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Host genetic susceptibility to viral infections: the role of type I interferon induction

Marie Bourdon, Caroline Manet, Xavier Montagutelli

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10 **Abstract**

11 The innate immune response is the major front line of defense against viral infections. It
12 involves hundreds of genes with antiviral properties which expression is induced by type I
13 interferons (IFNs) and are therefore called interferon stimulated genes (ISGs). Type I IFNs
14 are produced after viral recognition by pathogen recognition receptors which trigger a cascade
15 of activation events. Human and mouse studies have shown that defective type I IFNs
16 induction may hamper the ability to control viral infections. In humans, moderate to high-
17 effect variants have been identified in individuals with particularly severe complications
18 following viral infection. In mice, functional studies using knock-out alleles have revealed the
19 specific role of most genes of the IFN pathway. Here, we review the role of the molecular
20 partners of the type I IFNs induction pathway and their implication in the control of viral
21 infections and of their complications.

22

23 **Introduction**

24 Interferons (IFNs) are cytokines that represent one of the first innate immune barriers
25 against viruses. They were discovered in 1957 and were named after their capacity to
26 "interfere" with virus replication. Recognition of non-specific viral molecules such as viral
27 proteins, DNA and RNA leads to their expression. After recognition of virus components by
28 pathogen recognition receptors (PRR), an induction cascade leads to the activation of
29 interferon regulatory factors (IRFs), the transcriptional factors responsible for IFN genes
30 expression¹. IFNs are glycoproteins that are secreted into the extracellular medium and act as
31 autocrine and paracrine factors. The binding to their receptors induces the expression of
32 interferon stimulated genes (ISGs) with antiviral properties. Non exhaustively, ISGs can
33 inhibit nuclear import of nucleic acids, synthesis of RNA and proteins, or can enhance virus

34 degradation¹. Several proteins involved in IFN production and response are inhibited by non-
35 structural proteins of various viruses which therefore escape host innate defense².

36 IFNs are grouped in three types depending on their sequence, structure and function.
37 IFN γ is the only type II IFN. It is produced by natural killer cells and binds the IFN γ receptor
38 (IFNGR) composed of two subunits (IFNGR1/IFNGR2). This receptor recruits the Janus
39 kinases 1 (JAK1) and 2 (JAK2), which activate the signal transducer and activator of
40 transcription 1 (STAT1). STAT1 acts as homodimers³ and binds gamma-activated sites
41 present in the target ISGs promoters¹. Type III IFNs include four IFN lambda numbered
42 IFN λ 1 to IFN λ 4. The receptor to type III IFNs is composed of interleukin 28 receptor subunit
43 alpha (IL-28Ra) and interleukin 10 receptor subunit 2 (IL-10R2). It induces the activation of
44 the interferon-stimulated gene factor 3 (ISGF3), composed of STAT1, STAT2 and IRF9, that
45 binds to IFN-stimulated response elements on the promoter of target ISGs⁴. This review
46 focuses on type I IFNs (IFN-I) which are among the first cytokines produced after viral
47 infection³. IFN-I usually refer to IFN α and IFN β , but also include other cell- and species-
48 specific molecules. All IFN-I signal through the IFN α receptor composed of two subunits
49 (IFNAR1 and IFNAR2), which recruit JAK1 and non-receptor tyrosine-protein kinase
50 (TYK2). These kinases activate ISGF3 which binds to IFN-stimulated response elements³.

51 Considering the crucial role of IFN-I in host responses to invading viruses, the
52 inability to induce their expression often leads to severe symptoms. The variable outcome of
53 viral infections has triggered genetic studies in humans and in mice^{5, 6}. Unsurprisingly,
54 genetic variants or deficiencies in IFN-I induction pathway genes were associated with
55 susceptibility to diverse viruses. Here we provide a general presentation of the partners of this
56 pathway, and we review the genetic susceptibilities to viral infections associated with these
57 genes.

58

59 **Molecular mechanisms of type I IFN induction**

60 ***Type I interferons***

61 IFN-I is the largest family of IFN proteins. They have a common helical structure
62 composed of 5 α -helices and are encoded by genes clustered on chromosome 9 in humans and
63 on chromosome 4 in mice⁷.

64 The two main IFN-I are IFN α and IFN β . These proteins are not constitutively
65 expressed but are up-regulated during viral infection following the activation of the
66 transcription factors IRF3 and IRF7⁸. Most animal species have multiple IFN α genes, 13
67 genes with 80% nucleotide identity in human and 14 genes in mice. IFN α s are produced by
68 plasmacytoid dendritic cells and hematopoietic cells (mostly leucocytes). Each type of IFN α
69 has a different affinity for its receptor, and thus may trigger type-specific responses⁹. IFN β is
70 encoded by a single gene, *IFNB1*, and is also present in most animal species. It is produced by
71 fibroblasts, dendritic cells and epithelial cells⁹.

72 Other IFNs-I have been described in animal species or in humans. Each of them is
73 encoded by a single gene⁹. IFN ϵ is constitutively expressed in the brain, lungs, small intestine
74 and reproductive tissues. It is regulated by hormones and not during infections. IFN κ is
75 present in a few species including humans and mice. It is constitutively expressed in
76 keratinocytes and can be up-regulated after exposure to double-stranded RNA (dsRNA).
77 IFN ω is present in humans but not in mice. It is expressed mainly in leukocytes. IFN ζ , also
78 called limitin, is an IFN-like molecule present only in mice. It is expressed in mature T
79 lymphocytes, bronchial, epithelial and salivary duct cells. IFN τ and IFN δ have been described
80 but are not expressed in humans or in mice.

81

82 ***Virus recognition by PRR***

83 The production of IFN β and IFN α is induced by PRRs that recognize molecules
84 present in pathogens called pathogen-associated molecular patterns. PRRs include Toll-like
85 receptors (TLRs) and RIG-I-like receptors (RLRs). PRRs recognize components from
86 bacteria, viruses and fungi and have specific ligands. During viral infections, TLR3
87 recognizes dsRNA while TLR7 and TLR8 recognize single-stranded RNA (ssRNA) and
88 TLR9 recognizes DNA molecules. These TLRs are produced in the endoplasmic reticulum
89 and sense their ligands in endosomes after virus entry into host cells¹⁰. TLR2 and TLR4 are
90 present at the cell surface and recognize viral proteins^{11, 12}. Replication of viruses with
91 positive ssRNA genome produces dsRNA which is recognized by TLR3 and RLRs¹⁰.

