



University of Dundee

Identification of TBK1 complexes required for the phosphorylation of IRF3 and the production of interferon

Bakshi, Siddharth; Taylor, Jordan; Strickson, Sam; Macartney, Thomas ; Cohen, Philip

Published in:
Biochemical Journal

DOI:
[10.1042/BCJ20160992](https://doi.org/10.1042/BCJ20160992)

Publication date:
2017

Document Version
Publisher's PDF, also known as Version of record

[Link to publication in Discovery Research Portal](#)

Citation for published version (APA):
Bakshi, S., Taylor, J., Strickson, S., Macartney, T., & Cohen, P. (2017). Identification of TBK1 complexes required for the phosphorylation of IRF3 and the production of interferon . *Biochemical Journal*, 474(7), 1163-1174. <https://doi.org/10.1042/BCJ20160992>

General rights

Copyright and moral rights for the publications made accessible in Discovery Research Portal are retained by the authors and/or other copyright owners and it is a condition of accessing publications that users recognise and abide by the legal requirements associated with these rights.

- Users may download and print one copy of any publication from Discovery Research Portal for the purpose of private study or research.
- You may not further distribute the material or use it for any profit-making activity or commercial gain.
- You may freely distribute the URL identifying the publication in the public portal.

Take down policy

If you believe that this document breaches copyright please contact us providing details, and we will remove access to the work immediately and investigate your claim.

Research Article

Identification of TBK1 complexes required for the phosphorylation of IRF3 and the production of interferon β

Siddharth Bakshi, Jordan Taylor, Sam Strickson, Thomas McCartney and Philip Cohen

MRC Protein Phosphorylation and Ubiquitylation Unit, School of Life Sciences, University of Dundee, Dundee DD1 5EH, U.K.

Correspondence: Philip Cohen (p.cohen@dundee.ac.uk)



The double-stranded RNA mimetic poly(I:C) and lipopolysaccharide (LPS) activate Toll-like receptors 3 (TLR3) and TLR4, respectively, triggering the activation of TANK (TRAF family member-associated NF- κ B activator)-binding kinase 1 (TBK1) complexes, the phosphorylation of interferon regulatory factor 3 (IRF3) and transcription of the interferon β (IFN β) gene. Here, we demonstrate that the TANK–TBK1 and optineurin (OPTN)–TBK1 complexes control this pathway. The poly(I:C)- or LPS-stimulated phosphorylation of IRF3 at Ser396 and production of IFN β were greatly reduced in bone marrow-derived macrophages (BMDMs) from TANK knockout (KO) mice crossed to knockin mice expressing the ubiquitin-binding-defective OPTN[D477N] mutant. In contrast, IRF3 phosphorylation and IFN β production were not reduced significantly in BMDM from OPTN[D477N] knockin mice and only reduced partially in TANK KO BMDM. The TLR3/TLR4-dependent phosphorylation of IRF3 and IFN β gene transcription were not decreased in macrophages from OPTN[D477N] crossed to mice deficient in I κ B kinase ϵ , a TANK-binding kinase related to TBK1. In contrast with the OPTN–TBK1 complex, TBK1 associated with OPTN[D477N] did not undergo phosphorylation at Ser172 in response to poly(I:C) or LPS, indicating that the interaction of ubiquitin chains with OPTN is required to activate OPTN–TBK1 in BMDM. The phosphorylation of IRF3 and IFN β production induced by Sendai virus infection were unimpaired in BMDM from TANK KO \times OPTN[D477N] mice, suggesting that other/additional TBK1 complexes control the RIG-I-like receptor-dependent production of IFN β . Finally, we present evidence that, in human HACAT cells, the poly(I:C)-dependent phosphorylation of TBK1 at Ser172 involves a novel TBK1-activating kinase(s).

Introduction

Type 1 interferons (IFNs) have critical roles in host defence against viral and bacterial pathogens. The engagement of Toll-like receptor 3 (TLR3) by viral double-stranded (ds) RNA, or TLR4 by bacterial lipopolysaccharide (LPS), triggers the production of IFN β by a signalling network that requires, first, the recruitment of the adaptor protein TRIF (TIR-domain-containing adapter-inducing IFN- β , also known as TICAM1) [1], second, the activation of the I κ B kinase-related enzymes TBK1 [TRAF family member-associated NF- κ B activator (TANK)-binding kinase 1] [2] and I κ B kinase ϵ (IKK ϵ) [3–5] and, third, the phosphorylation of interferon regulatory factor 3 (IRF3) [6]. The phosphorylation of IRF3 at C-terminal serine residues, such as Ser396 [7,8], induces its dimerization and translocation to the nucleus where it binds to the promoter of the *IFN β* gene and stimulates transcription [9–12]. Other TBK1-regulated proteins, such as the transcription factor Deformed Epidermal Auto-regulatory Factor 1 [13] and the RNA helicase DDX3X [14,15], may also stimulate TLR3/TLR4-dependent IFN β gene transcription.

Received: 8 November 2016
Revised: 23 January 2017
Accepted: 3 February 2017

Accepted Manuscript online:
3 February 2017
Version of Record published:
15 March 2017

The critical importance of this pathway *in vivo* has been revealed by the identification of mutations in the genes encoding TLR3, TRIF, TBK1 or IRF3 that impair IFN β production and underlie Herpes simplex virus encephalitis, a devastating disease of the central nervous system in young children [16,17]. On the other hand, the overproduction of IFN β by the TLR4/TRIF signalling network causes endotoxaemia and endotoxic shock, since IFN β knockout (KO) mice or mice lacking expression of the type1 IFN receptor are resistant to LPS-induced sepsis [18–20].

The RNA helicases RIG-I and MDA-5 also recognize RNA molecules formed during the replication of single-stranded RNA viruses [21–23] and trigger the activation of TBK1, the phosphorylation of IRF3 and IFN β gene transcription. However, these RIG-I-like receptors (RLRs) do not signal via TRIF, but by the adaptor termed mitochondrial antiviral signalling protein (MAVS; also known as interferon β promoter stimulator-1; virus-induced-signaling adapter and CARD adapter-inducing interferon β) [24–27].

More recently, TBK1 was reported to have a dual role in these pathways. First, it phosphorylates TRIF and MAVS [28], which permit the interaction of the transcription factor IRF3 with these proteins; second, it phosphorylates IRF3 at amino acid residues that include Ser396 [29]. One attractive feature of this mechanism is that it can explain why the activation of TLR3 and TLR4, but not the activation of TLRs that signal via the adaptor MyD88 (myeloid differentiation primary response gene 88), triggers IRF3 phosphorylation [28], even though TBK1 is activated robustly when any TLR is activated [30].

TBK1 does not exist as a single entity in cells but as a variety of heterodimers in which it forms complexes with TANK [2], NF- κ B-activating kinase-associated protein 1 (NAP1) [31], SINTBAD (Similar to NAP1 TBK1 Binding Adaptor) [32] and the ubiquitin-binding protein optineurin (OPTN) [33]. IKK ϵ also interacts with TANK [34], NAP1 [31] and SINTBAD [32], but not with optineurin [33,35]. NAP1 was reported to interact with TRIF, whereas TANK did not [36], and RNA interference studies suggested that NAP1 was required for both TLR3-dependent and RIG-I/MDA-5-dependent phosphorylation of IRF3 and IFN β production [36,37]. The shRNA knockdown of NAP1, SINTBAD or TANK also led to decreases in Sendai virus-induced IFN β gene transcription in overexpression studies performed in human 293 cells. However, studies with TANK KO mice failed to find any involvement of TANK in viral responses, but instead revealed that it was a negative regulator of TLR signalling. As a consequence, TANK KO mice overexpressed proinflammatory cytokines and developed autoimmune nephritis, which could be prevented by crossing to MyD88 KO mice [38]. Subsequently, the TANK–TBK1 and TANK–IKK ϵ complexes were found to phosphorylate the catalytic and regulatory subunits of the canonical IKK complex on sites that inhibit their catalytic activity, explaining how TANK restricts MyD88 signalling [30,34]. TANK plays a key role in facilitating this process via its interaction with the NEMO (NF- κ B essential modulator) component of the IKK complex [39,40].

In the present paper, we have reinvestigated the roles that TANK and optineurin have in TLR3- and TLR4-dependent IFN β production after crossing TANK KO mice with knockin mice in which optineurin is replaced by a ubiquitin-binding-defective mutant. These studies have demonstrated that the TANK–TBK1 and OPTN–TBK1 complexes both participate in these signalling networks.

