



β -Catenin Upregulates the Constitutive and Virus-Induced Transcriptional Capacity of the Interferon Beta Promoter through T-Cell Factor Binding Sites.

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1 **Beta-catenin up-regulates the constitutive and virus-induced transcriptional capacity of**
2 **the interferon- β promoter through T-cell factor binding sites**

3

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22

Abstract

23 Rapid up regulation of interferon- β (IFN- β) expression following virus infection is essential
24 to set up an efficient innate antiviral response. Biological roles related to the antiviral and
25 immune response have also been associated to the constitutive production of IFN- β in naïve
26 cells. However, mechanisms capable to modulate constitutive IFN- β expression in the
27 absence of infection remain largely unknown. In this work we demonstrate that inhibition of
28 kinase GSK-3 leads to the up-regulation of the constitutive level of IFN- β expression in non-
29 infected cells, provided that GSK-3 inhibition be correlated with binding of β -catenin to the
30 IFN- β promoter. Under these conditions, IFN- β expression occurred through the T-cell factor
31 (TCF) binding sites present on the IFN- β promoter, independently of IRF3. Enhancement of
32 the constitutive level of IFN- β was *per se* capable to confer an efficient antiviral state to naïve
33 cells and acted in synergy with virus infection to stimulate virus-induced IFN- β expression.
34 Further emphasizing the role of β -catenin in the innate antiviral response, we show here that
35 highly pathogenic Rift Valley fever virus (RVFV) targets the Wnt/ β -catenin pathway and the
36 formation of active TCF/ β -catenin complexes at the transcriptional and protein level in
37 RVFV-infected cells and mice.

38

Introduction

39

40 Production of interferon- β (IFN- β) plays a central role in the induction of the innate
41 antiviral response (1,2). Rapid up-regulation of IFN- β gene expression occurs after
42 recognition of viral nucleic acids by pattern recognition receptors (PRRs) either cytosolic
43 such as retinoic acid-inducible gene I (RIG-I) and melanoma differentiation-associated
44 antigen 5 (MDA-5) or membrane-associated Toll-like receptors such as TLR3 (3). After
45 sensing single or double stranded RNA of viral origin, these receptors activate signaling
46 pathways implicating the phosphorylation and nuclear translocation of several transcription
47 factors among which the interferon regulatory factor 3 (IRF3), rapidly leading downstream to
48 a robust activation of the expression of IFN- β gene. After being secreted, IFN- β protein binds
49 to the type I interferon receptor and triggers the JAK-STAT1/2 signal transduction pathway.
50 This pathway leads to the activation and inhibition of the expression of a large set of genes
51 that constitute the type I IFN response mounted to antagonize viral infection at different levels
52 (4).

53 Mice lacking IFN- β (5) or the subunit of the type I interferon receptor (6,7) are highly
54 susceptible to viral infections. They succumb to sub-lethal doses of a variety of viruses thus
55 confirming the main role of IFN- β in the establishment of an innate antiviral response.
56 However, beyond the antiviral response, IFN- β affects a wide range of other biological
57 functions for the most related to modulation of the immune (innate and adaptive) and
58 inflammatory responses as well as to cell proliferation and differentiation. Even though IFN- β
59 has been described of anti-inflammatory benefit, it has also been implicated in the
60 development of several inflammatory and autoimmune diseases (8-10). Hence, the beneficial
61 or detrimental outcome of IFN- β expression for the organism will depend on the timing, the
62 kinetics and the amount of IFN- β being synthesized (11,12). If a marked activation of IFN- β
63 gene expression is required to efficiently set up the appropriate response to an external

64 aggression such as virus infection, this response needs to be adjusted in order to limit its
65 pathological side effects.

66 As expected for a gene with pleiotropic functions, its transcriptional state is regulated
67 at different levels. At the cellular level, only a stochastic fraction of the infected cells produce
68 IFN- β (13,14) as a way to avoid an exacerbated and uncontrolled IFN response. At the
69 nuclear level, one IFN- β allele localizes within interchromosomal regions rich in NF- κ B
70 DNA binding sites before and after infection (15) whereas the other allele localizes next to
71 pericentromeric heterochromatin (PCH) clusters in the absence of infection and dissociates
72 from PCH clusters during infection (16). The monoallelic characteristic of these particular
73 subnuclear localizations suggests that a yet non-deciphered regulatory mechanism exists at
74 the chromosome level. Finally, at the promoter level, the coordinated action of several
75 transcription factors and chromatin remodeling complexes (17-21) regulate the IFN- β
76 promoter transcriptional capacity. Among transcription factors, IRF3 plays an essential role
77 during pathogen dependent activation of IFN- β gene expression in most cell types (22).
78 Alongside with IRF3, are recruited over the promoter transcription factors such as NF- κ B
79 (15,23), ATF2/c-Jun and YY1 (20,24,25) that participate in the recruitment of chromatin
80 remodeling complexes associated with histone acetyltransferase CBP. Some of these factors
81 play dual roles, acting not only as activators but also as repressors of IFN- β expression. This
82 is the case for NF- κ B (26) and YY1 (27). Specially, YY1 participates in the transcriptional
83 activation through recruitment of CBP and in the establishment of the repressive state of the
84 IFN- β promoter through recruitment of co-repressor SAP30 (21) and association with
85 pericentromeric heterochromatin (16).

86 Even though the IFN- β gene has been considered as repressed in naïve cells, low
87 levels of IFN- β have been detected in different types of non-infected cells in the central
88 nervous system (28,29), splenocytes and mouse embryonic fibroblasts (MEFs) (30) implying

89 the existence of mechanisms capable to regulate the production of limited amounts of IFN- β
90 in the absence of infection. Using anti-IFN- α/β antibodies, Haller et al. (31) evidenced a role
91 of such IFN- β production with respect to the establishment of an active antiviral response.
92 Using a similar strategy, Vogel and Fertsch (32) showed that the IFN- β production detected in
93 non-infected cells had an autostimulatory role upon macrophage differentiation. More
94 recently, results obtained with mice lacking either IFN- β or its receptor have confirmed the
95 physiological role of such low amounts of IFN- β produced by non-infected animals in
96 relation with several biological functions such as immune cell function, antiviral defense,
97 bone remodeling and modulation of homeostatic balance (reviewed in 33). As in the case of
98 virus-induced IFN- β production, deregulation of virus-independent IFN- β expression can lead
99 to pathological effects. However, mechanisms capable to affect IFN- β expression in the
100 absence of infection remain to be clarified.

101 In the cytoplasm, β -catenin is found within a degradation complex associated with
102 Adenomatous Polyposis Coli (APC), Axin and GSK-3 as well as CK1A Ser/Thr kinases that
103 control the level of free β -catenin by a phosphorylation-dependent targeting of β -catenin
104 towards proteasome degradation (34,35). Disruption of the degradation complex through
105 inhibition of GSK-3 kinase leads to the increase of β -catenin and its subsequent nuclear
106 accumulation. In the nucleus, β -catenin physically interacts with T-cell factor (TCF) to
107 regulate the expression of target genes through the recruitment of a transcriptional activator
108 complex containing B-Cell Lymphoma 9 (BCL9) protein and CBP over promoter regions
109 carrying binding sites for TCF factors (36-38).

110 With the goal to identify mechanisms susceptible to affect the level of IFN- β
111 expression in the absence of infection, namely IRF3-NF κ B-ATF2/cJUN-independent
112 expression considered here as constitutive expression, we have questioned in this work the

113 capacity of nuclear β -catenin to regulate IFN- β expression, in naïve and infected cells, in
114 association with the TCF family of transcription factors for which we show that DNA binding
115 sites are present in the murine and human IFN- β promoter.

116 We demonstrate here that LiCl treatment, a potential inhibitor of GSK-3, enhanced the
117 constitutive level of IFN- β expression provided that it would lead to the interaction of β -
118 catenin with IFN- β promoter. While it has been previously reported that β -catenin would
119 modulate IFN- β expression either positively (39-43) or negatively (44) through IRF3, our
120 results uncover a new mechanism of up-regulation of the transcriptional capacity of the IFN- β
121 promoter following LiCl treatment mediated by TCF/ β -catenin complexes recruited over the
122 IFN- β promoter region. Moreover, we show that the up-regulation of the constitutive level of
123 IFN- β expression following LiCl treatment leads to the establishment of an efficient antiviral
124 state protecting naïve cells against virus-induced cytopathic effect and acts in synergy with
125 infection to increase IFN- β production. Further emphasizing the importance of TCF/ β -catenin
126 complex formation in the antiviral response, we show here that the pathogenicity induced by
127 Rift Valley fever virus (RVFV) infection of cell cultures and mice was correlated with viral
128 targeting of the TCF/ β -catenin pathway at different levels.

129

130

Materials and Methods

131 Virus, Cells and Mice

132 Stocks of RVFV ZH548 and RVFV ZHΔNSs were produced under BSL3 conditions
133 by infecting Vero cells at m.o.i. of 10^{-3} and by harvesting the medium at 72 hr p.i. Murine
134 fibroblastic L929 cell line and NDV infections were described previously (45). Murine
135 hepatocyte AML12 cell line was from ATCC (ref. CRL-2254). For preparation of bone
136 marrow-derived macrophages (BMDM) preparation, bone marrow from tibiae and femora of
137 8-12 weeks B6 mice was flushed and cultured for 7 days in DMEM containing 10% heat-
138 inactivated fetal bovine serum, 100 U/ml penicillin/streptomycin, 2 mM glutamine and 10
139 ng/ml murine M-CSF (PeproTech). Infection of mice was performed as previously described
140 (46). When indicated, LiCl, iCRT3 (Sigma) or LiCl+iCRT3 were directly added to the culture
141 medium.

142

143 Antibodies

144 Mouse anti-NSs and rabbit anti-N polyclonal antibodies were raised respectively
145 against the entire NSs or N protein (47). Anti-β-catenin from BD Transduction laboratories
146 (Cat#610154) was used for immunofluorescence, Western blot and gel retardation. Secondary
147 antibodies used for immunofluorescence were Alexa 488 fluor-conjugated chicken anti-
148 mouse from Invitrogen (A21200) and Alexa 555 fluor-conjugated donkey anti-rabbit from
149 Invitrogen (A31572). Secondary antibodies used for Western blot were ECL Mouse IgG,
150 HRP-linked whole Ab (NA931) an ECL Rabbit IgG, HRP-linked whole Ab (NA934) from GE
151 Healthcare Life Sciences.