92 Three RLRs recognize viral RNA. While DDX58 (also known as RIG-I) senses 5'-
93 phosphorylated RNA, IFIH1 (MDA5) recognizes long dsRNA. DHX58 (LGP2) facilitates
94 viral RNA recognition by DDX58 and IFIH1¹³ and enhances RLR-dependent IFN induction¹⁴.

95 Viral recognition by TLRs and RLRs triggers a cascade of molecular activations
96 which results in the production of IFN-I. This pathway is summarized in Figure 1.

97

98 ***TLR pathway***

99 TLR3 recognition of viral RNA induces its own phosphorylation which allows the
100 recruitment of the adaptor protein Toll-interleukin receptor (TIR) domain-containing adapter
101 molecule 1 (TICAM1, also called TRIF)¹⁵. Interaction between TLR3 and TICAM1 is
102 enabled by the phosphorylation of two TLR3 tyrosine residues¹⁵. TLR4 also can induce the
103 expression of IFN-I by recognizing viral proteins present in the extracellular medium and
104 signalling through the adaptors myeloid differentiation primary response protein (MYD88)
105 and myelin and lymphocyte protein (MAL). Once activated, TLR4 is endocytosed and
106 recruits TICAM1 and TIR domain-containing adapter molecule 2 (TICAM2, also called
107 TRAM) in the endosomes¹⁶. TICAM1 recruits the TNF receptor associated factor 3

108 (TRAF3)¹⁵, which then activates the kinases responsible for the activation of the IRFs.
109 TICAM1 is targeted by the viral 3C protease of hepatitis A virus and coxsackievirus B3
110 (CVB3) which allows these viruses to escape the host immune response¹⁰.

111 TLR2 also activates the expression of IFN-I, but the mechanisms are incompletely
112 understood. Signalling by TLR2 requires MAL, TICAM2 and MYD88 which, once activated,
113 relocate to the endosomes and induce a signalling cascade resulting in IRF7 activation and
114 IFN-I expression. Therefore TLR2 and TLR4 likely use similar mechanisms to induce IFN-I
115 production¹².

116 TLR7, TLR8 and TLR9 also induce IFN-I expression, but only in plasmacytoid
117 dendritic cells which are known to produce high levels of IFN after viral infection. These
118 TLRs use the MYD88 adaptor which, in plasmacytoid dendritic cells, forms a complex with
119 IRF7. This complex allows the phosphorylation and activation of IRF7 by interleukin 1
120 receptor associated kinase 1 (IRAK1) and triggers the expression of IFNs¹⁷.

121

122 ***RLR pathway***

123 Viral RNA binding on RLRs DDX58 and IFIH1 induces a conformational change of
124 these receptors which exposes their caspase activation and recruitment domains (CARD).
125 These domains interact with the CARD of the mitochondrial antiviral signalling protein
126 (MAVS, also called IPS-1). Subsequently, DDX58 and IFIH1 promote the formation of
127 prion-like MAVS aggregates, which induce TRAF3 recruitment¹⁸. Several proteins of the
128 RLR pathway are targeted by viruses. Influenza A virus (IAV) NS1 protein and respiratory
129 syncytial virus NS1 protein bind DDX58 and MAVS, respectively, and block their signalling.
130 IFIH1 is degraded following poliovirus infection, and encephalomyocarditis virus (EMCV)
131 3C protease can degrade DDX58¹⁰.

132

133 **Activation of IRFs**

134 TRAF3 recruits two kinases, TANK binding kinase 1 (TBK1) and inhibitor of nuclear
135 factor kappa-B kinase subunit epsilon (IKK ϵ), to phosphorylate and activate IRF3 and IRF7.
136 Once phosphorylated, IRF3 and IRF7 form homodimers or heterodimers, translocate to the
137 nucleus and promote IFN-I transcription^{15, 19}. Viral proteins also target these factors. Ebola
138 virus VP35 protein binds and blocks TBK1 and IKK ϵ . The hepatitis C virus NS3/4A protease
139 degrades IRF3 while viral homologues of IRFs, such as Kaposi's sarcoma-associated
140 herpesvirus vIRFs, bind host IRFs and inhibit IFN-I transcription¹⁰.

141 IFN β expression is regulated by four positive regulatory domains (PRD). NF κ B and
142 AP1 bind PRDII and PRDIV, respectively, and promote basal expression of *IFNBI*. After
143 viral infection, IRF3 and IRF7 are activated and bind PRDI and PRDIII to induce *IFNBI*
144 overexpression²⁰. IFN α genes have only PRDI- and PRDIII-like elements and their
145 expression is therefore controlled exclusively by IRF3 and IRF7. IRF3 has more affinity for
146 *IFNBI* while IRF7 has more affinity for IFN α genes. IRF3 is constitutively abundant but
147 inactive while *IRF7* is an ISG present at low levels before infection and up-regulated by IFN-I
148 signalling. Therefore, in the early phase after infection, IFN-I expression is induced by IRF3,
149 resulting in predominant IFN β production. IFN β signalling induces *IRF7* expression resulting
150 in IFN α production in a later phase⁸. IRF1 and IRF5 can also induce IFN-I expression,
151 however both are dispensable and their role remains unclear⁸. Furthermore, TLRs and RLRs
152 also activate the NF κ B pathway after infection through TICAM1, MYD88 and MAVS to
153 induce the production of inflammatory cytokines¹⁵.

154

155 **Genetic susceptibility to viral infections**

156 Several of the genes described above have been associated with susceptibilities to viral
157 infections. These studies are summarized in Table 1 and Table 2 for human and mouse genes,

158 respectively. Human studies split into case studies and association studies. Case studies aim to
159 identify mutations which strongly impact the severity of viral infection but are rare in the
160 population. Association studies generally identify common variants with a moderate impact
161 and require the analysis of large cohorts. Due to limited statistical power, they often focus on
162 a small number of candidate genes.