Materials and methods

Materials

MRT67307, a potent inhibitor of TBK1 and IKK ϵ [30], was dissolved in dimethyl sulphoxide and stored at -20°C as a 10 mM solution. LPS (*Escherichia coli* strain O5:B55) was from Alexis Biochemicals (ALX-581-013-L002), and poly(I:C) from InvivoGen (tlrl-pic). macrophage colony-stimulating factor (M-CSF) was purchased from R&D Systems (216-MC-025) and FuGene[®] HD transfection reagent from Promega (E2311).

Antibodies

Antibodies for immunoprecipitation were raised in sheep against amino acid residues 520–531 of human OPTN (sheep number S685D, fourth and fifth bleeds) and the full-length human TANK protein (sheep number S278C, third bleed), and were generated by the antibody production team of the Medical Research Council Protein Phosphorylation and Ubiquitylation Unit, University of Dundee (co-ordinated by Dr James Hastie). They can be ordered from the reagents section of the MRC-PPU website (<https://mrcppureagents.dundee.ac.uk/>). The following antibodies for immunoblotting were purchased from Cell Signaling Technology: TANK (Cat #2141), TBK1 (Cat #3504), TRIF (Cat #4596), IKK ϵ (Cat #3416), GAPDH (Cat #2118), c-Jun N-terminal kinase (JNK)1/2 (Cat #9258), p38 (Cat #9212), TBK1 phosphorylated at Ser172 (Cat #5483), IKK ϵ

phosphorylated at Ser172 (Cat #8766), TAK1 (TGF β -activated kinase 1; Cat #4505), IKK α phosphorylated at Ser176 and Ser180 and IKK β phosphorylated at Ser177 and Ser181 (Cat #2677), IRF3 phosphorylated at Ser396 (Cat #4947), JNK1 and JNK2 dually phosphorylated at their Thr-Pro-Tyr motifs (Cat #4668) and p38 α mitogen-activated protein (MAP) kinase dually phosphorylated at its Thr-Gly-Tyr motif (Cat #9211). An anti-OPTN antibody was obtained from Abcam (Cat #ab23667), an antibody that recognizes all forms of IRF3 was from Proteintech (Cat #11312-1-AP) and an antibody that recognizes all forms of IKK β was from Merck-Millipore (Cat #05-535). Rabbit- and sheep-specific secondary antibodies conjugated to horseradish peroxidase were from Thermo Scientific.

Mice, cell culture, cell stimulation and cell lysis

Heterozygous TANK KO mice (a gift from Professor Shizuo Akira, Laboratory of Host Defense, World Premier International Immunology Frontier Research Center, Osaka University, Japan) [38] and IKK ϵ KO mice (a gift from Dr Alastair Reith, GlaxoSmithKline, Stevenage, U.K.) were crossed to OPTN[D477N] mice [35] to generate TANK KO \times OPTN[D477N] and IKK ϵ KO \times OPTN[D477N] mice, respectively. BMDMs were obtained by differentiating bone marrow obtained from the femur and tibia with M-CSF or L929 preconditioned medium as the source of M-CSF [41]. Adherent BMDMs were re-plated into 12-well tissue culture plates (5×10^5 cells/well) or 10 cm tissue culture grade plates (5×10^6 cells/plate) using fresh culture medium. After re-plating, the BMDMs were stimulated with the TLR ligands indicated in the figure legends. The human keratinocyte HACAT cell line was cultured in Dulbecco's Modified Eagle's medium supplemented with 10% foetal bovine serum, 2 mM L-glutamine and antibiotics (100 Units/ml penicillin and 0.1 mg/ml streptomycin). Where indicated, cells were incubated for 1 h with MRT67307 dissolved in dimethyl sulphoxide or an equivalent volume of dimethyl sulphoxide for control incubations.

The cells were rinsed in ice-cold PBS and extracted in ice-cold lysis buffer [50 mM Tris-HCl (pH 7.5), 1 mM EGTA, 1 mM EDTA, 1% (v/v) Triton X-100, 1 mM sodium orthovanadate, 50 mM sodium fluoride, 5 mM sodium pyrophosphate, 0.27 M sucrose, 10 mM sodium 2-glycerophosphate, 1 mM phenylmethylsulphonyl fluoride, 1 mM benzamidine and 1 mM dithiothreitol]. Cell lysates were clarified by centrifugation at $14\,000\times g$ for 30 min at 4°C, and the supernatants (cell extracts) were collected and their protein concentrations were determined by the Bradford procedure.

Generation of TRIF- or TAK1-deficient HACAT cells

HACAT cells (2×10^6 cells) were plated onto a 10 cm diameter tissue culture grade plate and transfected the next day with 1 μ g each of guide (g) RNA plasmid targeting the gene of interest. FuGene[®] HD transfection reagent (5 μ l per 1 μ g of plasmid DNA) was used for transfection. At 24 and 48 h post-transfection, fresh media containing 2 μ g/ml puromycin was added to the cells, while 72 h after transfection the puromycin-containing medium was replaced by medium lacking puromycin. After a further 48 h, cells were single-cell plated onto 96-well plates and left for 2–3 weeks until colonies began to form. The colonies were then analyzed for the expression of TRIF and TAK1 by immunoblotting.

Immunoblotting and immunoprecipitation

Immunoblotting was performed using the ECL detection system (GE Healthcare). To immunoprecipitate TANK and OPTN, 1.0 mg of cell extract protein was incubated for 2 or 4 h with 3.0 μ g of anti-TANK or 6.0 μ g of anti-OPTN. Protein-G-Sepharose beads (20 μ l) were added and, after end-over-end rotation for 1 h at 4°C, the beads were collected by centrifugation, washed three times with cell lysis buffer, denatured in SDS, subjected to SDS-PAGE, transferred to polyvinylidene fluoride membranes and immunoblotted.

Quantitative RT-PCR and ELISA

Total RNA was extracted from macrophages using the MicroElute Total RNA kit (Omega bio-tek). RNA was reverse-transcribed using the iScript cDNA synthesis kit (Bio-Rad) following the manufacturer's instructions. Polymerase chain reaction (PCR) mixes were assembled using the SsoFast[™] EvaGreen[®] Supermix (Bio-Rad). Reactions were performed with the SYBR Green (plus melting curve analysis) programme on the C1000 thermal cycler quantitative PCR system (Bio-Rad). All reactions were performed in duplicate. The concentration of IFN β released into the cell culture medium was determined by using the LegendMax mouse IFN β ELISA kit (Biolegend). The primer sequences used in the present paper are given in Supplementary Table S1.

Quantitation of immunoblots of phosphorylated IRF3

This was performed using the Image J software and normalized to immunoblots obtained with antibodies that recognize all forms of IRF3.

Statistical analyses

Statistical analyses were performed using the GraphPad Prism software. Quantitative data were presented as the arithmetic mean \pm SEM. Statistical significance of differences between wild-type and the other genotypes was assessed using two-way ANOVA with Bonferroni post-test to compare each genotype with the control wild-type sample, unless stated otherwise. Differences in means were considered significant if $P < 0.05$; * $P < 0.05$, ** $P < 0.01$, *** $P < 0.001$. n.s. means not significant.

Results

TANK–TBK1 and OPTN–TBK1 control TLR3/4-dependent phosphorylation of IRF3 and IFN β gene transcription in BMDMs

OPTN is the protein with the greatest amino acid sequence similarity to NEMO, the regulatory component of the canonical IKK complex. The proteins have similar ubiquitin-binding domains and, like NEMO, OPTN binds to Met1-linked ubiquitin (M1-Ub) and Lys63-linked ubiquitin (K63-Ub) chains, but not to Lys48-linked ubiquitin chains [35]. To investigate which TBK1 complexes are required for IRF3 phosphorylation and IFN β production, we crossed knockin mice expressing the ubiquitin-binding-defective OPTN[D477N] mutant [35] to TANK KO mice [38], generating TANK KO \times OPTN[D477N] mice. Stimulation of BMDMs with the dsRNA-mimetic poly(I:C) to activate TLR3, or LPS to activate TLR4, induced the production of IFN β mRNA (Figure 1A,B) and secretion of IFN β (Figure 1C,D), which were partially reduced in BMDM from the TANK KO, not reduced significantly in BMDM from OPTN[D477N] mice, but greatly reduced in BMDM from the TANK KO \times OPTN[D477N] mice. Consistent with these findings, the TLR3-dependent phosphorylation of IRF3 at Ser396 was also reduced considerably in BMDM from the TANK KO \times OPTN[D477N] mice (top two panels of Figure 2A and Supplementary Figure S1A) and the TLR4-dependent phosphorylation of IRF3 was undetectable (top two panels of Figure 2B and Supplementary Figure S1B). Consistent with these observations, the LPS-dependent secretion of IFN β was reduced more strikingly than the poly(I:C)-stimulated secretion of IFN β in BMDM from TANK KO \times OPTN[D477N] mice. However, the TLR3- or TLR4-dependent phosphorylation of TBK1 at Ser172 was only reduced modestly in BMDM from TANK KO \times OPTN[D477N] mice (Figure 2A,B, panels 3 and 4), indicating that poly(I:C) and LPS activate other TBK1 complexes distinct from TANK–TBK1 and OPTN–TBK1.