152

153 **Immunofluorescence**

154 For immunofluorescence, cells grown in 6-well plates on coverslips were fixed with
155 4% formaldehyde in PBS for 15 minutes and permeabilized with 1% Triton X-100 in PBS for
156 20 minutes. Then cells were incubated for 1 hour at room temperature with the corresponding
157 primary antibodies diluted in PBS/BSA 5%. Cells were then washed with PBS and incubated
158 for 1 hour at room temperature with corresponding secondary antibodies.

159

160 **Image acquisition and manipulation**

161 Samples were analyzed at room temperature by confocal laser scanning microscopy
162 using a Zeiss LSM710 confocal system at the *Service Commun de Microscopie (SCM)* of
163 Université Paris Descartes. This system is equipped with a 63x, 1.4 O.N oil immersion lens
164 (Plan Neofluor). For oil immersion microscopy, we used oil with refractive index of 1.518
165 (Zeiss). Image capture was carried out with a definition of 1024x1024 pixels with 8 bit data
166 for each color. Images were analyzed using Image J software. Total pixel intensity was
167 quantified using Image J software.

168

169 **Chromatin immunoprecipitation**

170 Chromatin immunoprecipitation experiments were carried out as previously described (21).
171 PCR analysis of inputs or immunoprecipitated DNAs was performed using oligonucleotides
172 F-40 (5'-GTT TTC CCA GTC ACG AC-3') and CAT (5'-CCA TTT TAG CTT CCT TAG-
173 3') to reveal the integrated WT330 and WT110 IFN- β promoter. For the F-40, CAT set of
174 primers, PCR conditions were as follows: 1 cycle of 94°C for 5 minutes; 20 cycles of 94°C
175 for 30 seconds, 53°C for 30 seconds and 72°C for 30 seconds; 1 cycle of 72 °C for 10
176 minutes. A first “cold” PCR was carried out in the presence of 25 pmol of each primer; 1.5 μ l

177 of the product of the first PCR was subjected to a second “hot” PCR carried out in the
178 presence of 0.1 μ l α -³²PdATP (6000 Ci/mmol) and 25 pmol of each primer.

179

180 **RT-qPCR**

181 Total RNA was extracted using Tri Reagent (Sigma) according to the manufacturer’s
182 protocol. 1 μ g of total RNA was reversely transcribed using High Capacity cDNA Reverse
183 Transcription Kit (Applied Biosystems) according to the manufacturers' recommendations
184 using Random Primers. qPCR was performed using SYBR Green (Thermo Scientific)
185 reagents: 95°C 15 minutes, then 40 cycles at 95°C 15 seconds, 60°C 1 minute, followed by a
186 dissociation step. Relative quantification of mRNA expression was calculated using the $\Delta\Delta C_T$
187 method using three reference genes among Ppib, Hprt1, Utp6c and Rplp0). For fold changes
188 lower than 1 (translating a repression of the gene’s expression), the inverted values were
189 determined such that a 0.5 fold change corresponds to -2. Sequences of primers used for RT-
190 qPCR analysis are shown in Table I.

191 Statistical analysis was carried out using Student T-test or the REST software that uses a Pair-
192 Wise Fixed Reallocation Randomization Test© to determine a P-value.

193

194 **RNA interference experiments**

195 L929 cells were transfected using Lipofectamine 2000 (Invitrogen Life Technologies)
196 with the ON Target Plus SMART Pool of siRNA oligos specific for β -catenin (Thermo
197 Scientific Dharmacon® L-040628-00) or with a pool of control siRNA sequences (Thermo
198 Scientific Dharmacon® D-001810-10-05) at a final concentration of 50nM each during 72 h.

199

200

201

202 **Gel retardation assay**

203 Nuclear extracts of murine L929 cells either non-treated or treated with LiCl for 24 h
204 were incubated with the corresponding 5' ³²P-labeled probes in 20 µl (final volume) of 50
205 mM Tris-HCl (pH 7.5), 50 mM NaCl, 5 mM EDTA, 10% glycerol and 5 mM dithiothreitol.
206 When indicated, anti-β-catenin antibody was incubated with the nuclear extracts 1 h at 4°C
207 prior to the addition of the labeled probe.

208

209 **Cytopathic effect assays.**

210 Monolayer cultures of L929 cells in 96-well plates were incubated with LiCl for 24 h
211 before VSV infection. Before VSV infection, the medium containing LiCl was removed.
212 Viruses were diluted in medium with serum (2% final concentration) and added directly to the
213 culture medium. The monolayers were stained with crystal violet as vital dye 24 h after VSV
214 infection or fixed 8h after VSV infection for immunofluorescence analysis. For measurement
215 of the cytopathic effect of RVFV, L929 cells either non-treated or treated with LiCl for 24 h
216 were infected with RVFVZH548 and incubated under an overlay consisting of DMEM, 2%
217 fetal calf serum, antibiotics and 1% agarose at 37°C. At 3 day p.i., the lytic plaques were
218 counted after staining with a solution of crystal violet.

219

220 **Western blot**

221 For Western blot, total protein extracts were prepared in RIPA buffer and resolved by
222 sodium dodecyl sulfate-polyacrylamide gel electrophoresis (SDS-PAGE) in 4-12% precast
223 gels (Life Technologie). Relative quantification of proteins was carried out using Image
224 Quant software on scanned WB films.

225

226 **Ethics Statement**

227 Experiments on live mice were conducted according to the French and European
228 regulations on care and protection of laboratory animals (EC Directive 86/609, French Law
229 2001-486 issued on June 6, 2001) and the National Institutes of Health Animal Welfare
230 (Insurance #A5476-01 issued on 02/07/2007). Experimental protocols were approved by the
231 Animal Ethics Committee #1 of the *Comité Régional d’Ethique pour l’Expérimentation*
232 *Animale* (CREEA), Ile de France (N°2012-0025), and carried out in compliance with Institut
233 Pasteur Biosafety Committee.
234

Results

235

236 **LiCl treatment enhances constitutive IFN- β gene expression.**

237 The proximal region of the IFN- β promoter (Fig. 1A), made of negative and positive
238 regulatory domains, is highly conserved between murine and human cells. The Virus
239 Responsive Element (VRE) that contains binding sites for transcription factors IRF3, ATF2/c-
240 Jun, NF- κ B and YY1 is surrounded by two Negative Regulatory Domains (NRDI and II)
241 described as regions of nucleosome positioning (18). Sequence analysis of the murine IFN- β
242 promoter revealed the presence in the NRDI of two potential DNA-binding sequences for
243 TCF transcription factors. A first site, TCFa, between positions -374 and -367 (5'-
244 TTCAAAGG-3') that perfectly matches the consensus TCF DNA binding sequence 5'-
245 (A/T)(A/T)CAAAGG-3' (38). A second site, TCFb, between positions -233 and -226 (5'-
246 CCTTTGcT-3') that differs from the consensus TCF DNA binding sequence by one base.
247 Two sequences homologous to the murine TCFb sequence are present in the human IFN- β
248 promoter, between positions -260 and -253 and +26 and +33 respectively.

249 The presence of potential TCF binding sites within the proximal region of the IFN- β
250 promoter suggested that expression of the IFN- β gene could be modulated in response to
251 pathways inducing nuclear accumulation of β -catenin and formation of TCF/ β -catenin
252 complexes over the IFN- β promoter region. In order to test this hypothesis, we analyzed IFN-
253 β gene expression in non-infected cells, corresponding to an IRF3-NF- κ B-ATF2/c-Jun
254 independent expression that we have considered as constitutive IFN- β expression, before and
255 after nuclear accumulation of β -catenin. Experiments were carried out in murine fibroblastic
256 L929 cells, which are potent IFN- β producer cells. In the absence of GSK-3 inhibition, little if
257 any β -catenin was detected in the nucleus of L929 cells whereas the nuclear distribution of β -
258 catenin was significantly enhanced after treatment of the cells with LiCl, an inhibitor of GSK-

259 3 (Fig. 1B-D). IFN- β gene expression measured by RT-qPCR in LiCl-treated cells compared
260 to untreated cells, showed that LiCl treatment significantly enhanced the constitutive level of
261 IFN- β mRNAs ($p < 10^{-5}$) (Fig. 1E) independently of any virus infection. Even though the level
262 of IFN- β expression measured after LiCl treatment was much lower than that induced during
263 viral infection (16), it was sufficient to trigger an IFN- β response as reflected by a significant
264 induction of the expression of two major IFN-stimulated genes (ISGs), *Oas1b* and *Irf7* genes
265 (Fig. 1F). The effect of LiCl on IFN- β expression was dose dependent. The highest effect,
266 before reaching saturation, was observed at 20 mM LiCl (Fig. 1G).

267 Low constitutive levels of IFN- β have been previously shown to synergize with virus
268 infection for efficient virus-induced IFN- β production (30,48). In order to test if the
269 enhancement of the constitutive level of IFN- β gene expression induced by LiCl in naïve cells
270 could affect virus induced IFN- β expression, L929 cells were either pretreated or not with
271 LiCl before being infected with Newcastle Disease Virus (NDV) that, contrary to LiCl, does
272 not induce the nuclear accumulation of β -catenin (Fig. 1H and J). As shown in Fig. 1J,
273 pretreatment of the cells with LiCl significantly potentiated NDV-induced IFN- β expression.

274

275 **The effect of LiCl treatment on IFN- β expression is mediated by β -catenin.**

276 In order to confirm that the effect of LiCl treatment on constitutive IFN- β expression
277 was not due to LiCl treatment *per se* but required the nuclear accumulation of β -catenin, we
278 made use of murine hepatocyte AML12 cells that produce IFN- β in response to viral infection
279 but, by contrast to L929 cells, do not accumulate nuclear β -catenin after LiCl treatment (Fig.
280 2A and B). Measurement of the expression of IFN- β mRNA in AML12 cells either treated or
281 not with LiCl, before (Fig. 2C) and after (Fig. 2D) NDV infection, showed that the inability
282 of LiCl to induce the accumulation of nuclear β -catenin in this particular cell type correlated

283 with the inability of LiCl treatment to enhance IFN- β expression either in the absence
284 (Fig.2C) or presence (Fig. 2D) of virus infection.

285 The role of β -catenin during LiCl enhancement of IFN- β expression was further
286 confirmed using siRNAs. For this, L929 cells were mock-transfected or transfected either
287 with siRNAs directed against β -catenin or with control siRNAs (Fig. 2E-G) before being
288 treated with LiCl for 24h. Under conditions of diminution of β -catenin mRNA (Fig. 2E) and
289 protein (Fig. 2F) level, we observed that LiCl treatment had no significant effect on IFN- β
290 expression compared to cells treated with control siRNAs (Fig. 2G) confirming therefore that
291 the capacity of LiCl treatment to activate IFN- β expression was mediated by β -catenin.