163 In mice, forward and reverse genetics are used to analyze resistance to viral
164 infections²¹. Reverse genetics aims at characterizing the function of a given gene by altering
165 its sequence. Many studies have reported modified susceptibility to viral infections in mice
166 carrying loss-of-function mutations (gene knock-outs, KO) in IFN-I pathway. Forward
167 genetics starts with a difference of susceptibility between two strains and aims at identifying
168 the causal genetic variants. Differences may result from random chemical mutagenesis²² or
169 from natural variants between genetically diverse mouse strains such as the Collaborative
170 Cross⁶. Interestingly, studies performed on the same virus can be compared to assess the
171 specific or overlapping roles of the genes of the IFN-I cascade in the severity of a viral
172 infection and in its complications.

173

174 ***TLR-TICAM1 pathway***

175 As *TLR3* is the primary TLR involved in IFN-I expression after virus recognition, the
176 effects of its variants on the susceptibility to viral infections were extensively studied. In
177 humans, association studies and case studies identified *TLR3* variants linked to increased
178 susceptibility to IAV²³⁻²⁶, hepatitis B virus²⁷, herpes simplex virus 1 (HSV-1)²⁸⁻³⁰ and
179 measles virus³¹. Two SNPs associated with susceptibility to IAV are in intronic regions
180 upstream exon 4^{23, 24}. Since this exon contains the signal induction transmembrane protein
181 domain, these SNPs might alter TLR3 signalling. Other variants are in the luminal leucine-
182 rich repeats of TLR3^{25, 26, 28, 30, 31}. This region forms a solenoid critical for RNA binding³⁰ and

183 virus recognition. Lastly, mutations were identified in the TIR domain of TLR3^{28, 29}. In
184 particular, a non-sense mutation was identified in a case of herpes simplex encephalitis
185 (HSE), a complication of HSV-1 infection. This mutation removes the TIR domain which is
186 required for the recruitment of TICAM1 and downstream signalling²⁸.

187 In contrast, a common variant in *TLR3* was associated with increased resistance to
188 human immunodeficiency virus (HIV). The L412F allele, present in approximately 30% of
189 Europeans and over-represented in a cohort of HIV-exposed seronegative individuals, leads to
190 reduced viral replication and overexpression of inflammatory cytokines *in vitro*³², likely by
191 increasing TLR3 signalling. However, the same variant showed positive association with
192 subacute sclerosing panencephalitis, a severe complication of measles virus infection³¹. The
193 increased inflammatory response due to this mutation may be advantageous in the case of
194 HIV infection, but deleterious in the case of measles virus infection. Variants in the TLR
195 adaptor *TICAM1* can also alter susceptibility to viruses. In humans, four mutations were
196 identified in patients suffering from HSE, leading to decreased IFN-I expression in immune
197 cells^{33, 34}.

198 The TLR-TICAM1 pathway has been also extensively studied in mouse viral
199 infections. Compared to wild-type (WT) mice, *Tlr3*-deficient mice showed a decreased
200 survival rate with higher viral loads in coxsackievirus B3³⁵ and EMCV³⁶ infections and, while
201 they showed an increased serum viral load but unchanged mortality after murine
202 cytomegalovirus (MCMV) infection³⁷. In contrast, *Tlr3*-deficient mice displayed a decreased
203 mortality following IAV infection³⁸. Mice carrying a frameshift-induced deletion in the
204 *Ticam1* gene showed enhanced susceptibility to MCMV with increased viral load in the
205 spleen and higher mortality³⁹. Another study found that *Ticam1*-deficient mice were more
206 susceptible to CVB3. Interestingly, these mice presented a decreased IFN-I expression 72
207 hours post-infection, but an increased expression 7 days after infection⁴⁰, which may result

208 from an uncontrolled inflammatory response. *Tlr3*-deficient mice also developed cardiac
209 anomalies, a complication of CVB3 infection, with large myocarditic lesions and increased
210 heart viral load³⁵. Similarly, *Ticam1*-deficient mice presented left ventricular dysfunction and
211 severe myocardial damage including cardiac fibrosis. These mice also showed increased heart
212 viral load⁴⁰. The overlapping phenotypes observed in these two studies are consistent with the
213 direct interactions between *Tlr3* and *Ticam1* in the IFN-I induction cascade.

214 *Tlr3*-deficient mice were also less susceptible to vaccinia virus (VV) infection than
215 WT mice with higher viral load, while *Ticam1*- and *Tlr4*-deficient mice were more
216 susceptible (Hutchens et al., 2008a, 2008b). It was hypothesized that abrogating *Tlr3*
217 signaling decreases the inflammatory response and thus the complications resulting from VV
218 infection. In contrast, since *Tlr4* signaling activates IRFs and NFκB, *Tlr4* and *Ticam1* KOs
219 block both pathways and lead to increased susceptibility to VV infection^{41,42}.

220 The outcome of West Nile virus (WNV) infection in *Tlr3*-deficient mice was
221 investigated in two studies which used the same mouse strain and two closely related virus
222 strains with contrasted results. Wang *et al.* reported that *Tlr3*-deficient mice presented a
223 decreased mortality after infection with WNV isolate 2741, but an increased viral load.
224 Moreover, these mice showed decreased neuronal inflammation and blood-brain barrier
225 permeability, suggesting that *Tlr3* is involved in the virus brain entry⁴³. Daffis *et al.* who used
226 the WNV strain 3000.0259 reported that *Tlr3*-deficient mice also presented a higher brain
227 viral load but with susceptibility to WNV infection and mortality than WT mice. Unlike the
228 previous study, blood-brain barrier permeability and neuroinflammation were not affected,
229 compared with WT mice⁴⁴. These contrasted results were attributed to the infection route, the
230 viral dose and the cells used to produce the virus which differed between the two studies⁴⁴.
231 Interestingly, *Tlr3*-deficient mice produced normal amount of IFN-I in the first study, while
232 they were decreased in the second study, leading to the hypothesis that IFN-I expression

233 could also have a detrimental effect in WNV infection⁴³. These results illustrate the dual role
234 of *Tlr3* signalling which may lead to an excessive inflammatory response, while decreased
235 inflammation in *Tlr3* KO mice may reduce the risk of severe complication.

236

237 ***TLR-MYD88 pathway***

238 In mice, deficiency in *Tlr2*, *Tlr4*, *Tlr7* or *Tlr9* was associated with increased or
239 decreased susceptibility to viral infections. However, since these receptors signal through the
240 MYD88 adaptor which also activates the NFκB pathway, their role in the susceptibility to
241 viruses may not be solely associated with the IFN-I pathway.