TLR3 signals specifically via the adaptor protein TRIF, whereas TLR4 signals via MyD88 and TRIF. The decreased phosphorylation of TBK1 at Ser172 observed 15 min after stimulation with LPS in BMDM from TANK KO and TANK KO \times OPTN[D477N] mice is explained by the TANK–TBK1 complex making a major contribution to the MyD88-dependent activation of TBK1 [34], which occurs more rapidly than the TRIF-dependent activation of TBK1. Since only the slower TRIF-dependent activation of TBK1 induces IRF3 phosphorylation at Ser396, this explains why the LPS-dependent phosphorylation of TBK1 precedes the phosphorylation of IRF3.

The mRNAs encoding TLR3, TLR4 and TRIF were not decreased in BMDM from the TANK KO, OPTN [D477N] or TANK KO \times OPTN[D477N] mice (Supplementary Figure S2A–C), indicating that the decreased phosphorylation of IRF3 and reduced production of IFN β mRNA in BMDMs from TANK KO \times OPTN [D477N] mice were not explained by decreased expression of these receptor and adaptor molecules that are situated ‘upstream’ of IRF3 in this signalling pathway. The expression of UNC93B, which interacts with TLR3 and localizes it to endosomal membranes [42], was also unimpaired in the TANK KO \times OPTN[D477N] knockin mice (Supplementary Figure S2D). The expression of IRF3 in BMDM from TANK KO \times OPTN [D477N] mice was similar to that from wild-type mice, while the expression of TANK was similar in BMDM from OPTN[D477N] mice and the expression of OPTN was similar in TANK KO mice (Figure 2A,B).

IKK ϵ , the protein kinase most closely related to TBK1, also forms a complex with TANK [34] and has been reported to contribute to TLR3 and TLR4-dependent IFN β production in some cells (see Introduction). However, the poly(I:C)- or LPS-stimulated phosphorylation of IRF3 at Ser396 (Figure 2C,D, top two panels), IFN β mRNA production and IFN β secretion (Figure 3A–D) were not impaired in macrophages from the OPTN[D477N] \times IKK ϵ KO mice. Indeed, IFN β production was modestly elevated in the IKK ϵ -deficient macrophages compared

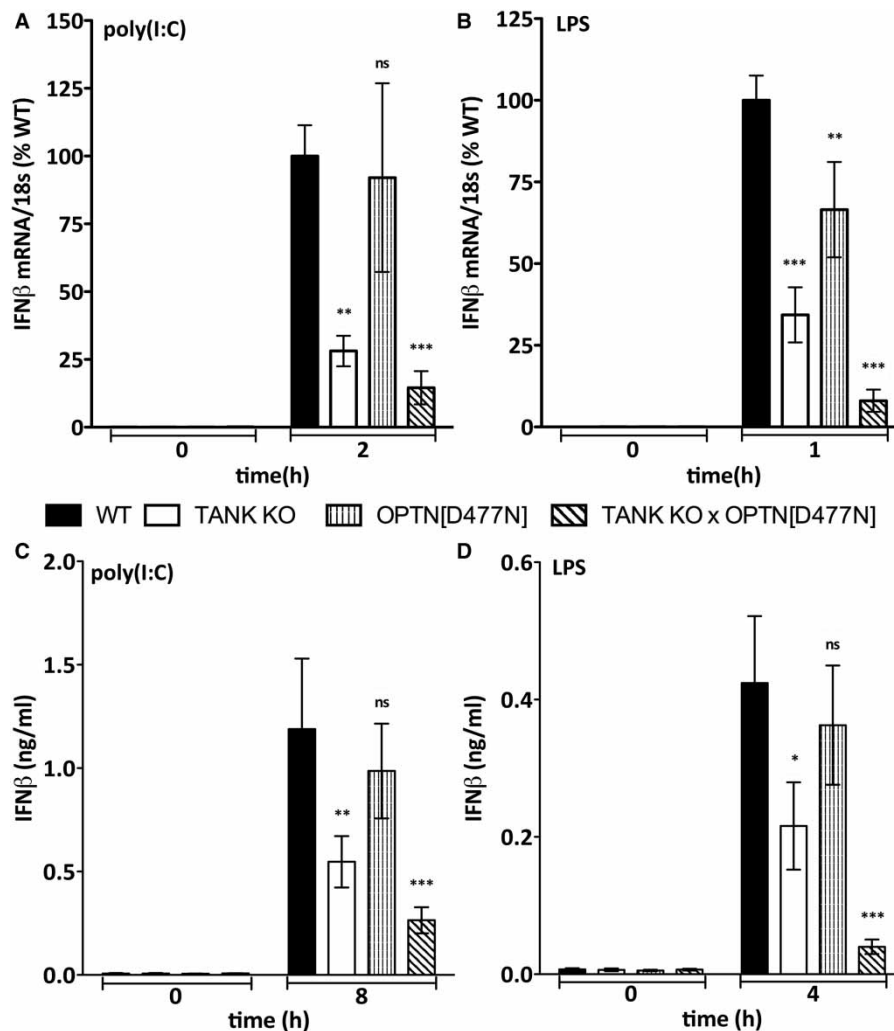


Figure 1. IFN β production is suppressed in BMDM from TANK KO x OPTN[D477N] mice.

BMDM from wild-type (WT) mice (closed bars), TANK KO mice (open bars), OPTN[D477N] mice (striped bars) and TANK KO x OPTN[D477N] mice (hatched bars) were stimulated with 10 μ g/ml poly(I:C) (A and C) or 100 ng/ml LPS (B and D) for the times indicated. (A and B) The IFN β mRNA produced was measured relative to 18S ribosomal mRNA and normalized to the level of wild-type IFN β mRNA (100%) measured after 2 h stimulation with poly(I:C) (A) or 1 h stimulation with LPS (B). (C and D) The amount of IFN β in the cell culture medium was measured by ELISA after 8 h stimulation with poly(I:C) (C) or 4 h stimulation with LPS (D). (A–D) The results are presented as arithmetic mean (\pm SEM for four independent experiments carried out on BMDM from nine different mice).

with wild-type macrophages. Taken together, these experiments indicate that the OPTN–TBK1 and TANK–TBK1 complexes are required for the TLR3- and TLR4-dependent phosphorylation of IRF3 at Ser396 and the production of IFN β in BMDM.

LPS stimulation decreased the electrophoretic mobility of TANK and OPTN (Figure 2). This is caused by the phosphorylation of these proteins, since it was reversed by treatment with phage λ phosphatase (Supplementary Figure S3). The LPS-induced decrease in the electrophoretic mobility of OPTN is less pronounced in the OPTN[D477N] mutant (Figure 2, panel 6 from top), indicating that it is phosphorylated less extensively than wild-type OPTN. The OPTN[D477N] mutant was also expressed at higher levels than wild-type OPTN. After stimulation with poly(I:C) for 1 or 2 h, there is an apparent decrease in the expression of TANK, which is largely restored after 4 h. The underlying molecular mechanism is unclear, but a possible explanation is that TANK undergoes a covalent modification that prevents its recognition by the TANK antibody.