292

293 **LiCl treatment stimulates the recruitment of β -catenin on the IFN- β promoter through**
294 **the NRDI promoter region containing a TCF binding site.**

295 IRF3 transcription factor is known to promote IFN- β expression, yet its activation,
296 nuclear translocation and subsequent IFN- β promoter binding, require the previous activation
297 of PRRs. The capacity of LiCl treatment to affect IFN- β gene expression in the absence of
298 infection showed that activation of the transcriptional capacity of the IFN- β promoter could
299 occur independently of IRF3, through a mechanism that we hypothesized to be TCF/ β -
300 catenin-dependent. In order to test this hypothesis, we made use of previously established
301 L929 cell lines carrying integrated into their genome the proximal IFN- β promoter region
302 fused to the CAT reporter gene either from positions -330 to +20 (L929 WT330 cells) or from
303 positions -110 to +20 (L929 WT110 cells) (45). The NRDI region and the entire VRE region,
304 containing the IRF3 binding site, are present in both promoters whereas the NRDI region,
305 containing a TCF binding site, is only present on the WT330 promoter (Fig. 3A). Therefore,
306 contrary to the WT330 promoter that contains a TCF binding site, no TCF binding site is
307 present in promoter WT110.

308 ChIP analysis presented in Fig. 3B indicates that LiCl treatment induced β -catenin
309 binding to the WT330 promoter but not to the WT110 promoter, demonstrating that β -catenin
310 binding to the IFN- β promoter that occurred in the absence of virus infection required the
311 NRDII region containing a TCF binding site.

312 If, as hypothesized, the activation of IFN- β expression induced after LiCl treatment
313 required the recruitment of β -catenin on the IFN- β promoter, then only the WT330 promoter
314 was expected to respond to LiCl treatment. In order to test this prediction, we pretreated L929
315 WT330 and WT110 cells with LiCl and assayed the corresponding CAT activities (Fig. 3C).
316 As expected, LiCl treatment enhanced by 4-folds the constitutive transcriptional capacity of
317 the WT330 promoter, but not that of the WT110 promoter. Thus reinforcing the indispensable
318 role of the promoter region positioned 5' of the VRE, containing a TCF binding site, for LiCl
319 treatment to enhance the constitutive transcriptional capacity of the IFN- β promoter.

320 The role of the NRDII region containing a TCF binding site during LiCl-dependent
321 promoter activation was also analyzed after virus infection. As shown in Fig. 3D, LiCl
322 treatment enhanced the virus-induced activity of the WT330 promoter, but not that of the
323 WT110 promoter. Therefore, the presence of the NRDII region containing a TCF-binding site
324 was also required for the LiCl-dependent enhancement of the virus-induced transcriptional
325 capacity of the IFN- β promoter. The presence of only the VRE region, containing the IRF3
326 binding site (promoter WT110), was not sufficient to either recruit β -catenin or mediate LiCl
327 enhancement of the constitutive as well as virus-induced transcriptional capacity of the IFN- β
328 promoter.

329 LiCl that is considered as an inhibitor of GSK-3 can also affect the activity of other
330 kinases. In order to further investigate if the effect of LiCl on IFN- β expression was the
331 consequence of the inhibition of GSK-3, L929wt330 and wt110 cells were treated with two
332 other inhibitors of GSK-3, SB216763 and inhibitor IX. Similarly to LiCl, a dose dependent

333 activation of the transcriptional capacity of the WT330 promoter was observed in the
334 presence of increasing amounts of SB216763 (Fig. 3E). Also, treatment with either SB216763
335 or inhibitor IX had the same effect than LiCl, activating the transcriptional capacity of
336 WT330 promoter but not that of WT110 promoter (Fig. 2E and F). Since GSK-3 is a common
337 target for these three inhibitors, the fact that LiCl, SB216763, and inhibitor IX had the same
338 effect on the transcriptional capacity of the IFN- β promoter strongly supports the hypothesis
339 that LiCl dependent enhancement of IFN- β expression is the consequence of the inhibition of
340 GSK-3.

341

342 **The effect of LiCl treatment on IFN- β expression is mediated by TCF.**

343 Gel retardation assays were used to analyze the capacity of TCF binding sites present
344 within the NRDII region of IFN- β promoter to form complexes displaying the characteristics
345 of TCF-DNA complexes. For this, we used oligonucleotides containing the sequence of wild-
346 type, mutated TCFa or mutated TCF b sites. TCF binding sites were mutated in their core
347 motif containing the stretches of A required for the HMG box of TCF factors to interact with
348 DNA. The TCFa site was mutated to give rise to TCFmutA (5'-TTCggAGG-3') site and the
349 TCFb site was mutated to give rise to TCFmutB (5'-CCccTGcT-3') site. The corresponding
350 radioactively labeled, double-stranded DNA probes were incubated with nuclear extracts
351 prepared from L929 cells either non-treated or treated by LiCl during 24h. Whereas complex
352 formation was only weakly observed in the presence of nuclear extracts from non-treated
353 cells, a protein-DNA complex (indicated by an arrow in Fig. 4A) was clearly formed when
354 the DNA probes containing the wild-type TCFa or TCFb sites were incubated with nuclear
355 extracts from LiCl treated cells. As expected for a TCF-DNA complex, complex formation
356 was disrupted when the core region of the TCF DNA binding sequence was mutated as in
357 TCFmutA and mutB probes (Fig. 4B). T-Cell Factors interact with the minor groove of A/T

358 base pairs through their HMG-box and therefore are known to display affinity for I/C
359 sequences that resemble A/T sequences in the minor groove (49, 50). Therefore, as expected
360 for a TCF-DNA complex, the previous incubation of nuclear extracts with non-labeled
361 polydI/dC sequences inhibited complex formation with the radioactively labeled TCFA probe
362 (Fig. 4B). Finally, incubation of the nuclear extracts with anti- β -catenin antibodies affected
363 the formation of the protein-DNA complex that in the presence of antibodies was less intense
364 and supershifted (Fig. 4B), indicative of the presence of β -catenin within the complex.

365 To confirm the role of TCF binding sites in the LiCl dependent activation of the IFN- β
366 promoter transcriptional capacity, the IFN- β promoter region from positions -458 to +36
367 either wild-type or mutated in one or both TCF binding sites was cloned in front of the
368 luciferase reporter gene. After transfecting the corresponding plasmids into L929 cells, the
369 transfected cells were either treated or not with LiCl before being infected with NDV. The
370 corresponding luciferase activities were measured (Fig. 4C). Contrary to wild-type and mutB
371 promoters whose corresponding transcriptional capacities could be activated following LiCl
372 treatment, promoter mutA partially lost its capacity to be activated by LiCl and no activation
373 was observed in the case of the promoter mutAB. Therefore, results obtained here with TCF
374 mutated promoters demonstrated that the presence of at least one TCF binding site was
375 required for LiCl to activate the transcriptional capacity of the IFN- β promoter. In the context
376 of the promoter region cloned in these constructions (from -458 to +36), the TCFA that
377 perfectly matches the consensus sequence site appeared more efficient than the TCFb site.

378 In order to definitively confirm the role of TCF/ β -catenin complexes during LiCl
379 enhancement of the transcriptional capacity of the endogenous IFN- β promoter, we used
380 iCRT3, which is a potent inhibitor of TCF4/ β -catenin complexes (51). The presence of IFN- β
381 mRNAs was measured in NDV-infected L929 cells that were either non-treated or pretreated
382 with LiCl during 24 or 48 h in the absence or presence of different amounts of iCRT3

383 corresponding to the range of iCRT3 concentration necessary to inhibit TCF/ β -catenin
384 dependent transcription of the Axin-2 and CycD1 (51). A dose-dependent inhibition of the
385 effect of LiCl on IFN- β expression was observed in the presence of iCRT3, and this in the
386 case of 24h as well as 48h (Fig. 4D) of LiCl treatment. In the same samples, iCRT3 also
387 inhibited the activation of the expression of the gene coding for CyclinD1 (Fig. 4E), which is
388 known to be regulated by TCF/ β -catenin complexes. Overall demonstrating that the capacity
389 of LiCl to enhance IFN- β expression was mediated by TCF/ β -catenin complexes.

390

391 **LiCl treatment confers an efficient antiviral response.**

392 Fig. 1E shows that LiCl-dependent enhancement of the constitutive level of IFN- β
393 expression was sufficient to lead to a significant activation of the expression of two major
394 ISGs, *Oas1b* and *Irf7*, responsible for the RNaseL-dependent degradation of viral ARN and
395 for the amplification of the IFN- β response respectively. In order to analyze the efficiency of
396 such LiCl-induced interferon response with respect to the establishment of an antiviral state,
397 we compared the cytopathic effect (CPE) of Vesicular Stomatitis Virus (VSV) in murine
398 L929 cells either pretreated or not with LiCl. Indeed, following infection of murine L929 cells
399 with VSV, cell viability is expected to decrease as the amount of VSV increases unless an
400 efficient IFN- β response had been mounted previously to VSV infection (52).

401 L929 cells pretreated or not with LiCl were infected with increasing titers of VSV.
402 Twenty-four hours after infection, the cells were stained with crystal violet, which detects
403 CPE as a decrease in staining intensity. As shown in Fig. 5A, at low multiplicity of infection
404 (MOI), cells pretreated with LiCl displayed less VSV-induced CPE than untreated cells,
405 highlighting the capacity of LiCl treatment to induce an efficient antiviral response protecting
406 cells against VSV-induced cell death. The capacity of LiCl treatment to confer an efficient
407 antiviral response at low MOI is further depicted in photographs of culture fields of LiCl-

408 treated versus untreated cells 24h after post infection (p.i.). Whereas the majority of non-
409 treated cells died 24h p.i., LiCl-treated cells grew to confluence displaying resistance to
410 infection (Fig. 5B).

411 Even though at higher MOI all cells died by 24 h p.i. regardless of LiCl treatment (Fig.
412 5A), at a MOI of 1 the percentage of cells detected as infected by fluorescent staining was
413 significantly lower at earlier times after infection (8h p.i.) among LiCl-treated cells than
414 among untreated cells (Fig. 5C and D). This is indicative of the capacity of LiCl-treated cells
415 to dampen the kinetics of virus multiplication.

