>
<td></td>
<td>Smaller lesion</td>
<td>Price et al. (2000)</td>
</tr>
<tr>
<td>WR</td>
<td>B8</td>
<td>Secreted IFNγ binding protein</td>
<td>No phenotype/attenuated</td>
<td>Histological changes in rabbit skin</td>
<td></td>
<td>Verardi et al. (2001); Symons et al. (2002b)</td>
</tr>
<tr>
<td>WR</td>
<td>B13</td>
<td>Inhibitor of caspases</td>
<td>No phenotype/attenuated</td>
<td>Larger lesion</td>
<td></td>
<td>Kettle et al. (1995); Tzarke et al. (2002); Legrand et al. (2004)</td>
</tr>
<tr>
<td>WR</td>
<td>B14</td>
<td>NF-κB inhibitor</td>
<td>No phenotype</td>
<td>Smaller lesion, more rapid virus clearance</td>
<td></td>
<td>Chen et al. (2006)</td>
</tr>
<tr>
<td>WR</td>
<td>B15</td>
<td>Secreted IL-1β binding protein</td>
<td>Increased virulence (high virus dose)/attenuated (low virus dose)</td>
<td>No phenotype</td>
<td>Attenuated</td>
<td>Alcamì &amp; Smith (1992, 1996a); Spriggs et al. (1992); Tzarke et al. (2002)</td>
</tr>
<tr>
<td>WR</td>
<td>B18</td>
<td>Type I IFN binding protein</td>
<td>Attenuated</td>
<td></td>
<td></td>
<td>Symons et al. (1995)</td>
</tr>
<tr>
<td>WR</td>
<td>B22</td>
<td>Serine protease inhibitor</td>
<td>No phenotype/attenuated</td>
<td></td>
<td></td>
<td>Kettle et al. (1995); Legrand et al. (2004)</td>
</tr>
<tr>
<td>WR</td>
<td>C2</td>
<td>Intracellular kelch protein immunomodulator</td>
<td>No phenotype</td>
<td>Larger lesion</td>
<td></td>
<td>Pires de Miranda et al. (2003)</td>
</tr>
<tr>
<td>WR</td>
<td>C4</td>
<td>NF-κB inhibitor</td>
<td>Attenuated</td>
<td>No phenotype</td>
<td></td>
<td>Ember et al. (2012)</td>
</tr>
<tr>
<td>WR</td>
<td>C6</td>
<td>IRF3 inhibitor</td>
<td>Attenuated</td>
<td>Smaller lesion</td>
<td></td>
<td>Unterholzner et al. (2011); Sumner et al. (2013)</td>
</tr>
<tr>
<td>WR &amp; Tian Tan</td>
<td>C12</td>
<td>IL-18-binding protein</td>
<td>Attenuated</td>
<td>Smaller lesion (rabbits)</td>
<td>Attenuated</td>
<td>Symons et al. (2002a); Reading &amp; Smith (2003); Dai et al. (2008)</td>
</tr>
<tr>
<td>WR</td>
<td>C16</td>
<td>Binds DNA-PK</td>
<td>Attenuated</td>
<td>No phenotype</td>
<td></td>
<td>Fahy et al. (2008)</td>
</tr>
</tbody>
</table>
evasion genes may help the destruction of specific tumours and optimize the adaptive immune response to provide long-term remission (Wang et al., 2012).

As described above, VACV secretes proteins from infected cells that bind to cytokines, chemokines and IFNs, such as B18, which binds type I IFNs (Colamonici et al., 1995; Symons et al., 1995). The secreted nature of such proteins makes them attractive therapeutics because they are stable outside the cell and are easy to express and purify. Such proteins may be used to treat both acute and chronic inflammatory conditions such as rheumatoid arthritis, where hyperactive or dysregulated inflammatory processes result in tissue destruction (Fallon & Alcamí, 2006), although as foreign proteins their repeated administration will eventually induce an antibody response that will restrict their activity. As an example, vCCI binds a wide range of CC chemokines (Alcamí et al., 1998; Burns et al., 2002) and, in an in vivo inflammatory model, can mediate effective reductions of eotaxin-induced eosinophilia (Alcamí et al., 1998). The potential of these proteins as therapeutics is best illustrated by SERP-1, a poxvirus serine protease inhibitor (Upton et al., 1990), which reduces vascular inflammation in patients with acute coronary syndromes and has undergone phase II clinical trials in patients receiving cardiac stents (Tardif et al., 2010).