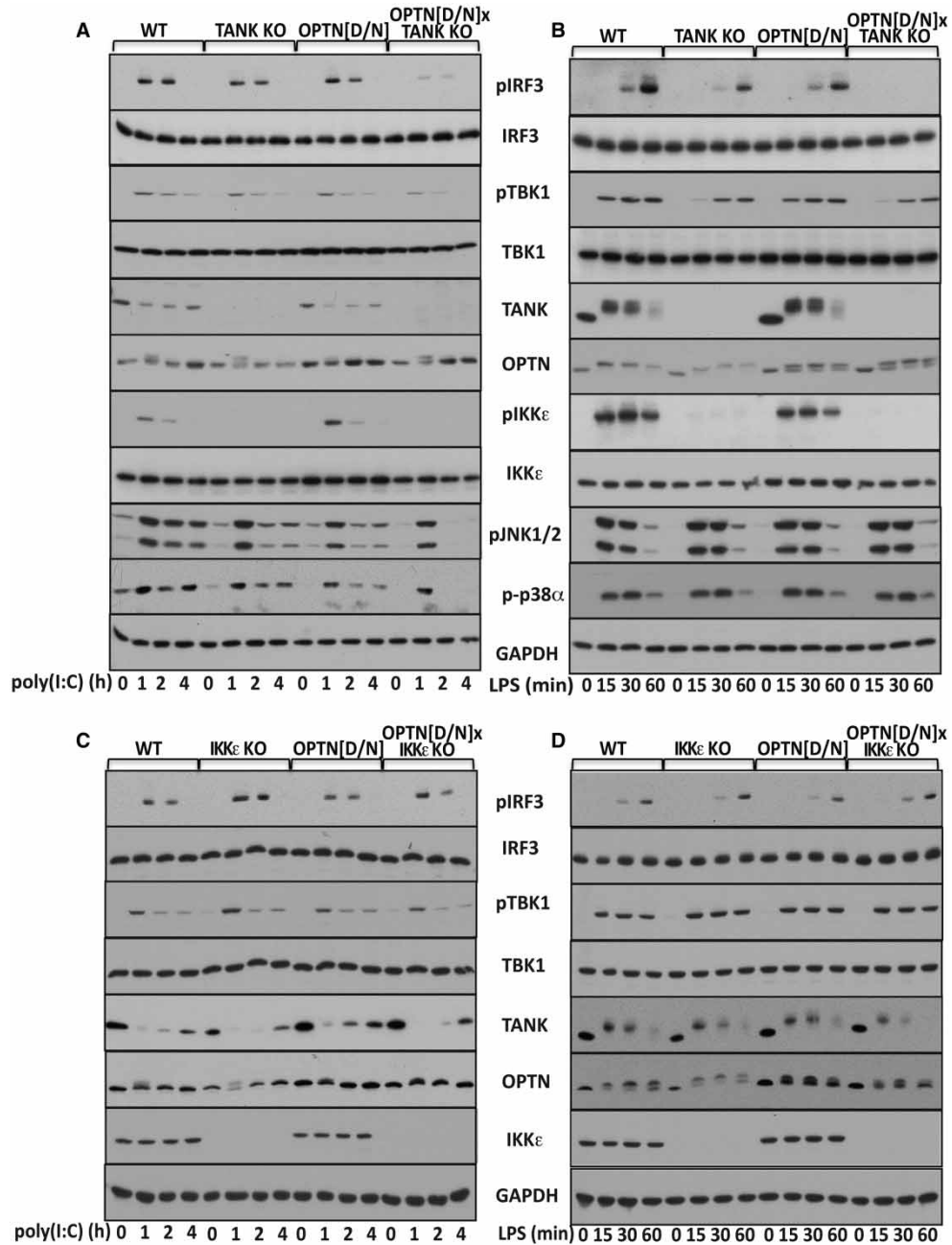


Figure 2. Poly(I:C)- or LPS-induced phosphorylation of TBK1, IRF3 and MAP kinases in BMDM from different mouse lines.

(A–D) BMDM from WT mice and TANK KO mice (A and B), IKK ϵ KO mice (C and D), OPTN[D477N] mice and either OPTN[D/N] \times TANK KO mice (A and B) or OPTN[D/N] \times IKK ϵ KO mice (C and D) were stimulated with 10 μ g/ml poly(I:C) or 100 ng/ml LPS for the times indicated. Aliquots of the cell extracts (20 μ g protein) were subjected to SDS–PAGE and immunoblotted with antibodies that recognize TBK1 or IKK ϵ phosphorylated at Ser172 (pTBK1 and pIKK ϵ , respectively), IRF3 phosphorylated at Ser396 (pIRF3), JNK1 and JNK2 phosphorylated at their Thr-Pro-Tyr motifs (p-JNK1/2) and p38 α phosphorylated at its Thr-Gly-Tyr motif (p-p38 α), and with antibodies that recognize all forms of TBK1, IKK ϵ , IRF3, TANK and OPTN. Antibodies to GAPDH were used as a loading control.

The LPS- and poly(I:C)-dependent phosphorylation of the MAP kinases, termed c-Jun N-terminal kinases 1 and 2 (JNK1/2) and p38 α , was similar in BMDM from TANK KO \times OPTN[D477N] and wild-type mice up to 1 h. However, the poly(I:C)-dependent activation of these MAP kinases then decreased much more rapidly between 1 and 4 h in TANK KO \times OPTN[D477N] BMDM compared with wild-type BMDM (Figure 2A,B, panels 9 and 10 from top). These observations, which were made in two independent experiments, suggest that these TBK1 heterodimers may have a role in maintaining JNK1/2 and p38 α activity during prolonged TLR3 activation. This could be important for sustaining *ifn* β gene transcription in mouse BMDM, since the JNK-dependent activation of the transcription factors c-Jun and ATF2 has been reported to co-ordinate the adenovirus-mediated induction of primary IRF3-responsive transcripts in conjunction with activated IRF3 [43].

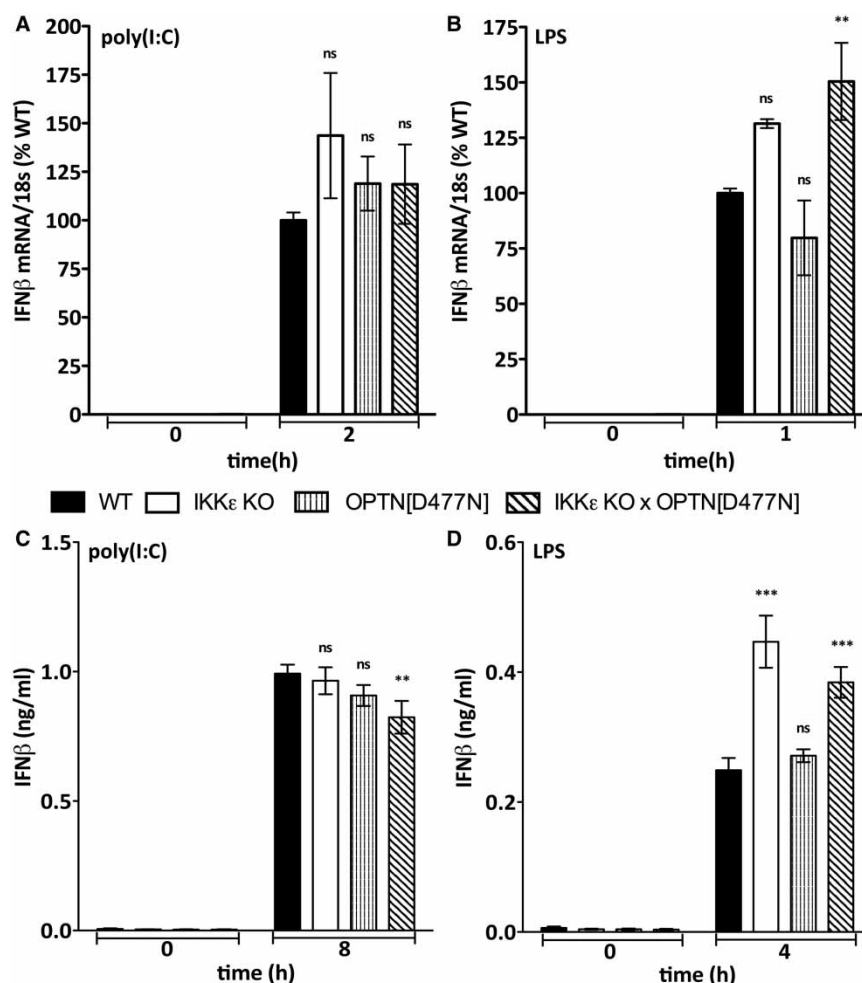


Figure 3. IFN β production is not suppressed in BMDM from IKK ϵ \times OPTN[D477N] mice.

BMDM from WT mice (closed bars), IKK ϵ KO mice (open bars), OPTN[D477N] mice (striped bars) and IKK ϵ KO \times OPTN[D477N] mice (hatched bars) were stimulated with 10 μ g/ml poly(I:C) (A and C) or 100 ng/ml LPS (B and D) for the times indicated.