416

417 **The canonical Wnt/ β -catenin pathway is a major target of Rift Valley fever virus.**

418 Cellular pathways participating in the establishment of an effective antiviral response
419 are expected to be affected during viral infections: either “positively”, leading to the
420 activation of the host antiviral response, or “negatively”, in the case of viruses capable to
421 efficiently inhibit the cellular antiviral response. Therefore, if as suggested in this work, a
422 TCF/ β -catenin transcription complex participates in the establishment of an efficient antiviral
423 response then pathways regulating active TCF/ β -catenin complex formation are expected to
424 be targeted during viral infection.

425 The effect of a viral infection upon the canonical Wnt/ β -catenin pathway, which is a
426 major regulator of the formation of active TCF/ β -catenin complexes, was analyzed here
427 during infection with Rift Valley fever virus (RVFV) for which two different strains,
428 pathogenic and non-pathogenic are available. The wild type RVFV ZH548 strain (ZH) of the
429 virus that codes for a non-structural NSs protein, suppresses IFN- β expression and is highly
430 pathogenic causing severe illness in humans and animals (53-55), whereas the RVFV
431 ZH548 Δ NSs strain (Δ NSs), deleted for the region coding for NSs protein, strongly activates
432 IFN- β expression and is fully avirulent (56).

433 The viral NSs protein, which is a major factor responsible of RVFV pathogenicity, has
434 the characteristic to form filamentous structures in nuclei of infected cells abnormally
435 trapping within these structures transcription factors and co-factors of the host (21,57).
436 During a recent genome wide search for regulatory DNA regions of the host interacting with
437 RVFV NSs protein, several genes associated with the canonical Wnt/ β -catenin pathway were
438 identified as interacting with NSs (Table II) (58). Among these were genes coding for several
439 WNT ligands (*Wnt1*, *Wnt2*, *Wnt6* and *Wnt8b*), for antagonists of Wnt signaling (*Apcddl*,
440 *Dkk1* and *Kremen2*), for members of the multiprotein complex regulating the degradation of
441 β -catenin (*Gsk3b*, *Gsk3a* and *Axin2*), for β -catenin itself (*Ctnnb1*) as well as for members of
442 the TCF/ β -catenin complex (*Tcf7l2*, *Lef1* and *Bcl9*). Also, DNA regulatory sequences
443 associated with genes coding for casein kinases (*Csnk1d*, *Csnk1g2*, *Csnk1g3* and *Csnk2a2*)
444 known to positively regulate the canonical Wnt/ β -catenin signaling pathway at different
445 levels were present among cellular DNA regions targeted by NSs.

446 Using RT-qPCR, we analyzed the effect of RVFV infection, either pathogenic (ZH
447 strain) or non-pathogenic (Δ NSs strain), upon the expression of the genes related to canonical
448 Wnt/ β -catenin pathway identified as significantly interacting with NSs. For this, RNA was
449 purified from three different cell types targeted by RVFV (L929 fibroblasts, AML12
450 hepatocytes and bone marrow derived macrophages (BMDM)) either non-, Δ NSs- or ZH-
451 infected. After reverse transcription, the fold change in the expression level of genes of
452 interest (including the gene coding for IFN- β) was calculated with respect to non-infected
453 cells using three different reference genes (Fig. 6).

454 As expected, infection with the avirulent Δ NSs strain strongly activated IFN- β gene
455 expression in the three cell types tested, whereas infection with the virulent ZH strain
456 maintained the IFN- β expression in an abnormally repressed state.

457 Both strains affected the Wnt/ β -catenin pathway but with opposite effects. Infection
458 with the non-pathogenic Δ NSs strain led to i) the activation of the expression of genes coding
459 for casein kinases, with *Csnk1d* and *Csnk2a2* genes activated in the three cell types tested,
460 and *Csnk1g3* activated in fibroblasts and BMDM; ii) the activation of the expression of genes
461 coding for factors essentials for the formation of an active β -catenin transcription complex
462 such as *Bcl9* and *Tcf7l2* in hepatocytes and BMDM; and iii) the repression of the expression
463 of the *Axin2* gene, a negative regulator of the canonical Wnt/ β -catenin pathway (59), in
464 hepatocytes. On the contrary, infection with ZH led in BMDM to the inhibition of the
465 expression of *Csnk1d* and *Csnk2a2* genes, and the activation of the expression of *Axin2* gene.
466 Also, a slight inhibition of the expression of *Bcl9* gene was observed in fibroblasts and
467 hepatocytes.

468 As shown in Fig. 7, all the effects observed after non-pathogenic Δ NSs infection
469 tended towards the formation of an active nuclear β -catenin complex. On the contrary, the
470 effects observed after infection with the pathogenic ZH strain of the virus tended against the
471 formation of a nuclear β -catenin transcription complex.

472 Virus-induced IFN- β expression depends on the presence of several transcription
473 factors and co-factors that synergize to give rise to a maximum of expression (16-27).
474 Therefore, even though TCF/ β -catenin complexes could participate on the induction of IFN- β
475 expression, they should not be considered as alone responsible of the strong IFN β expression
476 induced during infection by Δ NSs. Similarly, even though RVFV targeting of TCF/ β -catenin
477 complex formation could be participating in the RVFV-induced inhibition of IFN- β
478 expression, this should not be considered as alone responsible of the complete lack of IFN- β
479 expression in RVFV infected cells that we have previously shown to be related to the capacity
480 of NSs to maintain the IFN- β promoter region associated to a transcriptionally repressive
481 environment (16, 21).

482 Nevertheless, the fact that avirulent and virulent strains of RVFV had opposite, mirror,
483 effects upon the Wnt/ β -catenin pathway suggested that this pathway could be playing a role in
484 mounting an efficient innate antiviral response against RVFV infection.

485

486 **A potential role for β -catenin protein in setting up an antiviral response against RVFV**
487 **infection.**

488 In order to test the effect of RVFV infection upon the level of β -catenin *in vivo*, the
489 presence of β -catenin was analyzed in the liver and brain of mice that were either non-
490 infected, or infected with Δ NSs or ZH strains. Of note, the liver and brain are two main
491 organs targeted during RVFV infection (60). Mice were euthanized at days 3 and 5 p.i. and
492 the liver and brain were removed; one half of each organ was used for total protein
493 purification and Western blot analysis and the other half for RNA purification and RT-qPCR
494 analysis. Whereas no variation was observed for β -catenin at the transcriptional level (data
495 not shown), Western blot analysis showed significant variations at the protein level in the
496 liver of ZH-infected mice at day 5 p.i. (Fig. 8A). Under these conditions, the average relative
497 level of β -catenin significantly diminished in the liver of all ZH-infected mice compared to
498 non-infected and Δ NSs-infected mice where on the contrary, the level of β -catenin was
499 increased in Δ NSs-infected mice (Fig. 8A).

500 Viral targeting of β -catenin was further analyzed with respect to the presence of the
501 virus (as translated by the presence of viral mRNAs coding for viral proteins N and NSs) in
502 the liver and the brain of each mouse under each condition. In the case of ZH-infected mice,
503 viral N and NSs mRNAs were clearly detected at day 5 p.i. in the liver of mouse #1, 2 and 3
504 and by day 3 p.i. in the liver of mouse #1 (Fig. 8B) but remained essentially undetectable in
505 the brain of infected mice. Therefore, the effect of RVFV infection upon the level of β -

506 catenin appeared correlated with the presence of the virus suggesting that β -catenin could be
507 playing a role protecting against ZH replication.

508 If as hypothesized β -catenin played a role in the antiviral response against RVFV
509 infection, then LiCl treatment should have a protective effect. In order to test this, L929 cells
510 were either non-treated or pretreated with LiCl during 24 h before infection with the virulent
511 ZH strain of RVFV. In agreement with a potential physiological role for β -catenin inhibiting
512 RVFV replication, pretreatment with LiCl significantly diminished the number of lytic
513 plaques induced by RVFV (Fig. 8C).

514

Discussion

515

516 In this work we have demonstrated that cell treatment with LiCl, an inhibitor of GSK-
517 3, leads to the enhancement of the constitutive (namely IRF3-NF κ B-ATF2/cJUN-
518 independent) as well as virus-induced level of IFN- β gene expression, provided that LiCl
519 treatment be correlated with the IFN- β promoter recruitment of β -catenin. The effect of LiCl
520 on the constitutive as well as virus-induced transcriptional capacity of the IFN- β promoter
521 required the presence of the IFN- β promoter region containing TCF-binding sites, positioned
522 5' of the VRE region. Results obtained in this work with siRNA directed against β -catenin
523 added to results obtained with iCRT3, an inhibitor of TCF/ β -catenin complexes (51) as well
524 as results obtained with IFN- β promoters carrying mutated TCF sites, demonstrated that the
525 capacity of LiCl to enhance IFN- β expression was mediated through TCF/ β -catenin
526 complexes rather than IRF3 as suggested until now in the literature.

527 In the absence of β -catenin, TCFs act as transcriptional repressors recruiting co-
528 repressor complexes. The TCF sites we describe here on the IFN β promoter are positioned
529 over the NRDII region that corresponds to a negative regulatory region. It is therefore
530 possible that in the absence of β -catenin, TCF factors could be participating in the
531 establishment of the repressive state of the IFN- β promoter alongside with other repressors
532 and co-repressors previously described as participating in the establishment of the repressive
533 state of the IFN β promoter such as the SAP30/Sin3A/NCoR/HDAC3 complex (21).

534 Such capacity of LiCl to enhance the transcriptional activity of the IFN- β promoter,
535 we also observed it after treatment of the cells with SB216763 and inhibitor IX, which are
536 two other inhibitors of GSK-3, suggesting that the capacity of LiCl to enhance IFN- β
537 expression observed in this work could be the consequence of the inhibition of GSK-3 that is
538 a target that these three inhibitors have in common. In agreement with our results, activation

539 of IFN- β expression after GSK-3 inhibition by SB216763 has been previously described by
540 several groups in the context of the IFN- β expression induced in response to LPS or polyI:C
541 (39, 61, 62), and a positive effect for β -catenin on IFN- β expression has been reported under
542 different contexts (41, 43, 63).