242 *Tlr7*-deficient mice were more susceptible to WNV infection⁴⁵. However, they
243 presented an increased IFN-I expression which could result from the signaling through other
244 receptors such as *Tlr3* and RLRs. *Tlr9* and *Myd88*-deficient mice were more susceptible to
245 MCMV with decreased IFN-I production³⁷. *Myd88* KO mice had a reduced number of splenic
246 plasmacytoid dendritic cells which could explain reduced levels of IFN-I. By contrast, *Tlr2*
247 KO mice were less susceptible to HSV-1 with reduced mortality compared to WT mice. They
248 also showed decreased NFκB-induced cytokine production which may explain a milder
249 inflammatory state and the absence of severe complications⁴⁶. IFN-I expression was not
250 investigated although it could contribute to the pathology.

251 *Myd88* deficiency in mice also resulted in increased susceptibility to chikungunya
252 virus (CHIKV) and severe acute respiratory syndrome coronavirus (SARS-CoV). Indeed,
253 *Myd88* KO mice presented higher viral loads following CHIKV infection⁴⁷, and higher
254 mortality and increased viral load following SARS-CoV infection⁴⁸. Two studies with WNV
255 led to similar results^{45, 49}. Interestingly, in one study, *Myd88* KO mice had higher levels of
256 IFN-I after infection than WT mice due to an increased expression in bone marrow-derived
257 macrophages. This might result from high viral replication in these cells and from the

258 signaling of other pathways, such as RLR- or *Tlr3*-dependent pathways⁴⁹. The role of *Ticam2*
259 in the susceptibility to SARS-CoV was suspected in an association study using the
260 Collaborative Cross and was confirmed with a *Ticam2*-deficient strain which showed higher
261 lung viral loads than WT mice⁵⁰.

262

263 ***RLR pathway***

264 In humans, two variants were identified in *DDX58* in a patient who suffered from
265 severe IAV infection. The R71H variant is in the CARD protein domain, while the P885
266 variant is in the regulatory domain involved in viral RNA recognition. These variants lead to
267 impaired IFN-I expression following IAV infection when expressed in *DDX58* deficient
268 human embryonic kidney cells 293, but not in the patient's peripheral blood mononuclear
269 cells where other pathways, such as *TLR7*-dependant signalling might ensure a correct
270 expression⁵¹. Variants were identified in *IFIH1* in patients suffering from bronchiolitis
271 following rhinovirus or respiratory syncytial virus infection and led to decreased expression
272 of IFN β ⁵². Moreover, the K365E mutation was identified in a 5-year-old child suffering from
273 numerous recurrent respiratory virus infections. This mutation prevents IFIH1 from
274 interacting with viral RNA, thus inhibiting IFN-I induction⁵³. The H843A mutation in *IFIH1*
275 was also associated with susceptibility to HCV by comparing patients with spontaneously
276 resolved hepatitis or chronic hepatitis⁵⁴. In two studies, *Ddx58*-deficient mice showed similar
277 mortality after IAV infection compared with WT individuals^{55, 56}. Notably, one study showed
278 that *Ddx58* deficiency also led to defects in adaptive immunity affecting antigen presentation
279 by dendritic cells and activation of T cell responses⁵⁵. *Ifih1*-deficient mice were more
280 susceptible to mouse hepatitis virus. Interestingly, they showed decreased expression of IFN-I
281 but normal induction of ISGs⁵⁷. Moreover, they were found to be more susceptible to human

282 metapneumovirus⁵⁸, to hepatitis B virus⁵⁹, to murine norovirus 1⁶⁰, and more prone to develop
283 demyelinating disease following Theiler's murine encephalomyelitis virus infection⁶¹.

284 In mice, RLRs and MAVS have often been studied together, which has unraveled their
285 specificity. Using *Ddx58*- and *Ifih1*-deficient mouse embryonic fibroblasts (MEFs) infected
286 with several viruses, Kato *et al.* found that these two receptors recognize different viruses.
287 Moreover, they showed that *Ddx58*- and *Ifih1*-deficient mice were more susceptible to
288 Japanese encephalitis virus than WT mice, and that *Ifih1*- but not *Ddx58*-deficient mice were
289 more susceptible to EMCV⁶². Susceptibility of *Ifih1*-deficient mice to EMCV infection was
290 also reported in another study⁶³. Furthermore, *Ddx58*-deficient mice showed increased serum
291 viral load following CHIKV infection, which was not the case for *Ifih1*-deficient mice⁴⁷.
292 These results show that *Ddx58* and *Ifih1* have complementary roles in the recognition of viral
293 RNA, consistently with their known differences in molecular pattern recognition.

294 By contrast, both *Ddx58*- and *Ifih1*-deficient mice showed increased susceptibility to
295 WNV. Double-deficient mice were even more susceptible and invariably died within 8 days
296 after infection, showing that both receptors are involved in the recognition of WNV. The
297 phenotype of double-deficient mice was very similar to that of *Mavs*-deficient mice through
298 which both RLRs signal⁶⁴. Indeed, *Mavs* deficiency resulted in increased susceptibility to
299 WNV with higher mortality and viral load, and deficient activation of IFN β ⁶⁵. *Mavs* and *Ifih1*
300 deficiencies resulted also in increased mortality following CVB3 infection and decreased
301 expression of IFN-I although viral titers were identical to WT mice⁶⁶. *Mavs* deficiency also
302 resulted in increased susceptibility to EMCV⁶⁷, to vesicular stomatitis virus^{67, 68} and to dengue
303 virus (DENV)⁶⁹, and in increased serum viral load following CHIKV infection⁴⁷.

304 Mice deficient for the auxiliary RLR *Dhx58* gene also showed increased susceptibility
305 to EMCV¹³ and to WNV¹⁴. WNV-infected, *Dhx58*-deficient mice showed increased mortality
306 but similar kinetics of IFN β production and tissue viral loads compared with WT mice. In the

307 brain they displayed increased neuronal damage, elevated viral load in a late phase of
308 infection, low neuroinflammation and decreased recruitment of CD8+ T cells¹⁴. *Dhx58* is
309 therefore required for protection against WNV infection. Furthermore, mice overexpressing
310 *Dhx58* were more resistant to IAV infection⁷⁰. *In vitro*, *Dhx58*-deficient cells exposed to
311 several RNA viruses produced less IFN-I than WT cells suggesting that *Dhx58* is required for
312 *Ddx58*- and *Ifih1*-mediated antiviral responses¹³.