VACV intracellular immunomodulators are harder to deliver as therapeutic agents. The functions of several of these proteins, however, represent attractive therapeutic targets. For example, inhibitors of IKKβ are sought as therapy for treatment of inflammatory diseases such as rheumatoid arthritis and chronic obstructive pulmonary disease, as well as cancer, thanks to their potential to block NF-κB activation (Luo et al., 2005; Lee & Hung, 2008). Indeed, several IKKβ kinase inhibitors are in clinical trials (Lee & Hung, 2008). As VACV WR protein B14 binds to and inhibits the activity of IKKβ (Chen et al., 2008), its function might be mimicked by a small molecule to provide a novel therapeutic. This approach relies on a more detailed structural understanding of the interaction between IKKβ and B14, but as B14 is not a kinase inhibitor and instead blocks the phosphorylation of IKKβ itself (Chen et al., 2008), this information may reveal a novel allosteric target site for IKKβ inhibition. In a similar vein, the function of C6 could be mimicked to provide a novel TBK1 inhibitor (Unterholzner et al., 2011). TBK1 is considered a therapeutic target for rheumatoid arthritis (Hammaker et al., 2012) and certain specific cancers (Migita & Nakamura, 2012). Proof of principle for this approach has been provided by the development of peptide mimetics of the VACV A52 (McCoy et al., 2005) and A46 (Lysakova-Devine et al., 2010) proteins. These peptides have a cell-penetrating peptide at the N terminus to allow cell entry and inhibit TLR signalling, thereby blocking inflammatory responses both in vitro and in vivo (McCoy et al., 2005; Lysakova-Devine et al., 2010). TLR inhibitors are sought as targets for many inflammatory disorders (Kanzler et al., 2007) and compounds such as these

### Table 1. cont.

<table>
<thead>
<tr>
<th>Strain</th>
<th>Protein</th>
<th>Function</th>
<th>Intranasal</th>
<th>Intradermal</th>
<th>Intracranial</th>
</tr>
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<tr>
<td>WR</td>
<td>C1A VCP</td>
<td>Secreted complement regulatory protein</td>
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<td>Attenuated</td>
<td>Attenuated</td>
</tr>
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<td>WR</td>
<td>COP</td>
<td>Secreted protein, dsRNA-binding protein</td>
<td>Attenuated</td>
<td>Attenuated</td>
<td>Attenuated</td>
</tr>
<tr>
<td>WR</td>
<td>E3</td>
<td>Anti-apoptotic, inflammation modifier</td>
<td>Attenuated</td>
<td>Attenuated</td>
<td>Attenuated</td>
</tr>
<tr>
<td>WR</td>
<td>F1</td>
<td>Intracellular kash protein inhibitor</td>
<td>Attenuated</td>
<td>Attenuated</td>
<td>Attenuated</td>
</tr>
<tr>
<td>WR</td>
<td>F3</td>
<td>eIF2α mimic</td>
<td>Attenuated</td>
<td>Attenuated</td>
<td>Attenuated</td>
</tr>
<tr>
<td>WR</td>
<td>K3</td>
<td>NF-κB/BDRF3 inhibitor</td>
<td>Attenuated</td>
<td>Attenuated</td>
<td>Attenuated</td>
</tr>
<tr>
<td>WR</td>
<td>K7</td>
<td>NF-κB/BDRF3 inhibitor, anti-apoptotic</td>
<td>Attenuated</td>
<td>Attenuated</td>
<td>Attenuated</td>
</tr>
<tr>
<td>WR</td>
<td>N1</td>
<td>IκB inhibitor</td>
<td>Attenuated</td>
<td>Attenuated</td>
<td>Attenuated</td>
</tr>
<tr>
<td>WR</td>
<td>N2</td>
<td>IκBα inhibitor</td>
<td>Attenuated</td>
<td>Attenuated</td>
<td>Attenuated</td>
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<tr>
<td>WR</td>
<td>USSR WR</td>
<td>CmE receptor, TNFR-1 inhibitor</td>
<td>Attenuated</td>
<td>Attenuated</td>
<td>Attenuated</td>
</tr>
<tr>
<td>WR</td>
<td>vGAAP</td>
<td>Anti-apoptotic, Ca²⁺ regulator</td>
<td>Attenuated</td>
<td>Attenuated</td>
<td>Attenuated</td>
</tr>
<tr>
<td>USSR</td>
<td>WR vGAAP</td>
<td>Anti-apoptotic, Ca²⁺ regulator</td>
<td>Attenuated</td>
<td>Attenuated</td>
<td>Attenuated</td>
</tr>
<tr>
<td>Evans</td>
<td>vGAAP</td>
<td>Anti-apoptotic, Ca²⁺ regulator</td>
<td>Attenuated</td>
<td>Attenuated</td>
<td>Attenuated</td>
</tr>
</tbody>
</table>