543 However, inhibition of GSK-3 has also been associated to a negative effect on virus-
544 induced IFN- β expression (44). This was observed in the context of SeV infection and
545 required the SeV-induced secretion of WNT2B and WNT9 ligands that in association with the
546 nuclear accumulation of β -catenin triggered a negative feedback loop to reduce and control an
547 excessive IFN- β response. The SeV-dependent negative effect of GSK-3 inhibition on IFN- β
548 expression was shown to be independent of TCF/ β -catenin driven transcription and therefore
549 different from the positive effect of GSK-3 inhibition we have observed here on IFN- β
550 expression. Even though the exact mechanism leading to IFN- β inhibition in the case of SeV
551 infection has remained undetermined, it was suggested to depend on the association of IRF3
552 with β -catenin, affecting the late stage of IRF3 transcriptional activity (44). In our study, the
553 TCF/ β -catenin activation of IFN- β expression observed in the presence of LiCl, was observed
554 not only in non-infected cells but also after NDV infection including during the period of the
555 establishment of the post-transcriptional turn-off of the IFN- β gene (Fig. 1 I, 6 and 8 hr p.i.).
556 Differences between our results and those of Baril et al. could be related to the fact that
557 contrary to SeV, NDV infection does not induce WNT signaling as translated by the inability
558 of NDV to induce accumulation of nuclear β -catenin even at late times after infection.

559 WNT ligands lead to the nuclear accumulation of β -catenin through a mechanism
560 different from that of LiCl. While LiCl inhibits the kinase activity of GSK-3 preventing β -
561 catenin degradation, WNT ligands induce the plasma membrane recruitment of GSK-3 and
562 AXIN1, disrupting the cytoplasmic GSK3/AXIN/APC destruction complex of β -catenin.

563 Thus, WNT ligands lead to the accumulation of nuclear β -catenin without affecting the kinase
564 activity of GSK3. Lei et al. (64) have described a positive effect of GSK-3 upon IFN- β
565 expression and response independent of the kinase activity of GSK-3, that required the direct
566 interaction of GSK-3 with TBK1 necessary for the TBK1-dependent activation of IRF3 (64).
567 It is possible that the plasma membrane recruitment of GSK-3 induced by WNT ligands in the
568 context of SeV infection, could interfere with the capacity of GSK-3 to interact with and
569 activate TBK1, therefore diminishing through a feedback loop the pool of phosphorylated
570 active IRF3.

571 Our results showed that the LiCl-dependent activation of the IFN- β expression was
572 correlated with the induction of an effective antiviral response. This in agreement with
573 recently published data describing the capacity of LiCl to inhibit H7N7 influenza A (43) and
574 Porcine Reproductive and Respiratory Syndrome (PRRS) (65) virus replication. Interestingly,
575 both these works show results indicative of a role for TCF/ β -catenin complexes on these
576 LiCl-dependent inhibitions of viral infection. Contrary to these and our results, Wang et al.
577 (62) have described a LiCl-dependent attenuation of IFN- β expression and viral infection,
578 through a mechanism independent of LiCl/ β -catenin complexes related with the capacity of
579 LiCl to inhibition TBK1. To our knowledge, this is the only work that has described an
580 inhibitory effect of LiCl on TBK1. This is an effect of LiCl that we did not observe under our
581 experimental conditions. Notwithstanding that NDV-induced IFN- β expression relies on the
582 activation of RIG-I and TBK1, we never observed an inhibitory effect of LiCl treatment on
583 the IFN- β expression induced by NDV. Not even under conditions when the positive effect of
584 LiCl was not detected, such as when LiCl was unable to induce accumulation of nuclear β -
585 catenin in AML12 cells (Fig. 2 A-D) or unable to induce β -catenin recruitment as in the case
586 of the WT110 IFN- β promoter (Fig. 3). Differences between our results, as well as results
587 obtained in the context of influenza (43) and PPRS (65) virus, and the work of Wang et al.

588 (62) could result from variations on the state of TBK1 under our respective cellular models.
589 TBK1 is an enzyme whose activity strongly relies on its cellular localization that can be
590 affected by a wide diversity of mechanisms and signaling pathways including not only
591 pathogens but also cell growth and proliferation (66).

592 Further emphasizing the potential role for TCF/ β -catenin complexes in the
593 establishment of an efficient innate antiviral response, we show here that LiCl treatment of
594 L929 cells protected these cells against the cytopathic effect of RVFV that we show here to
595 negatively target β -catenin in the liver of infected mice. Viral targeting of the formation of
596 active nuclear β -catenin transcription complexes has been observed in the context of
597 infections with other viruses such as influenza H1N1 virus, Human Cytomegalovirus
598 (HCMV), Venezuelan Equine Encephalitis Virus (VEEV) and HIV-1 (40,67-69). Such
599 tendency of viruses to negatively target β -catenin, is in a agreement with the scenario of a
600 positive role for β -catenin during the establishment of an efficient antiviral response.

601 Several reports in the literature point at physiological roles for constitutive IFN- β
602 expression in the absence of viral infection (33). However, little is known concerning the
603 mechanism(s) capable to directly modulate IFN- β expression in naïve cells except for results
604 obtained with *c-Jun*^{-/-} murine embryonic fibroblasts that identified transcription factor c-Jun
605 as a potential regulator of the constitutive level of IFN- β expression (70). Since inhibition of
606 GSK-3, leading to the formation of nuclear TCF/ β -catenin complexes, can be reached not
607 only physiologically through pathways associated with Wnt ligands and Akt phosphorylation
608 but also pharmaceutically, results shown here open the possibility of a wide range of cellular
609 and extra-cellular mechanisms susceptible to modulate the level of IFN- β expression in the
610 absence of infection.

611 If we consider that TCF/ β -catenin complexes can directly affect constitutive levels of
612 IFN- β expression in the absence of pathogens as described here, then the existence of cross-

613 talks between β -catenin and IFN- β should also be considered beyond the issue of pathogen
614 infection. For example, the capacity of β -catenin to modulate inflammatory and immune
615 responses (71) could be related to its ability to modulate the expression of IFN- β , which is a
616 major regulator of immunity and inflammatory responses. Also, a cross-talk between β -
617 catenin and IFN- β during the establishment and/or treatment of neurological disorders such as
618 Alzheimer disease and multiple sclerosis should be considered since both Wnt/ β -catenin
619 pathway and IFN- β response have been associated to these neurological pathologies (72-74).

620 Although modulation of the constitutive level of IFN- β expression has probably been
621 observed in the past by many researchers, it has often been neglected because it seemed only
622 minor compared to pathogen-induced IFN- β expression. Nevertheless, even though weak, the
623 biological significance of constitutive IFN- β expression is no longer to be demonstrated (33).
624 Therefore, mechanisms capable to modulate constitutive IFN- β expression, such as the one
625 our results demonstrate here, should gain interest in the future.

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856 synaptogenesis. Front Cell Neurosci **7**:103.

857

858

Figure legends

859 **Figure 1. LiCl treatment enhances the constitutive and virus-induced IFN- β expression.**

860 (A) Schematic representation of the general organization of the murine IFN- β promoter
861 showing the Negative Regulatory Domain (NRD) I and II as well as the Virus Responsive
862 Element (VRE). (B and H) Immunolocalisation of β -catenin in L929. Cells were either non-
863 treated (NT), treated with 20mM LiCl (LiCl) during 24h, or infected with NDV, labeled with
864 an anti- β -catenin antibody (a, d, g, h) and a DNA intercalating agent to visualize the nucleus
865 (ToPro3; b, e, h, k). Nuclei were outlined as shown in merge images and total green pixel
866 intensity corresponding to β -catenin labeling in the nucleus was quantified (C). β -catenin was
867 analyzed by Western blot (D) in nuclear extracts from L929 cells either non treated (NT) or
868 treated with 20 mM LiCl (LiCl) during 24h. IFN- β mRNA (E and I) and Oas1b or IRF7
869 mRNA (F) were analyzed by RT-qPCR: in non-infected L929 cells either non-treated (NT) or
870 LiCl treated (LiCl) (E-G); at different times post-infection (p.i) in L929 cells mock- or NDV-
871 infected, either non-treated (NT) or pre-treated with LiCl (LiCl) (I). In (E-G), the
872 corresponding fold inductions were calculated with respect to non treated cells; and in (I), the
873 corresponding fold inductions were calculated with respect to non-infected and non-treated
874 cells. C) n=33 (minimum) to 71 (maximum) counted nuclei; E) n=42 from 13 independent
875 experiences; F) n=18 from 6 independent experiences; I) n=6. Student test: p-value less than
876 0.001 (***), 0.01 (**) and 0.05 (*). All images correspond to one confocal section. Scale bar
877 = 10 μ M.

878

879 **Figure 2. LiCl enhancement of IFN- β expression is mediated by β -catenin. (A-D) AML12**

880 cells were either non-treated (NT) or treated with 20mM LiCl (LiCl) during 24h and either
881 non-infected (A-C) or NDV-infected (D). (A and B) Cells were labeled with an anti- β -catenin
882 antibody (a, d) and a DNA intercalating agent to visualize the nucleus (ToPro3; b, e). Nuclei

883 were outlined as shown in merge images (c, f), and total green pixel intensity corresponding
884 to β -catenin labeling in the nucleus was quantified (**B**). IFN- β mRNA (**C** and **D**) was
885 analyzed by RT-qPCR in non-infected (**C**) and NDV-infected (6h p.i.) (**D**) cells either non-
886 treated (NT) or pre-treated with LiCl (LiCl). The corresponding fold inductions were
887 calculated with respect to non-treated (**C**) or non-infected and non-treated (**D**) cells. (**E-G**)
888 L929 cells were either mock-transfected (mock) or transfected with β -catenin specific (si β cat)
889 or control (siCtrl) siRNA for 72h. β -catenin mRNA (**E**) and protein level (**F**) were analyzed
890 by RT-qPCR and WB respectively. (**G**) Post-siRNA, cells were either non-treated (NT) or
891 treated with 20mM LiCl (LiCl) during 24h before being NDV-infected. IFN- β mRNA was
892 analyzed by RT-qPCR. (**E** and **G**) the corresponding fold inductions were calculated with
893 respect to mock-transfected, non-treated and NDV-infected cells (n=3). Student test: p-value
894 less than 0.001 (***) and 0.01 (**). All images correspond to one confocal section. Scale bar
895 = 10 μ M.