313

314 ***Activation of IRFs and IFNs***

315 Sequencing of candidate genes in HSE patients identified a heterozygous missense
316 mutation in *TRAF3* associated with decreased IFN-I expression⁷¹ and two missense mutations
317 in *TBK1* affecting the kinase domain and thus preventing the phosphorylation of target
318 proteins⁷². These mutations resulted in reduced IFN-I expression in cells stimulated with
319 synthetic RNA.

320 In mice, no genetic variants in *Traf3* or in *Tbk1* have been associated with altered
321 susceptibility to viral infections. However, mice deficient for the *Ikkε* gene (encoding IKKε,
322 a kinase involved in IRFs activation) showed extreme susceptibility to IAV despite normal
323 expression of IFN-I. Mechanistic studies revealed that IKKε indirectly controls the expression
324 of a subset of ISGs⁷³.

325 Mutations in IRFs have been repeatedly associated with susceptibility to viral
326 infections in humans and in mice. In humans, two missense mutations were found in *IRF3* in
327 patients suffering from HSE^{33, 74}. These mutations are located in the IRF association domain
328 and might therefore prevent IRF3 dimerization⁷⁵. A non-coding variant in *IRF3* was also
329 associated with susceptibility to WNV by comparing asymptomatic and symptomatic infected
330 individuals⁷⁶. Moreover, a compound heterozygosity was found in *IRF7* in a patient suffering
331 from life-threatening infection following IAV infection⁷⁷.

332 In mice, *Irf3* and *Irf7* deficiencies have been studied in isolation or in combination.
333 Both single deficiencies increased mortality following IAV infection and susceptibility was
334 further enhanced in double deficient mice^{78, 79}. Viral load in lungs was not significantly
335 altered in *Irf7*-deficient mice but was increased in *Irf3*-deficient mice and even more in
336 double-deficient mice, suggesting that *Irf7* also contributes to controlling viral replication. On
337 day 2 after infection, IFN α expression was reduced in *Irf3*- but not in *Irf7*-deficient mice
338 while IFN β expression was reduced in *Irf7* but not in *Irf3*-deficient mice⁷⁸. This result is
339 consistent with the distinct affinities of the two IRFs for the IFN-I genes. Mice deficient for
340 *Irf3* and *Irf7* were also susceptible to WNV with increased mortality rate and viral load,
341 decreased expression of IFN-I and increased viral load in the brain^{80, 81}.

342 However, the consequences of *Irf3* and *Irf7* deficiencies are variable between viruses.
343 *Irf7*- but not *Irf3*-deficient mice were susceptible to HSV-1 and they were more susceptible to
344 EMCV than *Irf3*-deficient mice⁸². In the case of CHIKV infection, *Irf3-Irf7* double KO mice
345 were highly susceptible with increased viremia and mortality, while *Irf3*- and *Irf7*-deficient
346 mice survived and had normal viremia⁸³. Following DENV infection, *Irf3-Irf7* double KO
347 mice and *Irf7*-deficient mice showed increased viral load and decreased IFN-I expression but
348 survived the infection⁸⁴. In the case of Zika virus infection, *Irf3-Irf5-Irf7* triple KO mice died
349 with neurological disease signs, while *Irf3*-deficient mice survived⁸⁵. Interestingly, *Irf3-Irf5*-
350 *Irf7* triple KO mice survived to DENV infection through robust induction of type II IFNs, but
351 showed increased viremia. This resistance to DENV was abolished when *Irf1* was also
352 inactivated, which led to the identification of a protective *Irf1*-dependent pathway⁸⁶.

353 Lastly, variants in IFN-I genes themselves were associated with susceptibility to viral
354 diseases in mice. The role of IFN-I in viral infections has been extensively investigated using
355 mice deficient for their receptor. *Ifnar1*-deficient mice showed increased susceptibility to a
356 number of viruses including CHIKV⁴⁷, Zika virus⁸⁵, DENV⁶⁹ and Ebola virus⁸⁷. Transient

357 blockade of IFN α and IFN β with monoclonal antibodies resulted in increased mortality after
358 WNV infection⁸⁸. WNV susceptibility was also studied in *Ifnb1*^{-/-} mice and led to similar
359 results⁸⁹. IFN β -deficient mice were also found more susceptible to VV than WT mice⁹⁰.
360 These two studies led to opposite results regarding IFN α expression. The absence of IFN β is
361 expected to abrogate *Irf7* induction and thus to decrease IFN α expression. This was indeed
362 observed after VV infection. However, after WNV infection, IFN α was upregulated, which
363 was hypothesized to result from the high viral load⁸⁹. IFN β -deficient mice also showed
364 increased susceptibility to IAV⁹¹ and CVB3⁹², and increased spleen viral load following
365 Friend virus infection⁹³.

366

367

368 **Discussion**

369 Type I IFNs are critical components of the immediate response against invading viruses.
370 Indeed, their induction allows the expression of many ISGs which can control viral infection.
371 The pathway leading to IFN-I production is complex as many genes are involved, and viral
372 proteins target this pathway at multiple levels. Moreover, some of these genes, such as *IRF7*,
373 are also ISGs, which further complicates the kinetics of IFN-I activation. Despite the vast
374 number of studies carried out on the induction of IFN-I, not all mechanisms are yet fully
375 understood.

376 In accordance with the functions of IFN-I, mutations in most genes of the induction
377 pathway have been associated with increased susceptibility to viral infections in human and
378 mice. In humans, whole exome or candidate gene sequencing has identified coding and non-
379 coding variants, primarily in patients with severe forms of infections. It is likely that other
380 variants are present in the human population but the power to detect them in association
381 studies depends on their frequency, on their impact on host response to infections and on

382 cohort size. In mice, most studies have used reverse genetics approaches and have
383 investigated the consequences of complete loss-of-function mutations in infected mice which,
384 in most cases, led to higher susceptibility, with mortality and elevated viral load in tissues.
385 While all mutants reported here were constitutively deficient, tissue-specific conditional
386 alleles allow investigating the pathway in specific cell lineages. For example, myeloid-
387 conditional *Tbk1*-deficient mice showed increased survival to IAV infection with reduced
388 inflammation in the respiratory tract, demonstrating the role of myeloid cells in disease
389 pathophysiology⁹⁴.