Vaccinia virus immune evasion
peptides can provide the specificity needed to inhibit specific aspects of TLR signalling necessary for such treatments.

Vaccines
Following the development of VACV as an expression vector in 1982, its potential as a vaccine vector has been investigated extensively. Although attenuated VACV strains have a good safety profile, improving immunogenicity remains a priority (Jacobs et al., 2009), and this depends on a deeper understanding of the effects of VACV immunomodulators on the immune response. Deletion of immunomodulators is one strategy to increase VACV immunogenicity. As outlined above, VACV encodes many immunomodulator genes, and in several cases their deletion has increased the immune response to VACV and provided better protection against challenge.

An alternative attenuation strategy is to express host genes encoding immunomodulatory proteins in VACV. For example, expression of IL-2 (Flexner et al., 1987), IFN-γ (Kohonen-Corish et al., 1990), IFN-β (Bartlett et al., 2005) and IL-15 (Perera et al., 2007) in VACV WR caused a reduction in virus virulence, and in the latter case there was also a greater CD8+ T-cell memory response and an enhanced cellular and humoral response (Perera et al., 2007). However, this strategy requires care because of the potential of some cytokines to increase virus virulence, as illustrated by the expression of IL-4 in VACV (Sharma et al., 1996) and ECTV (Jackson et al., 2001). A further possibility is the expression of immune-stimulating proteins that can selectively enhance recruitment and activation of specifically targeted immune cells, such as antigen-presenting cells, and thereby induce a more selective and specific immune response. For instance, increased anti-MVA antibody titre and an increased cellular immune response were obtained with an MVA strain expressing GM-CSF or CCL20 in mice (Chavan et al., 2006).

In spite of the large number of studies and applications of VACV, a clear understanding of the immunological basis of its protective properties is lacking (Moss, 2011). The immunogenicity of VACV is striking considering the large number of immunosuppressive proteins expressed by the virus. Recent studies have started unravelling the fundamental mechanisms by which the innate immune system orchestrates the adaptive response and protective response to vaccination (Pulendran & Ahmed, 2006). The study of VACV immune evasion may help identify specific molecular signatures in the early response to vaccination that correlate with the development of a protective immune response, or indicate how different subsets of T-cells or antibodies influence protection. Such studies may also illustrate how their induction can be fine tuned, and how different components of the innate immune system interact to integrate signals that impact on adaptive immunity. Recent advances in virus immunology and the application of vaccine engineering, proteomics and systems biology to the study of vaccines can help address these issues and provide information on how the immune system responds to vaccination (Querec et al., 2009; Pulendran et al., 2010). A deeper understanding of VACV and its multitude of immunomodulators has the potential to reveal the underlying signalling networks that underpin development of immunological protection, and to enable more rational vaccine design.

Acknowledgements
The work of this laboratory has been supported by grants from the UK Medical Research Council and the Welcome Trust. G. L. S. is a Welcome Trust Principal Research Fellow.

References


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