(A and B) The IFN β mRNA produced was measured relative to 18S ribosomal mRNA and normalized to the level of wild-type IFN β mRNA (100%) measured after 2 h stimulation with poly(I:C) (A) or 1 h stimulation with LPS (B). (C and D) The amount of IFN β in the cell culture medium was measured by ELISA after stimulation for 8 h with poly(I:C) (C) or 4 h with LPS (D). (A–D)

The results are presented as arithmetic mean (\pm SEM for three independent experiments carried out on BMDM from eight different mice).

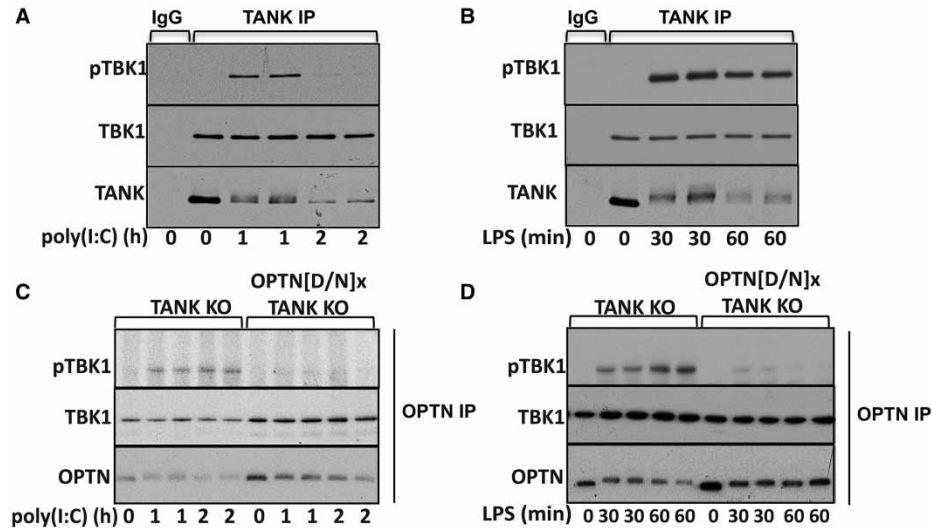


Figure 4. Poly(I:C)- or LPS-dependent activation of the individual TANK–TBK1 and OPTN–TBK1 complexes in BMDM. (A and B) WT BMDMs were stimulated with 10 μ g/ml poly(I:C) (A) or 100 ng/ml LPS (B) for the times indicated in Figure 1. TANK was immunoprecipitated from the extracts and phosphorylation of the TBK1 in the immunoprecipitates (pTBK1) was analyzed by immunoblotting as described in Materials and Methods. The membranes were also immunoblotted with antibodies that recognize all forms of TBK1 and TANK. (C and D) As in A, B except that OPTN was immunoprecipitated from the extracts of TANK KO and TANK KO x OPTN[D477N] mice and the presence of phospho-TBK1, total TBK1 and OPTN in the immunoprecipitates was analyzed by immunoblotting.

Activation of the TANK–TBK1 and OPTN–TBK1 complexes

To study the activation of the individual TANK–TBK1 and OPTN–TBK1 complexes, we immunoprecipitated TANK (Figure 4A,B) or OPTN (Figure 4C,D) from BMDM extracts and examined phosphorylation of the associated TBK1 catalytic subunit at Ser172. These experiments showed that poly(I:C)- or LPS stimulation induced the activation of both the TANK–TBK1 and OPTN–TBK1 complexes. Importantly, the phosphorylation of TBK1 at Ser172 was reduced in the OPTN[D477N]–TBK1 complex compared with that in the OPTN–TBK1 complex (Figure 4C,D), implying that the interaction of OPTN with ubiquitin chains is required for the robust phosphorylation and activation of the OPTN–TBK1 complex.

TANK–TBK1 and OPTN–TBK1 are not rate-limiting for Sendai virus-induced IRF3 phosphorylation and IFN β gene transcription in BMDM

To investigate whether the TANK–TBK1 and OPTN–TBK1 complexes were rate-limiting in the RLR-dependent signalling pathway (see Introduction), we studied Sendai virus-induced IFN β production in BMDM. These experiments showed that IRF3 phosphorylation at Ser396 and IFN β secretion were similar in BMDM from TANK KO, OPTN[D477N], TANK KO x OPTN[D477N] and wild-type mice (Supplementary Figure S4). Therefore, in contrast with the TLR3- and TLR4-signalling networks, the TANK–TBK1 and OPTN–TBK1 complexes were not rate-limiting for RLR-dependent IFN β production under the conditions that were studied.

The poly(I:C)-dependent phosphorylation of TBK1 at Ser172 in HACAT cells involves a novel ‘upstream’ kinase

The interleukin-1 (IL-1)-dependent phosphorylation of TBK1 at Ser172 in mouse embryonic fibroblasts (MEFs) is catalyzed by IKK β and by TBK1 itself, and is therefore prevented by incubating IKK α -deficient MEFs with an IKK β inhibitor plus a dual TBK1/IKK ϵ inhibitor, but not by either inhibitor alone. Since the IL-1-dependent activation of IKK α and IKK β in MEFs is catalyzed by the protein kinase TAK1 (also called MAP3K7), the IL-1-dependent phosphorylation of TBK1 can also be suppressed by a TBK1 inhibitor in MEFs

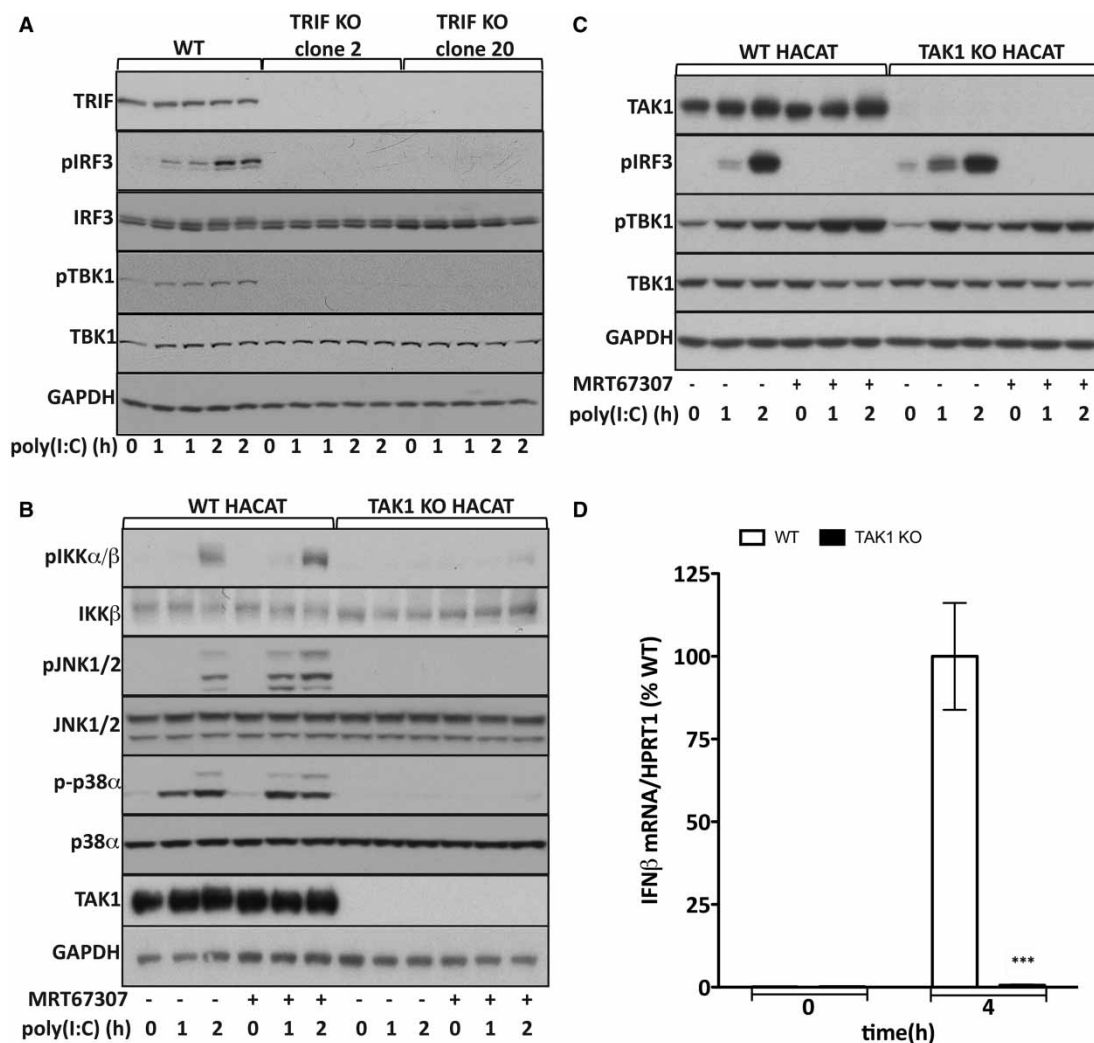


Figure 5. Poly(I:C)-dependent phosphorylation of TBK1 and IFN β gene transcription in TRIF KO and TAK1 KO HACAT cells.