896 **Figure 3. Interaction of β -catenin with the IFN- β promoter region containing a TCF**
897 **binding site is necessary for LiCl enhancement of IFN- β promoter activity. (A)**
898 Schematic representation of the WT330 and WT110 murine IFN- β promoters fused to the
899 CAT reporter gene and integrated into the genome of L929 WT330 and L929 WT110 cell
900 lines respectively. (**B** to **D**) β -catenin binding to WT330 and WT110 promoters and
901 corresponding CAT activities were analysed in L929 WT330 and WT110 cells either non-
902 treated (NT) or treated with LiCl 20mM (LiCl). (**B**) Genomic DNA was collected 24h post-
903 LiCl treatment and immunoprecipitated with anti β -catenin (α - β -cat) or anti NSs (α -NSs,
904 negative control) antibodies. Increasing amounts (μ L) of immunoprecipitated DNA (IP), as
905 well as non immunoprecipitated genomic DNA (Input) were amplified by semi-quantitative
906 PCR using specific primers for the WT330 and WT110 integrated promoters. (**C**) Cells were

907 collected post-LiCl treatment and their CAT activities quantified. The corresponding fold
908 inductions were calculated with respect to non-treated cells (n=12 for WT330 and n=6 for
909 WT110 cell lines). **(D)** Post-LiCl treatment, cells were further mock- or NDV-infected,
910 collected at different times post-infection and the corresponding CAT activities were
911 quantified. The corresponding fold inductions were calculated with respect to non-infected
912 non-treated cells (n=4). **(E and F)** CAT activities of L929 cells either non-treated (NT) or
913 treated with 50 μ M of SB216763 **(E)** or 30 μ M of IX inhibitor during 24h **(F)**. Cells were
914 further mock- or NDV-infected, collected 8h post-infection and the corresponding CAT
915 activities quantified. The corresponding fold inductions were calculated with respect to non-
916 infected non-treated cells.

917

918 **Figure 4. TCF binding sites mediate LiCl-dependent activation of the IFN- β promoter.**

919 **(A and B)** Equal amounts of nuclear extracts (N.E) prepared from L929 either non-treated (-
920 LiCl) or treated with 20mM LiCl (+LiCl) during 24h were incubated with the radioactively
921 labeled probes corresponding to wild type TCFA (TCFA) and TCFb (TCFB) or mutated TCFA
922 (TCFmutA) and TCFb (TCFmutB) sites. When indicated, nuclear extracts were incubated
923 with 500 ng of poly dl/dC or anti- β -catenin antibodies before adding the probes. **(C)** L929
924 cells transfected with plasmids containing luciferase reporter gene under the control of the
925 IFN- β promoter either WT or mutated at the TCFA site (mutA), the TCFb site (mutB) or the
926 TCFA and b sites (mutAB) were either non-treated (NT) or pre-treated with LiCl (LiCl) before
927 infection with NDV. Cells were collected 7h p.i. and the luminescence was quantified with
928 n=3. **(D and E)** L929 cells were either non-treated (NT) or treated with 20mM LiCl (LiCl)
929 during 24h or 48h in the presence or absence of iCRT3 before being NDV-infected. IFN- β
930 **(D)** or cyclin D1 **(E)** mRNA was analyzed by RT-qPCR and the corresponding fold

931 inductions were calculated with respect to non-treated NDV-infected (**D**) or non-infected (**E**)
932 cells; **D**) n=3. Student test: p-value less than 0.01 (***) and 0.05 (*).

933 **Figure 5. LiCl treatment confers an antiviral state.** Monolayers of L929 cells either non-
934 treated (NT) or pre-treated with LiCl 20mM for 24h were infected with VSV. (**A**) Cytopathic
935 effect induced by increasing MOI of VSV was assayed by crystal violet dye staining 24h after
936 infection; (**B**) Photographs of typical culture fields. (**C** and **D**) Cells were fixed 8h after
937 infection (MOI=1), labeled with an antibody directed against the N protein of VSV (displayed
938 in gray) and ToPro3 (blue); merge images of the corresponding culture fields are displayed in
939 (**C**). The % of infected cells, as determined by the presence of N protein encoded by VSV
940 (fluorescence displayed in gray) was determined from a total of 7876 untreated and 9024
941 LiCl-treated cells counted with n=4 (**D**).

942

943 **Figure 6. Infection with RVFV affects the Wnt/ β -catenin pathway at the transcriptional**
944 **level.** The expression of genes associated to the Wnt/ β -catenin pathway previously identified
945 as interacting with the NSs protein of RVFV (listed in Table II) was measured in three
946 different cell types corresponding to fibroblast (L929), hepatocytes (AML12) and Bone
947 Marrow Derived Macrophages (BMDM) either mock-, RVFZH548- (ZH) or RVFV Δ NSs-
948 (Δ NSs) infected. RNAs purified from mock- or virus-infected cells (8h p.i.) were analyzed by
949 RT-qPCR with primers specific for each gene of interest. The change in gene expression was
950 calculated in ZH and Δ NSs-infected cells with respect to mock-infected cells. The horizontal
951 broken lines indicate the cutoff value for upregulation (+1.5 fold) and downregulation (-1.5
952 fold). The effect of virus infection upon the expression of genes coding for WNT ligands as
953 well as for antagonist of Wnt signaling (*Apcdd1*, *Dkk1* and *Kremen2*) could not be tested
954 since the corresponding mRNA remained undetectable in the three cell types analyzed here.
955 n \geq 3 for each cell line.

956

957 **Figure 7. Non-pathogenic and pathogenic strains of RVFV have opposite effects on the**
958 **Wnt/ β -catenin pathway.** Genes participating in the Wnt/ β -catenin pathway whose promoter
959 regions were identified as significantly interacting with RVFV NSs protein during ChIP-on-
960 chip experiments, listed in Table II, are shown in gray. Genes whose expressions were
961 affected after infection with either the non-pathogenic Δ NSs or the pathogenic ZH strain of
962 RVFV with respect to mock-infected cells are indicated by blue (upregulated) or red
963 (downregulated) arrows.

964

965 **Figure 8. A physiological relevance for β -catenin protein level during RVFV infection.**
966 **(A and B)** β -catenin protein and viral N and NSs RNA levels were evaluated in liver and
967 brain of mice either non-infected (NI) or at days 3 and 5 p.i. with RVFVZH548 (ZH) or
968 RVFV Δ NSs (Δ NSs). **(A)** β -catenin protein level was analysed by Western blot and estimated
969 densitometrically by comparison with the band intensity of GAPDH; values were averaged
970 from (n) independent samples per time point with n=3 mice (NI), n=6 mice (ZH 3 days and
971 Δ NSs 3 and 5 days) and n=4 mice (ZH 5 days). Fold induction was calculated by comparison
972 of the relative β -catenin level in infected versus non-infected (NI) samples. **(B)** The relative
973 level of viral N and NSs mRNA were estimated by comparison with the expression of three
974 reference genes (Ppib, Hprt1 and Utp6c). **(C)** Number of lytic plaques formed in monolayers
975 of L929 cells either non treated or pre-treated with LiCl 20 mM during 24h and infected with
976 RVFVZH548. Cells were fixed and stained with crystal violet 3 days p.i. (n=4). Student test:
977 p-value less than 0.001 (***), 0.01 (**), and 0.05 (*). All images correspond to one confocal
978 section.

979

980 **Table I.** Sequences of the different primers used during qPCR assays.

	Forward	Reverse
Ppib	GGAGATGGCACAGGAGGAAA	CCGTAGTGCTTCAGTTTGAAGTTCT
Hprt1	TCCTCCTCAGACCGCTTTT	CCTGGTTCATCATCGCTAATC
Utp6c	TTTCGGTTGAGTTTTTCAGGA	CCCTCAGGTTTACCATCTTGC
Rplp0	CACTGGTCTAGGACCCGAGAAG	GGTGCCTCTGGAGATTTTCG
Ifnb1	ATGAACAACAGGTGGATCCTCC	AGGAGCTCCTGACATTTCCGAA
Os1b	GAGGTGCCGACGGAGGT	TCCAGATGAAGTCTTCCCAAAG
IRF7	CAGCGAGTGCTGTTTGGAGAC	AAGTTCGTACACCTTATGCGG
Ctnnb1	GCCACAGGATTACAAGAAGC	CCACCAGAGTGAAAAGAACG
Bcl9	AGTGCTCTCTCCAGGATATGATG	GGGCAAAGAGTGTGAAATGTTG
Csnk1d	ACGCCGGGATCGAGAAGAA	CCGACCGGGAATCTGTGAG
Csnk1g2	CAAACCTCCGAGTCGGCAAGA	GCTTGTAAGCGGTAAGTCCAG
Csnk1g3	TGGGACCGAGTTTGGAGGATT	CTGGCCGTCCTATTAAGAAGTTC
Csnk2a2	TCCCGAGCTGGGGTAATCAA	TGTTCCACCACGAAGGTTCTC
Tcf7l2	CACGACAGGAGGATTCAGA	GGGGCTTCTTCTTCTTCTC
Axin2	TGACTCTCCTCCAGATCCCA	TGCCCACTAGGCTGACA
Gsk3b	TGGCAGCAAGGTAACCACAG	CGGTTCTTAAATCGCTTGTCTG

981

982 **Table II.** List of canonical Wnt/ β -catenin genes whose regulatory DNA regions were
 983 identified as interacting with RVFV NSs protein during ChIP-on-chip assays (55).

	Gene	Chromo- some	NSs interacting Region Start	Region Length (bps)	Probes in Region	p-value
986	Apcdd1	Chr18	63078268	563	16	0.007658
987	Axin2	Chr11	108827835	502	14	0.00618531
988	Bcl9	Chr3	97004948	751	21	0.00823024
989	Csnk1d	Chr11	120859171	651	18	0.0033914
990	Csnk1g2	Chr10	80096623	865	24	0.00136329
991	Csnk1g2	Chr10	80082196	920	22	0.00671548
992	Csnk1g3	Chr18	54109583	850	18	0.00104351
993	Csnk1g3	Chr18	54156237	499	10	0.00828074
994	Csnk2a2	Chr8	97965333	511	12	0.00827232
995	Ctnnb1	Chr9	120803511	517	15	0.00766641
996	Gsk3a	Chr7	26016588	488	14	0.00998065
997	Gsk3b	Chr16	38213326	554	16	0.006564
998	Kremen2	Chr17	23882003	542	14	0.00559623
999	Lef1	Chr3	130837713	488	13	0.00916435
1000	Tcf7l2	Chr19	55894582	531	15	0.00931583
1001	Wnt1	Chr15	98620114	407	11	0.00822183
1002	Wnt2	Chr6	17981380	579	17	0.00595809
1003	Wnt6	Chr1	74823318	824	23	0.00226374
1004	Wnt6	Chr1	74830849	550	14	0.00750652
1005	Wnt6	Chr1	74828942	494	14	0.00782631
1006	Wnt6	Chr1	74818891	394	11	0.00812085
1007	Wnt6	Chr1	74816494	489	13	0.00885298
1008	Wnt8b	Chr19	44545480	754	20	0.00226374
1009	Wnt8b	Chr19	44544618	808	23	0.00506606