390 Notably, a few genes of the pathways were not tested by reverse genetics. *Tlr2* and
391 *Tlr4* have been investigated mostly for their role in bacterial infections¹¹. For other genes, like
392 *Tbk1* and *Traf3*, deficiency was only studied *in vitro* on MEFs or macrophages since
393 homozygous mice die either *in utero* (*Tkb1*) or a few days after birth (*Traf3*)⁹⁵. Interestingly,
394 Marchlik *et al.* produced a *Tbk1* mutation which resulted in a catalytically inactive protein
395 and they could obtain homozygous deficient mice with complete ablation of IFN β
396 production⁹⁶. This difference in survival of *Tbk1*-deficient mice is likely due to the 129S5
397 genetic background on which this allele was created, compared with the C57BL/6 background
398 used for most KO alleles. This case highlights the importance of mouse genetic background
399 when evaluating the phenotype resulting from gene inactivation⁹⁷.

400 The formal description of the IFN-I activation cascade incompletely reflects the
401 complexity of the mechanisms from viral components recognition to IFN-I-induced effectors.
402 As exemplified by *Irf3* and *Irf7*, the effect of a host gene variant may be different between
403 viruses. Moreover, while deficiency of most pathway genes resulted in increased
404 susceptibility to viral infections due to impaired IFN β production, it could also be associated
405 with reduced susceptibility as in the case of *Tlr3*. This observation underlines the complexity
406 of immune mechanisms, and the importance of balanced and well-controlled IFN response.

407 While rapid activation of ISGs is critical to the control of viral replication, excessive or
408 persistent IFN-I production can be detrimental by triggering inflammatory processes
409 responsible for tissue damage and organ failure. Notably, dysregulation of immune responses
410 with delayed expression of IFN-I and robust cytokine response could be at the origin of the
411 clinical manifestations observed in severe SARS-CoV⁹⁸ and SARS-CoV-2 infections⁹⁹.
412 Investigating the role of every gene of the IFN-I induction cascade by gene inactivation has
413 contributed to dissecting the mechanisms of the pathway. However, a non-functional step may
414 result from defective interactions between functional but incompatible partner proteins. Such
415 interactions could occur for example if the two partners were inherited from genetically
416 distant parents. In mice, investigating strains produced by crosses between founders of
417 different subspecific origins, like the Collaborative Cross, may identify such situations and
418 provide new variants for functional analysis⁶. With the growing evidence that microbiota can
419 also modify the IFN-I response and therefore the susceptibility to infectious diseases¹⁰⁰, it is
420 clear that we are still far from understanding the subtle regulations of an essential pathway.

421

422 **Conflict of interest**

423 The authors declare no conflict of interest.

424

425 **References**

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807 **Legends**

808

809 **Figure 1: Induction of IFN α and IFN β**

810 Viral molecules (DNA, RNA and proteins) induce the expression of IFN-I after their
811 recognition by TLRs and RLRs. Signalization leads the activation of kinases, TBK1 and
812 IKK ϵ responsible for the activation of the transcription factors IRF3 and IRF7 which induce
813 the expression of IFN α and IFN β . Proteins for which the corresponding gene was associated
814 with susceptibility to virus infection are indicated in orange for mouse studies and in purple
815 for human studies. Blue, yellow and green helices depict viral RNA, viral DNA and cellular
816 DNA molecules, respectively. Gene names are spelled according to the nomenclature rules for
817 human genes.

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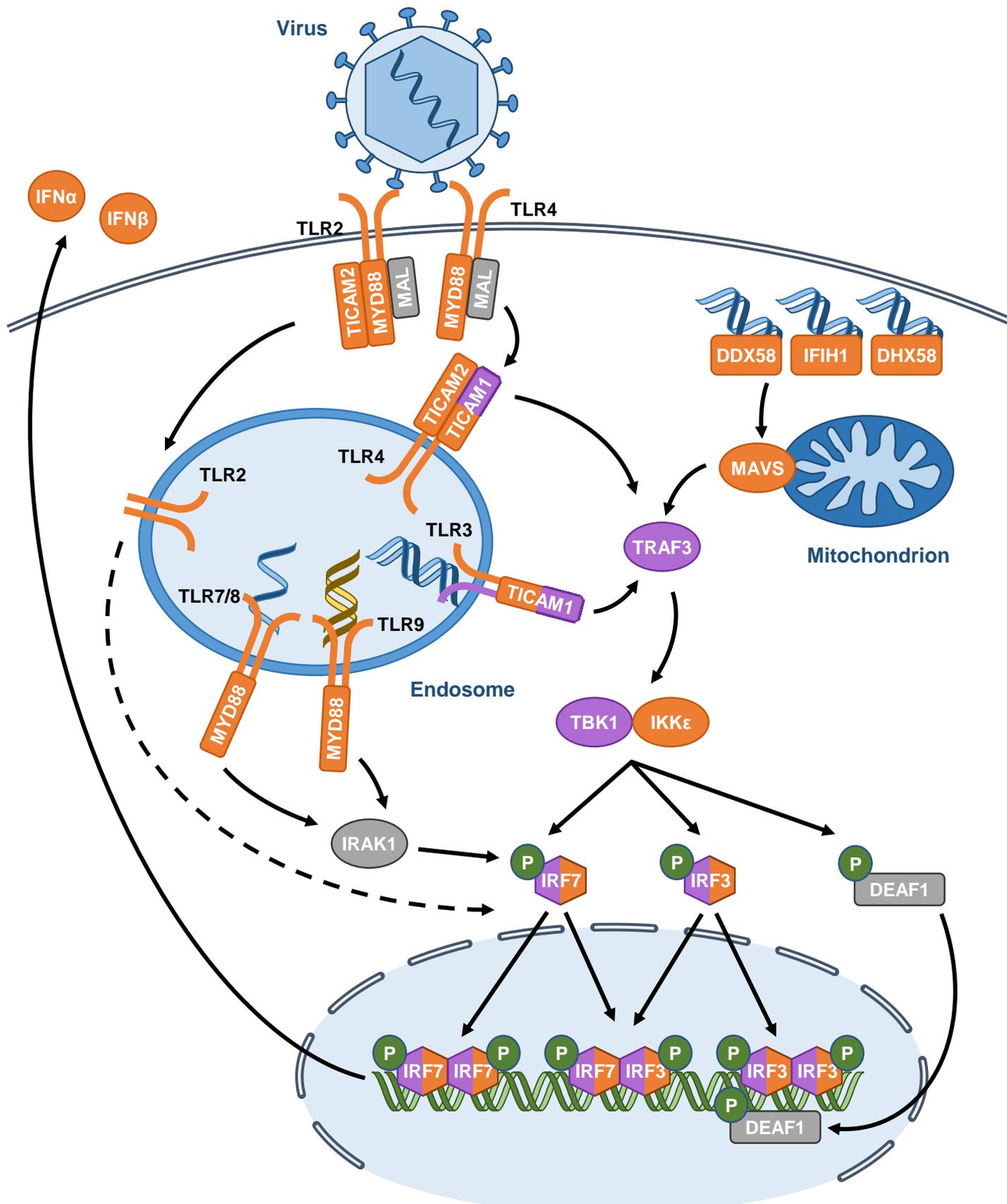