(A) Poly(I:C)-dependent phosphorylation of TBK1 and IRF3 is abolished in TRIF KO HACAT cells. Cells were stimulated with 10 μ g/ml poly(I:C) for the times indicated as in Figure 1, and the cell extracts (20 μ g of protein) were subjected to SDS-PAGE and immunoblotting with antibodies that recognize TBK1 phosphorylated at Ser172 (pTBK1) or IRF3 phosphorylated at Ser396 (pIRF3), and with antibodies that recognize all forms of TBK1, IRF3 and TRIF. Antibodies to GAPDH were used as a loading control. (B) TAK1 KO and WT HACAT cells were incubated for 1 h with 2.0 μ M MRT67307 and then stimulated with 10 μ g/ml poly(I:C) for the times indicated. The cell extracts were processed as in A and immunoblotted with antibodies that recognize the phosphorylated (p), activated forms of IKK α/β , JNK1/2 and p38 α MAP kinase (p38 α) and all forms of TAK1, IKK β , JNK and p38 α . (C) The TAK1 KO and WT cells were incubated for 1 h with or without 2 μ M MRT67307 prior to stimulation with poly(I:C). Other details are as in A,B. (D) WT HACAT cells (open bars) and TAK1 KO HACAT cells (closed bars) were stimulated with poly(I:C). IFN β mRNA production was then measured relative to hypoxanthine-guanine phosphoribosyltransferase 1 (HPRT1) mRNA and normalized to the level of IFN β mRNA measured in WT cells (100%) after stimulation for 4 h with poly(I:C). The results are presented as arithmetic mean (\pm SEM for two independent experiments each performed in triplicate).

from knockin mice expressing a kinase-inactive form of TAK1 [30]. In contrast, the tumour necrosis factor-induced activation of TBK1 in IKK α -deficient MEFs is prevented by the inhibition of IKK β alone [30].

MEFs do not respond robustly to either poly(I:C) or LPS, and TAK1 KO/knockin mice display early embryonic lethality. To investigate which protein kinases activate TBK1 in the TLR3/TLR4-TRIF signalling network, we therefore used human keratinocyte HACAT cells, which respond to poly(I:C) (Figure 5A) [44]. The poly(I:C)-dependent phosphorylation of IRF3 at Ser396 in HACAT cells was mediated by the activation of TLR3, since it was abolished by the KO of TRIF (Figure 5A). We next disrupted the gene encoding the TAK1 catalytic subunit in HACAT cells by clustered regularly interspaced short palindromic repeats (CRISPR)/Cas9 gene-editing

technology and found that the poly(I:C)-dependent activation of the canonical IKK complex, JNK1/2 and p38 α MAP kinase was abolished (Figure 5B), but the phosphorylation of IRF3 at Ser396 was unaffected (Figure 5C). However, the phosphorylation of TBK1 at Ser172 was only reduced modestly, even when the TAK1 KO cells were additionally incubated with the dual TBK1/IKK ϵ inhibitor MRT67307 prior to stimulation with poly(I:C) to prevent the autophosphorylation of TBK1 at Ser172 (Figure 5C). Taken together, these experiments indicate that the poly(I:C)-dependent phosphorylation of TBK1 at Ser172 involves a novel TBK1-activating kinase distinct from IKK α , IKK β and TBK1 itself. Incubation of the wild-type HACAT cells with MRT67307 increased the poly(I:C)-dependent phosphorylation of TBK1 at Ser172 (Figure 5C). This observation, which has been made previously in other cells [30], indicates that TBK1 controls a feedback loop that restricts its own activation.

Interestingly, although the poly(I:C)-dependent phosphorylation of IRF3 at Ser396 was unimpaired in TAK1 KO HACAT cells (Figure 5C), IFN β gene transcription was abolished (Figure 5D), demonstrating that TAK1 controls IFN β gene transcription by a mechanism that is independent of IRF3 phosphorylation at Ser396. This might be explained by the suppression of JNK1/2 in TAK1 KO HACAT cells (Figure 5B), since JNKs have been reported to control IFN β gene transcription by phosphorylating IRF3 at Ser173 [45].

Discussion

Although it is well established that the activation of TBK1 and the phosphorylation of IRF3 are key events in the TLR3/4 signalling pathway leading to IFN β gene transcription, the molecular events that trigger the activation of TBK1 and the phosphorylation of IRF3 are still incompletely understood. Here, we have shown that the TANK–TBK1 and OPTN–TBK1 complexes are rate-limiting for the TLR3/4-dependent phosphorylation of IRF3 (Figure 2A,B) and *ifnb* gene transcription (Figure 1), whereas the TANK–IKK ϵ heterodimer is not (Figures 2C,D and 3). However, our results do not exclude roles for other TBK1 heterodimers in this pathway, such as the NAP1–TBK1 and SINTBAD–TBK1 heterodimers which might, for example, mediate the TBK1-catalyzed activation of other proteins that control this process, such as DDX3X [14,15]. Moreover, the TANK–TBK1 and OPTN–TBK1 heterodimers were not rate-limiting for Sendai virus-induced IRF3 phosphorylation and IFN β secretion, indicating the involvement of additional/other TBK1 heterodimers in the RIG-I/MDA-5 pathway (Supplementary Figure S4). Our experiments have also revealed that the poly(I:C)/TRIF-dependent phosphorylation of TBK1 at Ser172 in human HACAT cells involves a protein kinase(s) distinct from or additional to the canonical IKK complex and TBK1 itself (Figure 5), which are the protein kinases known to phosphorylate TBK1 at Ser172 in the IL-1- and TNF-signalling pathways [30].

We observed that the poly(I:C)- or LPS-induced phosphorylation of Ser172 in the OPTN–TBK1 complex is prevented in the OPTN[D477N]–TBK1 heterodimer (Figure 4), implying that the interaction of ubiquitin chains with OPTN is required to activate the TBK1 catalytic subunit in this complex. Consistent with this finding, the poly(I:C) or LPS-stimulated phosphorylation of OPTN was reduced in macrophages expressing the ubiquitin-binding-defective OPTN[D477N] mutant (Figure 2); TBK1 is known to phosphorylate OPTN at Ser177 [35,46]. The activation of the OPTN–TBK1 complex in the TLR3/4 signalling pathway therefore appears to resemble the IL-1-dependent activation of the NEMO–IKK β complex where the formation of Met1-linked ubiquitin chains (catalyzed by the linear ubiquitin assembly complex) and their binding to NEMO are required before TAK1 can phosphorylate the activation loop of IKK β at Ser177 [47]. In the IL-1 signalling pathway, the Met1-linked ubiquitin oligomers are attached covalently to preformed Lys63-linked ubiquitin oligomers, providing a mechanism for the co-recruitment of the canonical IKK complex and its activator TAK1 [48]. Hybrid ubiquitin chains containing both Met1- and Lys63-ubiquitin linkages are also formed when the TLR3–TRIF signalling pathway is activated [49]. It is therefore tempting to speculate that these hybrid ubiquitin chains recruit the OPTN–TBK1 complex to its as yet unknown activating kinase.

Abbreviations

BMDM, bone marrow-derived macrophages; CRISPR, clustered regularly interspaced short palindromic repeats; ds, double-stranded; IFN, interferon; IL-1, interleukin-1; IKK, I κ B kinase; IRF3, interferon regulatory factor 3; JNK1/2, c-Jun N-terminal kinases 1 and 2; KO, knockout; LPS, lipopolysaccharide; MAP, mitogen-activated protein; MAVS, mitochondrial antiviral signalling protein; M-CSF, macrophage colony-stimulating factor; MDA-5, melanoma differentiation-associated protein 5; MEF, mouse embryonic fibroblast; MyD88, myeloid differentiation primary response gene 88; NAP1, NF- κ B-activating kinase-associated protein 1; NEMO, NF- κ B essential modulator; OPTN, optineurin; PCR, polymerase chain reaction; RLRs, RIG-I-like receptors; SINTBAD, Similar to NAP1 TBK1 Binding Adaptor; TAK1, TGF β -activated kinase-1; TBK1 TANK, binding kinase 1; TRAF-, tumour

necrosis factor (TNF) receptor associated factor; TLR, Toll-like receptor; TANK, TRAF family member-associated NF- κ B activator; TRIF, TIR-domain-containing adapter-inducing IFN β .