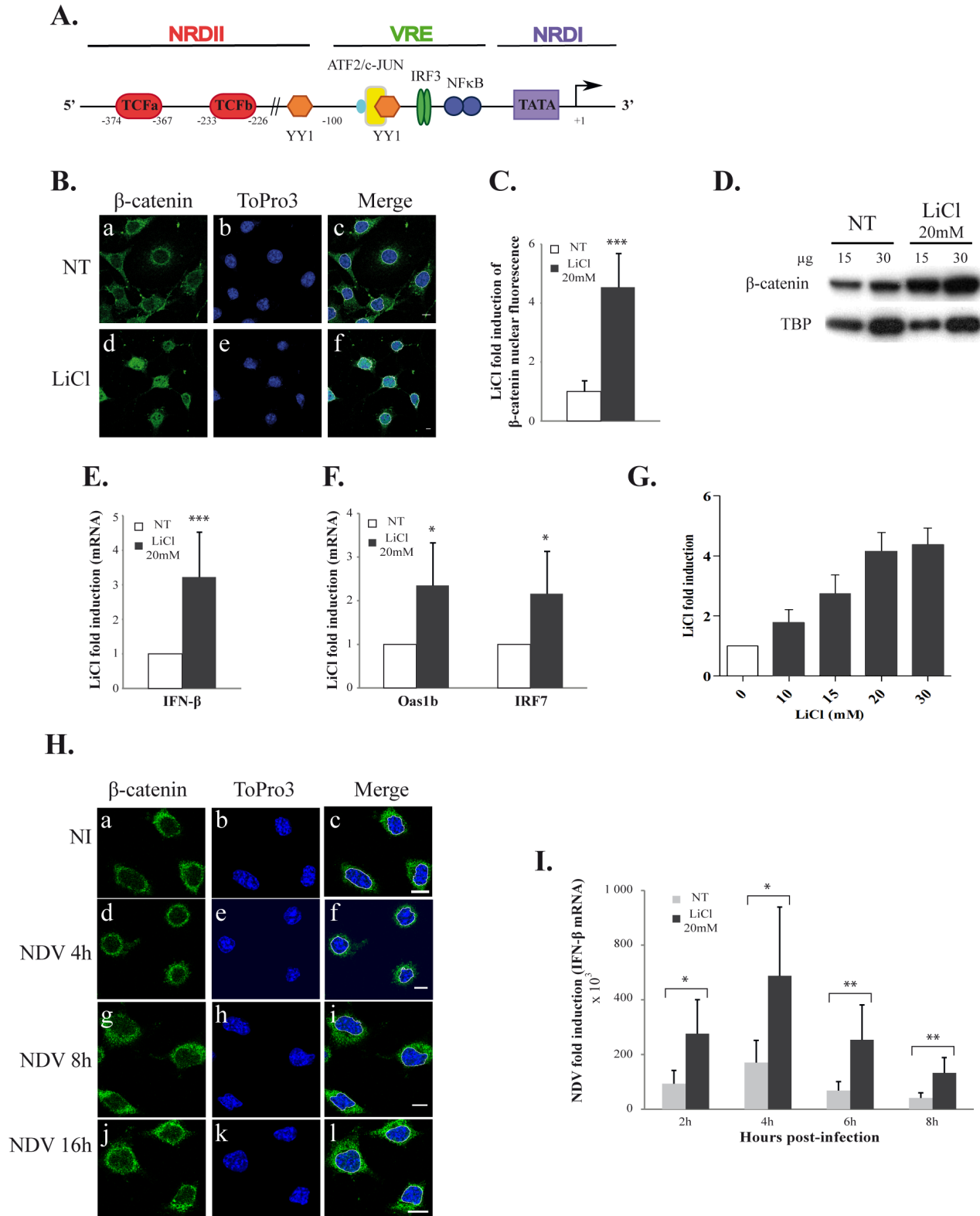


Figure 1. LiCl treatment enhances the constitutive and virus-induced IFN- β expression. (A) Schematic representation of the general organization of the murine IFN- β promoter showing the Negative Regulatory Domain (NRD) I and II as well as the Virus Responsive Element (VRE). (B and H) Immunolocalisation of β -catenin in L929 cells. Cells were either non-treated (NT), treated with 20mM LiCl (LiCl) during 24h, non infected (NI) or infected with NDV, labeled with an anti- β -catenin antibody (a,d,g,j) and a DNA intercalating agent to visualize the nucleus (ToPro3; b,e,h,k). Nuclei were outlined as shown in merge images, and total green pixel intensity corresponding to β -catenin labeling in the nucleus was quantified (C). β -catenin protein level was analyzed by Western Blot (D) in nuclear extracts from L929 cells either non treated (NT) or treated with 20mM LiCl (LiCl) during 24h. IFN- β mRNA (E and I) and Oas1b or IRF7 mRNA (F) were analyzed by RT-qPCR: in non-infected L929 cells either non-treated (NT) or LiCl treated (LiCl) (E - G); at different times post-infection (p.i) in L929 cells mock- or NDV-infected, either non-treated (NT) or pre-treated with LiCl (LiCl) (I). In (E - G), the corresponding fold inductions were calculated with respect to non-treated cells; and in (I), the corresponding fold inductions were calculated with respect to non-infected and non-treated cells. (C) n=33 (minimum) to 71 (maximum) counted nuclei; (E) n=42 from 13 independent experiences; (F) n=18 from 6 independent experiences; (I) n=6. Student test: p-value less than 0.001 (***) , 0.01 (**) and 0.05 (*). All images correspond to one confocal section. Scale bar = 10 μ M.

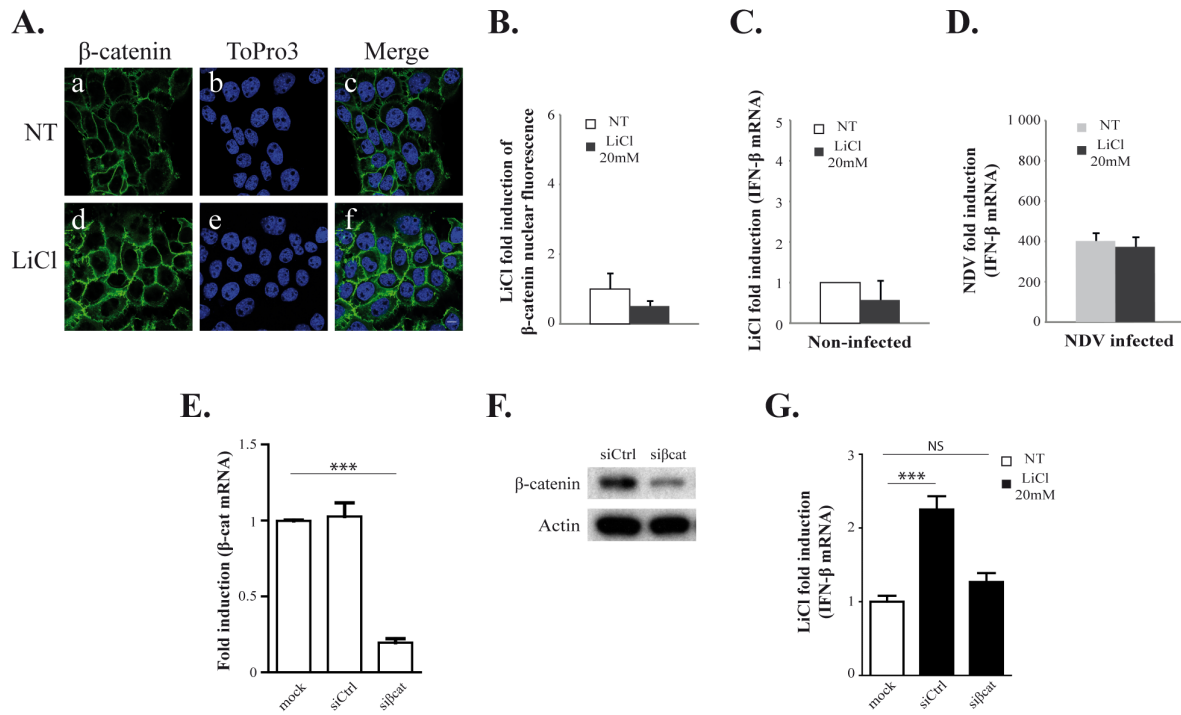


Figure 2. LiCl enhancement of IFN- β expression is mediated by β -catenin. (A-D) AML12 cells were either non-treated (NT) or treated with 20mM LiCl (LiCl) during 24h and either non-infected (A-C) or NDV-infected (D). (A and B) Cells were labeled with an anti- β -catenin antibody (a, d) and a DNA intercalating agent to visualize the nucleus (ToPro3; b, e). Nuclei were outlined as shown in merge images (c, f), and total green pixel intensity corresponding to β -catenin labeling in the nucleus was quantified (B). IFN- β mRNA (C and D) was analyzed by RT-qPCR in non-infected (C) and NDV-infected (6h p.i.) (D) cells either non-treated (NT) or pre-treated with LiCl (LiCl). The corresponding fold inductions were calculated with respect to non-treated (C) or non-infected and non-treated (D) cells. (E-G) L929 cells were either mock-transfected (mock) or transfected with β -catenin specific (si β cat) or control (siCtrl) siRNA for 72h. β -catenin mRNA (E) and protein level (F) were analyzed by RT-qPCR and WB respectively. (G) Post-siRNA, cells were either non-treated (NT) or treated with 20mM LiCl (LiCl) during 24h before being NDV-infected. IFN- β mRNA was analyzed by RT-qPCR (E and G) the corresponding fold inductions were calculated with respect to mock-transfected, non-treated and NDV-infected cells (n=3). Student test: p-value less than 0.001 (***) and 0.01 (**). All images correspond to one confocal section. Scale bar = 10 μ M.