Table 1: Genes with variants associated with susceptibility to viral infections in humans

Virus	Type of study	Method	Polymorphism	Impact on gene function	Phenotype	Reference
<i>TLR3</i>						
HIV	Association study	Genotyping of a candidate gene	L412F [missense]	Increased cytokine production following stimulation of TLR3 and lower viral load	Decreased risk of infection	32
IAV	Association study	Genotyping of candidate genes	rs5743313 [intronic]	ND	Increased risk of pneumonia	23
IAV	Association study	Sequencing of candidate genes	rs5743313 [intronic]	ND	Increased risk of fatal infection	24
IAV	Case study	Sequencing of candidate genes	F303S [missense]	No induction of IFN β and no activation of NF κ B	Influenza-associated encephalopathy	25
IAV	Case study	WES	P554S [missense], P680L [missense]	Decreased expression of IFN β and IFN λ	Acute respiratory distress syndrome	26
HBV	Association study	Genotyping of a candidate gene	rs1879026 [intronic]	ND	Increased risk of being infected	27
HSV-1	Case study	Sequencing of a candidate gene	P554S [missense], E746X [nonsense], G743D [missense], R811I [missense], L360P [missense]	Decreased induction of cytokines and higher viral replication rate	Herpes simplex encephalitis	28-30
MV	Association study	Genotyping of candidate genes	L412F [missense]	ND	Increased risk of subacute sclerosing panencephalitis	31
<i>TICAM1</i>						
HSV-1	Case study	WES	A568T, S160F [missense]	Decreased induction of cytokines	Herpes simplex encephalitis	33
HSV-1	Case study	Sequencing of candidate genes	R141X [nonsense], S186L [missense]	Impaired activation of IRF3 and NF κ B, decreased induction of cytokines	Herpes simplex encephalitis	34
<i>DDX58</i>						
IAV	Case study	WES	R71H + P885S [missense]	Decreased response to ligand and expression of IFN β	Severe influenza infection	51
<i>IFIH1</i>						
HCV	Association study	Genotyping of candidate genes	H843A [missense]	Decreased expression of IFN β and other cytokines	Chronic hepatitis C	54
HRV	Case study	WES	rs35732034 [intronic]	Lack of exon 14, decreased expression of IFN β	Bronchiolitis	52
HRV	Case study	WES	E627X [nonsense]	Lack of CTD, decreased expression of IFN β	Bronchiolitis, pneumonia	52
RSV	Case study	WES	rs35732034 [intronic]	Lack of exon 14, decreased expression of IFN β	Bronchiolitis, pneumonia	52
RSV	Case study	WES	rs35337543 [intronic]	Lack of exon 8, decreased expression of IFN β	Bronchiolitis	52
<i>TRAF3</i>						
HSV-1	Case study	Sequencing of a candidate gene	R118W [missense]	Decreased TRAF3 production	Herpes simplex encephalitis	71
<i>TBK1</i>						
HSV-1	Case study	Sequencing of a candidate gene	D50A [missense]	Decreased amount of TBK1 mRNA and protein, decreased cytokine production	Herpes simplex encephalitis	72
HSV-1	Case study	Sequencing of a candidate gene	D159A [missense]	No enzyme activity, decreased cytokine production	Herpes simplex encephalitis	72
<i>IRF3</i>						
HSV-1	Case study	WES	R285Q [missense]	No phosphorylation and dimerization of IRF3, decreased cytokine production	Herpes simplex encephalitis	33, 74
HSV-1	Case study	WES	A277T [missense]	Decreased cytokine production	Herpes simplex encephalitis	33
WNV	Association study	Genotyping of candidate genes	rs2304207 [intronic]	ND	Increased risk to have a symptomatic infection	76
<i>IRF7</i>						
IAV	Case study	WES	Q421X [nonsense]	Absence of phosphorylation and nuclear localization in absence of infection, impaired IFN α production (in the case of compound heterozygosity with F410V)	Life-threatening infection	77
IAV	Case study	WES	F410V [missense]	Inability to translocate to the nucleus, impaired IFN α production (in the case of compound heterozygosity with Q421X)	Life-threatening infection	77

For exonic variants, the effect is indicated [missense/nonsense]

Abbreviations: HBV: hepatitis B virus; HRV: human rhinovirus; HSV-1: herpes simplex virus type 1; IAV: influenza A virus; MV: measles virus; RSV: respiratory syncytial virus; WNV: West Nile virus WES: whole exome sequencing, ND: not

Table 2: Genes with variants associated with susceptibility to viral infections in mice