Author Contribution

S.B. and P.C. designed the experiments, S.B., J.T. and S.S. performed the experiments. T.M. designed and made the guide RNAs for CRISPR/Cas9 gene editing technology. S.B. and P.C. wrote the paper.

Funding

This work reported in the study was supported by a Wellcome Trust Senior Investigator Grant [WT100294 to P.C.], by a Wellcome Trust Prize Studentship [WT109112/Z/15/Z to J.T.] and by Boehringer Ingelheim, GlaxoSmithKline and Merck-Serono.

Competing Interests

The Authors declare that there are no competing interests associated with the manuscript.

References

- 1 Yamamoto, M., Sato, S., Hemmi, H., Hoshino, K., Kaisho, T., Sanjo, H. et al. (2003) Role of adaptor TRIF in the MyD88-independent toll-like receptor signaling pathway. *Science* **301**, 640–643 doi:10.1126/science.1087262
- 2 Pomerantz, J.L. and Baltimore, D. (1999) NF- κ B activation by a signaling complex containing TRAF2, TANK and TBK1, a novel IKK-related kinase. *EMBO J.* **18**, 6694–6704 doi:10.1093/emboj/18.23.6694
- 3 Shimada, T., Kawai, T., Takeda, K., Matsumoto, M., Inoue, J., Tatsumi, Y. et al. (1999) IKK- α , a novel lipopolysaccharide-inducible kinase that is related to κ B kinases. *Int. Immunol.* **11**, 1357–1362 doi:10.1093/intimm/11.8.1357
- 4 Bonnard, M., Mirtsos, C., Suzuki, S., Graham, K., Huang, J., Ng, M. et al. (2000) Deficiency of T2K leads to apoptotic liver degeneration and impaired NF- κ B-dependent gene transcription. *EMBO J.* **19**, 4976–4985 doi:10.1093/emboj/19.18.4976
- 5 Tojima, Y., Fujimoto, A., Delhase, M., Chen, Y., Hatakeyama, S., Nakayama, K. et al. (2000) NAK is an κ B kinase-activating kinase. *Nature* **404**, 778–782 doi:10.1038/35008109
- 6 Fitzgerald, K.A., McWhirter, S.M., Faia, K.L., Rowe, D.C., Latz, E., Golenbock, D.T. et al. (2003) IKK ϵ and TBK1 are essential components of the IRF3 signaling pathway. *Nat. Immunol.* **4**, 491–496 doi:10.1038/ni921
- 7 Servant, M.J., Grandvaux, N., ten Oever, B.R., Duguay, D., Lin, R. and Hiscott, J. (2003) Identification of the minimal phosphoacceptor site required for in vivo activation of interferon regulatory factor 3 in response to virus and double-stranded RNA. *J. Biol. Chem.* **278**, 9441–9447 doi:10.1074/jbc.M209851200
- 8 Panne, D., McWhirter, S.M., Maniatis, T. and Harrison, S.C. (2007) Interferon regulatory factor 3 is regulated by a dual phosphorylation-dependent switch. *J. Biol. Chem.* **282**, 22816–22822 doi:10.1074/jbc.M703019200
- 9 Wathlet, M.G., Lin, C.H., Parekh, B.S., Ronco, L.V., Howley, P.M. and Maniatis, T. (1998) Virus infection induces the assembly of coordinately activated transcription factors on the IFN- β enhancer in vivo. *Mol. Cell* **1**, 507–518 doi:10.1016/S1097-2765(00)80051-9
- 10 Lin, R., Heylbroeck, C., Pitha, P.M. and Hiscott, J. (1998) Virus-dependent phosphorylation of the IRF-3 transcription factor regulates nuclear translocation, transactivation potential, and proteasome-mediated degradation. *Mol. Cell. Biol.* **18**, 2986–2996 doi:10.1128/MCB.18.5.2986
- 11 Yoneyama, M., Suhara, W., Fukuhara, Y., Fukuda, M., Nishida, E. and Fujita, T. (1998) Direct triggering of the type I interferon system by virus infection: activation of a transcription factor complex containing IRF-3 and CBP/p300. *EMBO J.* **17**, 1087–1095 doi:10.1093/emboj/17.4.1087
- 12 Weaver, B.K., Kumar, K.P. and Reich, N.C. (1998) Interferon regulatory factor 3 and CREB-binding protein/p300 are subunits of double-stranded RNA-activated transcription factor DRAF1. *Mol. Cell. Biol.* **18**, 1359–1368 doi:10.1128/MCB.18.3.1359
- 13 Ordureau, A., Enesa, K., Nanda, S., Le Francois, B., Pegg, M., Prescott, A. et al. (2013) DEAF1 is a Pellino1-interacting protein required for interferon production by Sendai virus and double-stranded RNA. *J. Biol. Chem.* **288**, 24569–24580 doi:10.1074/jbc.M113.479550
- 14 Soulat, D., Bürckstümmer, T., Westermayer, S., Goncalves, A., Bauch, A., Stefanovic, A. et al. (2008) The DEAD-box helicase DDX3X is a critical component of the TANK-binding kinase 1-dependent innate immune response. *EMBO J.* **27**, 2135–2146 doi:10.1038/emboj.2008.126
- 15 Schröder, M., Baran, M. and Bowie, A.G. (2008) Viral targeting of DEAD box protein 3 reveals its role in TBK1/IKK ϵ -mediated IRF activation. *EMBO J.* **27**, 2147–2157 doi:10.1038/emboj.2008.143
- 16 Herman, M., Ciancanelli, M., Ou, Y.H., Lorenzo, L., Klauedel-Dreszler, M., Pauwels, E. et al. (2012) Heterozygous *TBK1* mutations impair TLR3 immunity and underlie herpes simplex encephalitis of childhood. *J. Exp. Med.* **209**, 1567–1582 doi:10.1084/jem.20111316
- 17 Sancho-Shimizu, V., Perez de Diego, R., Lorenzo, L., Halwani, R., Alangari, A., Israelsson, E. et al. (2011) Herpes simplex encephalitis in children with autosomal recessive and dominant TRIF deficiency. *J. Clin. Invest.* **121**, 4889–4902 doi:10.1172/JCI59259
- 18 Karaghiosoff, M., Steinborn, R., Kovarik, P., Kriegshauser, G., Baccarini, M., Donabauer, B. et al. (2003) Central role for type I interferons and Tyk2 in lipopolysaccharide-induced endotoxin shock. *Nat. Immunol.* **4**, 471–477 doi:10.1038/ni910
- 19 Mahieu, T., Park, J.M., Revets, H., Pasche, B., Lengeling, A., Staelens, J. et al. (2006) The wild-derived inbred mouse strain SPRET/Ei is resistant to LPS and defective in IFN- β production. *Proc. Natl Acad. Sci. U.S.A.* **103**, 2292–2297 doi:10.1073/pnas.0510874103
- 20 Dejager, L., Vandevyver, S., Ballegeer, M., Van Wouterghem, E., An, L.-L., Riggs, J. et al. (2014) Pharmacological inhibition of type I interferon signaling protects mice against lethal sepsis. *J. Infect. Dis.* **209**, 960–970 doi:10.1093/infdis/jit600
- 21 Yoneyama, M., Kikuchi, M., Natsukawa, T., Shinobu, N., Imaizumi, T., Miyagishi, M. et al. (2004) The RNA helicase RIG-I has an essential function in double-stranded RNA-induced innate antiviral responses. *Nat. Immunol.* **5**, 730–737 doi:10.1038/ni1087
- 22 Kato, H., Sato, S., Yoneyama, M., Yamamoto, M., Uematsu, S., Matsui, K. et al. (2005) Cell type-specific involvement of RIG-I in antiviral response. *Immunity* **23**, 19–28 doi:10.1016/j.immuni.2005.04.010