Virus	Variant*	Mortality**	Viral titer [tissue]**	Type I IFN expression [tissue]**	Reference
<i>Tlr3</i>					
CVB3	KO	+	+ [heart, serum, splenocytes]	= [heart]	35
EMCV	KO	+	+ [heart, liver]	+ [heart]	36
IAV	KO	-	+ [lung]	ND	38
MCMV	KO	=	+ [spleen]	- [serum]	37
VV	KO	-	- [abdomen, lung, chest]	= [lung]	41
WNV	KO	+	+ [brain, spinal cord, spleen]	= [lymph node, serum]	44
WNV	KO	-	+ [blood] - [brain]	- [blood, brain]	43
<i>Ticam1</i>					
CVB3	KO	+	+ [heart]	- 72h + 7 days [heart]	40
MCMV	Point mutation	+	+ [spleen]	- [serum]	39
VV	KO	ND	+ [chest]	ND	42
<i>Tlr2</i>					
HSV-1	KO	-	= [brain]	ND	46
<i>Tlr4</i>					
VV	Point mutation	+	+ [abdomen, chest, head, lung]	= [lung]	42
<i>Tlr7</i>					
WNV	KO	+	+ [blood, brain, spleen]	+ [blood]	45
<i>Tlr9</i>					
MCMV	Point mutation	+	+ [spleen]	- [serum]	37
<i>Myd88</i>					
CHIKV	KO	ND	+ [joint, serum, spleen]	ND	47
MCMV	KO	+	+ [spleen]	- [serum]	37
SARS-CoV	KO	+	+ [lung]	= [lung]	48
WNV	KO	+	+ [blood, brain, spleen]	ND	45
WNV	KO	+	+ [brain, lymph node, spleen]	+ [serum]	49
<i>Ticam2</i>					
SARS-CoV	KO	ND	+ [lung]	ND	50
<i>Ddx58</i>					
IAV	KO	=	+ [lung]	ND	55
CHIKV	KO	ND	+ [serum]	ND	47
JEV	KO	+ §	ND	- [serum] §	62
WNV	KO	+	+ [MEF]	- [MEF]	64
<i>Ifih1</i>					
CVB3	KO	+	= [liver, pancreas, serum]	- [pancreas, serum]	66
EMCV	KO	+ §	+ [heart] §	- [serum] §	62
EMCV	KO	+	ND	- [DC, MP]	63
HBV	KO	ND	+ [liver, serum]	ND	59
hMPV	KO	ND	+ [lung]	- [lung]	58
MHV	KO	+	+ [brain, heart, kidney, lung, spinal cord, spleen]	- [liver]	57
MNV-1	KO	ND	+ [intestine, spleen, lymph node]	- [DC]	60
TMEV	KO	ND	+ [brain, spinal cord]	- [brain, spinal cord]	61
WNV	KO	+	+ [DC, MP]	- [DC, MEF, MP]	64
<i>Dhx58</i>					
EMCV	KO + point mutation	+	+ [heart]	- [serum]	13
IAV	TG	-	= [lung]	- [lung]	70
WNV	KO	+	+ [brain, DC, MP]	- [DC, MP]	14
<i>Mavs</i>					
CHIKV	KO	ND	+ [serum]	ND	47
CVB3	KO	+	= [liver, pancreas, serum]	- [pancreas, serum]	66
DENV	KO	=	+ [bone marrow, lymph node, serum, spleen]	- [bone marrow, lymph node, serum, spleen]	69
EMCV	KO	+	+ [heart] §	- [serum]	67
VSV	KO	+	+ [brain, liver]	ND	67
VSV	KO	+	+ [serum]	= [serum]	68
WNV	KO	+	+ [brain, DC, kidney, MP, serum, spinal cord, spleen]	- [DC, MP]	65
WNV	KO	+	+ [DC]	- [DC]	64
<i>Ikbke</i>					
IAV	KO	+	+ [lung, MEF]	= [lung, MEF]	73
<i>Irf3</i>					
IAV	KO	+	+ [lung]	- [lung]	78
WNV	KO	+	+ [brain, kidney, lymph node, serum, spinal cord, spleen]	- [lymph node]	80
<i>Irf7</i>					
DENV	KO	ND	+ [spleen]	- [serum]	84
IAV	KO	+	ND	- [serum]	79
IAV	KO	+	= [lung]	- [lung]	78

EMCV	KO	+	ND	- [serum]	82
HSV	KO	+	ND	- [serum]	82
WNV	KO	+	+ [brain, kidney, lymph node, serum, spinal cord, spleen]	- [brain, DC, MEF, MP, serum]	82
WNV	KO	+	+ [brain, cortical neurons, DC, kidney, lymph node, MEF, MP, serum, spleen, spinal cord]	- [brain, cortical neurons, DC, MEF, MP]	81
<i>Irf3-Irf7</i>					
CHIKV	KO	+	+ [blood, brain, liver, muscle, spleen]	- [blood, feet]	83
<i>Irf3-Irf5-Irf7</i>					
ZIKV	KO	+	ND	ND	85
<i>Irf1-Irf3-Irf5-Irf7</i>					
DENV	KO	+	+ [MP]	- [MP, serum]	86
<i>Ifna</i>					
WNV	mAb treated	+	ND	ND	88
<i>Ifnb1</i>					
CVB3	KO	+	+ [liver, spleen]	ND	92
FV	KO	ND	+ [spleen]	= [plasma]	93
IAV	KO	+	+ [lung, MEF]	ND	91
VV	KO	+	+ [lung]	- [MEF]	90
WNV	KO	+	+ [brain, granule cell neurons, kidney, lymph node, myeloid cells, MEF, serum, spinal cord]	+ [serum]	89
WNV	mAb treated	+	ND	ND	88

* Genetic variant except for 'mAb treated' in which case gene product was transiently inhibited using a monoclonal antibody. The phenotype was compared with wild type mice, except for § (compared with heterozygous mice).

** + : increased; - : decreased; = : unchanged; ND: not determined.

Abbreviations: CVB3: coxsackievirus B3; CHIKV: chikungunya virus; DENV: dengue virus; EMCV: encephalomyocarditis virus; FV: friend virus; hMPV: human metapneumovirus; HSV-1: herpes simplex virus type 1; IAV: influenza A virus; JEV: Japanese encephalitis virus; MCMV: murine cytomegalovirus; MNV-1: murine norovirus 1; SARS-CoV: severe acute respiratory syndrome coronavirus; TMEV: Theiler's murine encephalomyelitis virus; VSV: vesicular stomatitis virus; VV: vaccinia virus; WNV: West Nile virus; KO: knocked-out mice, TG: transgenic mice; MEF: mouse embryonic fibroblasts, DC: dendritic cells, MP: macrophages.