- 23 Gitlin, L., Barchet, W., Gilfillan, S., Cella, M., Beutler, B., Flavell, R.A. et al. (2006) Essential role of mda-5 in type I IFN responses to polyriboinosinic: polyribocytidylic acid and encephalomyocarditis picornavirus. *Proc. Natl Acad. Sci. U.S.A.* **103**, 8459–8464 doi:10.1073/pnas.0603082103
- 24 Kawai, T., Takahashi, K., Sato, S., Coban, C., Kumar, H., Kato, H. et al. (2005) IPS-1, an adaptor triggering RIG-I- and Mda5-mediated type I interferon induction. *Nat. Immunol.* **6**, 981–988 doi:10.1038/ni1243
- 25 Meylan, E., Curran, J., Hofmann, K., Moradpour, D., Binder, M., Bartenschlager, R. et al. (2005) Cardif is an adaptor protein in the RIG-I antiviral pathway and is targeted by hepatitis C virus. *Nature* **437**, 1167–1172 doi:10.1038/nature04193
- 26 Seth, R.B., Sun, L., Ea, C.-K. and Chen, Z.J. (2005) Identification and characterization of MAVS, a mitochondrial antiviral signaling protein that activates NF- κ B and IRF 3. *Cell* **122**, 669–682 doi:10.1016/j.cell.2005.08.012
- 27 Xu, L.-G., Wang, Y.-Y., Han, K.-J., Li, L.-Y., Zhai, Z. and Shu, H.-B. (2005) VISA is an adapter protein required for virus-triggered IFN- β signaling. *Mol. Cell* **19**, 727–740 doi:10.1016/j.molcel.2005.08.014
- 28 Liu, S., Cai, X., Wu, J., Cong, Q., Chen, X., Li, T. et al. (2015) Phosphorylation of innate immune adaptor proteins MAVS, STING, and TRIF induces IRF3 activation. *Science* **347**, aaa2630 doi:10.1126/science.aaa2630
- 29 Perry, A.K., Chow, E.K., Goodnough, J.B., Yeh, W.-C. and Cheng, G. (2004) Differential requirement for TANK-binding kinase-1 in type I interferon responses to toll-like receptor activation and viral infection. *J. Exp. Med.* **199**, 1651–1658 doi:10.1084/jem.20040528
- 30 Clark, K., Peggie, M., Plater, L., Sorcek, R.J., Young, E.R., Madwed, J.B. et al. (2011) Novel cross-talk within the IKK family controls innate immunity. *Biochem. J.* **434**, 93–104 doi:10.1042/BJ20101701
- 31 Fujita, F., Taniguchi, Y., Kato, T., Narita, Y., Furuya, A., Ogawa, T. et al. (2003) Identification of NAP1, a regulatory subunit of I κ B kinase-related kinases that potentiates NF- κ B signaling. *Mol. Cell Biol.* **23**, 7780–7793 doi:10.1128/MCB.23.21.7780-7793.2003
- 32 Chau, T.-L., Gioia, R., Gatot, J.-S., Patrascu, F., Carpentier, I., Chapelle, J.P. et al. (2008) Are the IKKs and IKK-related kinases TBK1 and IKK- ϵ similarly activated? *Trends Biochem. Sci.* **33**, 171–180 doi:10.1016/j.tibs.2008.01.002
- 33 Morton, S., Hesson, L., Peggie, M. and Cohen, P. (2008) Enhanced binding of TBK1 by an optineurin mutant that causes a familial form of primary open angle glaucoma. *FEBS Lett.* **582**, 997–1002 doi:10.1016/j.febslet.2008.02.047
- 34 Clark, K., Takeuchi, O., Akira, S. and Cohen, P. (2011) The TRAF-associated protein TANK facilitates cross-talk within the I κ B kinase family during Toll-like receptor signaling. *Proc. Natl Acad. Sci. U.S.A.* **108**, 17093–17098 doi:10.1073/pnas.1114194108
- 35 Gleason, C.E., Ordureau, A., Gourlay, R., Arthur, J.S.C. and Cohen, P. (2011) Polyubiquitin binding to optineurin is required for optimal activation of TANK-binding kinase 1 and production of interferon β . *J. Biol. Chem.* **286**, 35663–35674 doi:10.1074/jbc.M111.267567
- 36 Sasai, M., Oshiumi, H., Matsumoto, M., Inoue, N., Fujita, F., Nakanishi, M. et al. (2005) Cutting edge: NF- κ B-activating kinase-associated protein 1 participates in TLR3/Toll-IL-1 homology domain-containing adapter molecule-1-mediated IFN regulatory factor 3 activation. *J. Immunol.* **174**, 27–30 doi:10.4049/jimmunol.174.1.27
- 37 Sasai, M., Shingai, M., Funami, K., Yoneyama, M., Fujita, T., Matsumoto, M. et al. (2006) NAK-associated protein 1 participates in both the TLR3 and the cytoplasmic pathways in type I IFN induction. *J. Immunol.* **177**, 8676–8683 doi:10.4049/jimmunol.177.12.8676
- 38 Kawagoe, T., Takeuchi, O., Takabatake, Y., Kato, H., Isaka, Y., Tsujimura, T. et al. (2009) TANK is a negative regulator of Toll-like receptor signaling and is critical for the prevention of autoimmune nephritis. *Nat. Immunol.* **10**, 965–972 doi:10.1038/ni.1771
- 39 Zhao, T., Yang, L., Sun, Q., Arguello, M., Ballard, D.W., Hiscott, J. et al. (2007) The NEMO adaptor bridges the nuclear factor- κ B and interferon regulatory factor signaling pathways. *Nat. Immunol.* **8**, 592–600 doi:10.1038/ni1465
- 40 Chariot, A., Leonardi, A., Muller, J., Bonif, M., Brown, K. and Siebenlist, U. (2002) Association of the adaptor TANK with the I κ B kinase (IKK) regulator NEMO connects IKK complexes with IKK ϵ and TBK1 kinases. *J. Biol. Chem.* **277**, 37029–37036 doi:10.1074/jbc.M205069200
- 41 Pauls, E., Nanda, S.K., Smith, H., Toth, R., Arthur, J.S.C. and Cohen, P. (2013) Two phases of inflammatory mediator production defined by the study of IRAK2 and IRAK1 knock-in mice. *J. Immunol.* **191**, 2717–2730 doi:10.4049/jimmunol.1203268
- 42 Brinkmann, M.M., Spooner, E., Hoebe, K., Beutler, B., Ploegh, H.L. and Kim, Y.M. (2007) The interaction between the ER membrane protein UNC93B and TLR3, 7, and 9 is crucial for TLR signaling. *J. Cell Biol.* **177**, 265–275 doi:10.1083/jcb.200612056
- 43 Nociari, M., Ocheretina, O., Murphy, M. and Falck-Pedersen, E. (2009) Adenovirus induction of IRF3 occurs through a binary trigger targeting Jun N-terminal kinase and TBK1 kinase cascades and type I interferon autocrine signaling. *J. Virol.* **83**, 4081–4091 doi:10.1128/JVI.02591-08
- 44 Zinngrebe, J., Rieser, E., Taraborrelli, L., Peltzer, N., Hartwig, T., Ren, H. et al. (2016) LUBAC deficiency perturbs TLR3 signaling to cause immunodeficiency and autoinflammation. *J. Exp. Med.* **213**, 2671–2689 doi:10.1084/jem.20160041
- 45 Zhang, B., Li, M., Chen, L., Yang, K., Shan, Y., Zhu, L. et al. (2009) The TAK1-JNK cascade is required for IRF3 function in the innate immune response. *Cell Res.* **19**, 412–428 doi:10.1038/cr.2009.8
- 46 Wild, P., Farhan, H., McEwan, D.G., Wagner, S., Rogov, V.V., Brady, N.R. et al. (2011) Phosphorylation of the autophagy receptor optineurin restricts *Salmonella* growth. *Science* **333**, 228–233 doi:10.1126/science.1205405
- 47 Zhang, J., Clark, K., Lawrence, T., Peggie, M.W. and Cohen, P. (2014) An unexpected twist to the activation of IKK β : TAK1 primes IKK β for activation by autophosphorylation. *Biochem. J.* **461**, 531–537 doi:10.1042/BJ20140444
- 48 Emmerich, C.H., Ordureau, A., Strickson, S., Arthur, J.S., Pedrioli, P.G., Komander, D. et al. (2013) Activation of the canonical IKK complex by K63/M1-linked hybrid ubiquitin chains. *Proc. Natl Acad. Sci. U.S.A.* **110**, 15247–15252 doi:10.1073/pnas.1314715110
- 49 Emmerich, C.H., Bakshi, S., Kelsall, I.R., Ortiz-Guerrero, J., Shpiro, N. and Cohen, P. (2016) Lys63/Met1-hybrid ubiquitin chains are commonly formed during the activation of innate immune signalling. *Biochem. Biophys. Res. Commun.* **474**, 452–461 doi:10.1016/j.bbrc.2016.04.141