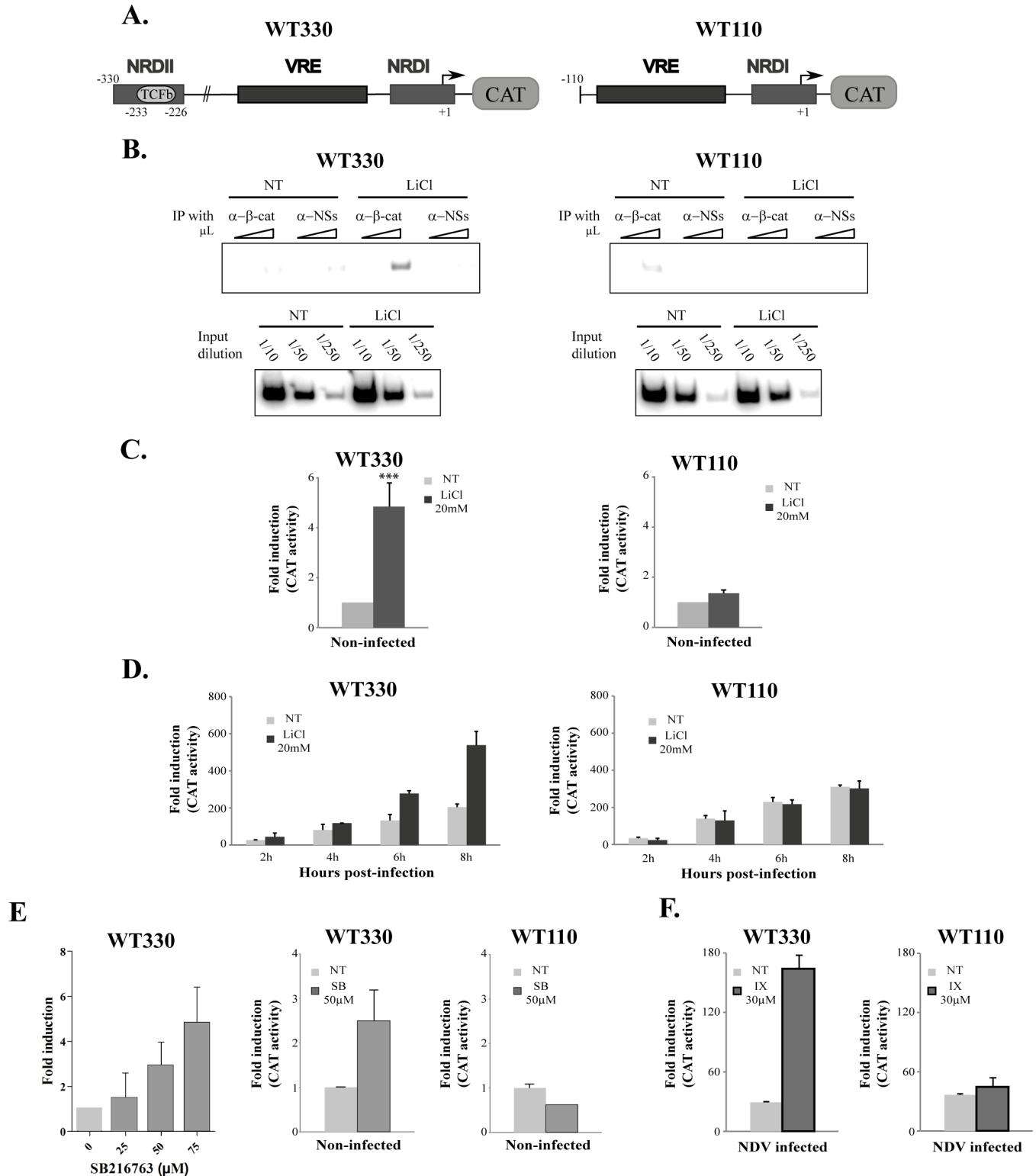
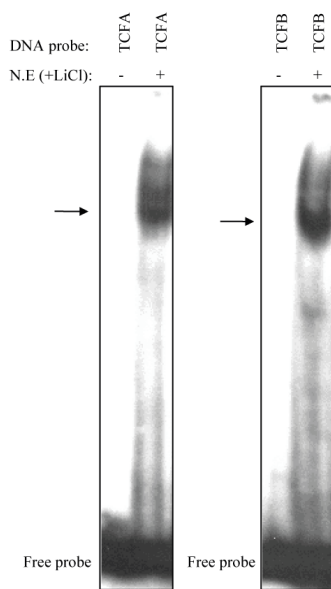


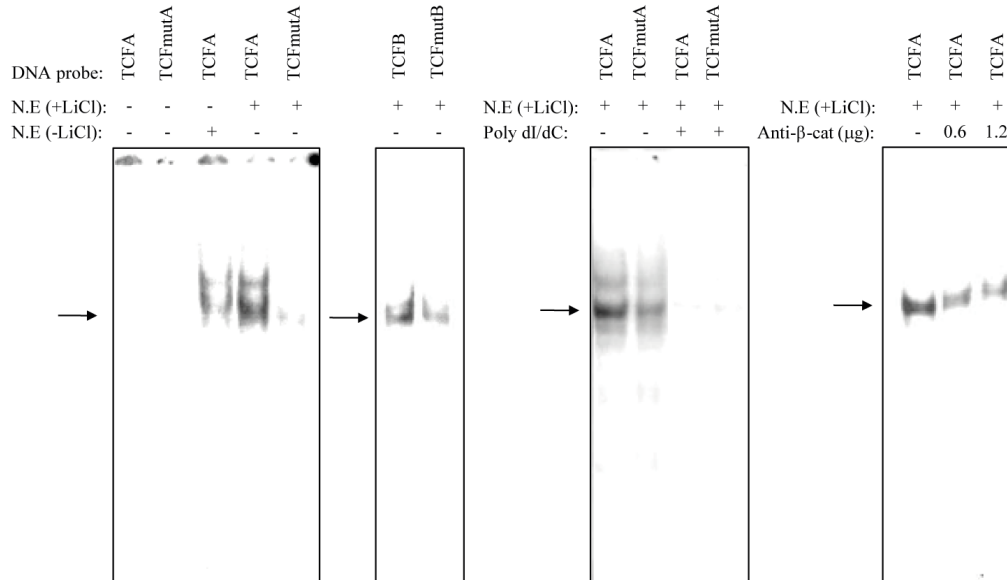
Figure 3. Interaction of β -catenin with the IFN- β promoter region containing a TCF binding site is necessary for LiCl enhancement of IFN- β promoter activity. (A) Schematic representation of the WT330 and WT110 murine IFN- β promoters fused to the CAT reporter gene and integrated into the genome of L929 WT330 and L929 WT110 cell lines respectively. (B to D) β -catenin binding to WT330 and WT110 promoters and corresponding CAT activities were analysed in L929 WT330 and WT110 cells either non-treated (NT) or treated with LiCl 20mM (LiCl). (B) Genomic DNA was collected 24h post-LiCl treatment and immunoprecipitated with anti β -catenin (α - β -cat) or anti NSs (α -NSs, negative control) antibodies. Increasing amounts of immunoprecipitated DNA (IP), as well as non immunoprecipitated genomic DNA (Input) were amplified by semi-quantitative PCR using specific primers for the WT330 and WT110 integrated promoters. (C) Cells were collected post-LiCl treatment and their CAT activities quantified. The corresponding fold inductions were calculated with respect to non-treated cells (n=12 for WT330 and n=6 for WT110 cell lines). (D) Post-LiCl treatment, cells were further mock- or NDV-infected, collected at different times post-infection and the corresponding CAT activities were quantified. The corresponding fold inductions were calculated with respect to non-infected non-treated cells (n=4).

(E and F). CAT activities of L929 cells either non-treated (NT) or treated with 50 μ M of SB 216763 (E) or 30 μ M of IX inhibitor during 24h. (F). Cells were further mock or NDV-infected, collected 8h post-infection and the corresponding CAT activities quantified. The corresponding fold inductions were calculated with respect to non-infected non-treated cells.

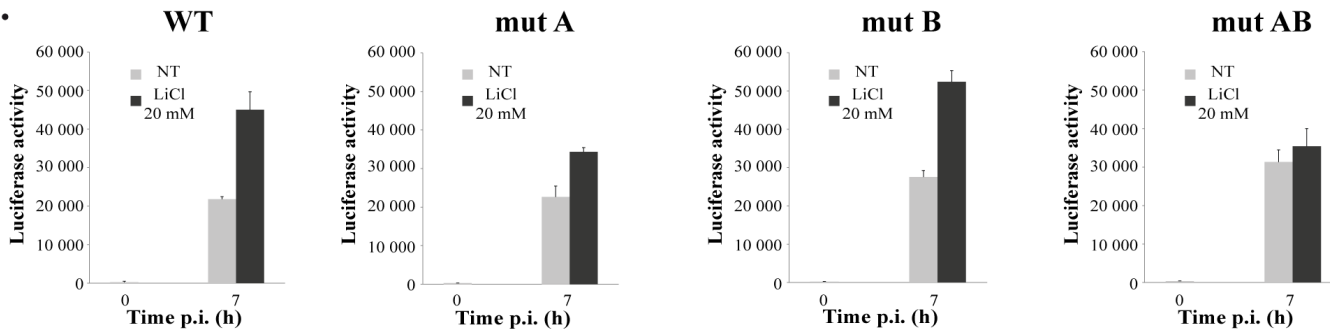
A.



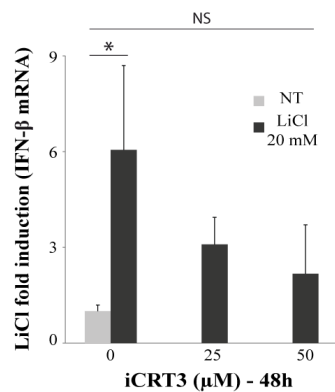
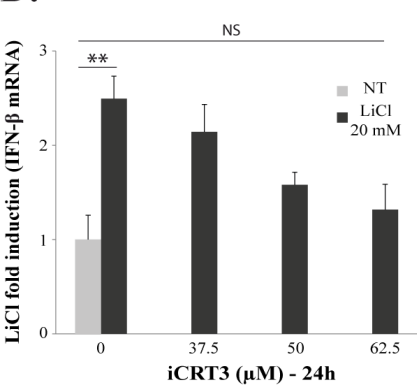
B.



C.



D.



E.

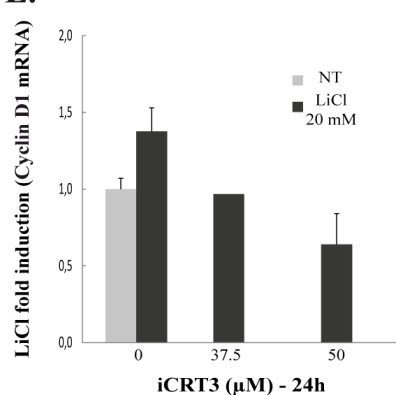


Figure 4. TCF binding sites mediate LiCl-dependent activation of the IFN- β promoter. (A and B) Equal amounts of nuclear extracts (N.E) prepared from L929 either non-treated (-LiCl) or treated with 20mM LiCl (+LiCl) during 24h were incubated with the radioactively labeled probes corresponding to wild type TCFA (TCFA) and TCFb (TCFB) or mutated TCFA (TCFmutA) and TCFb (TCFmutB) sites. When indicated, nuclear extracts were incubated with 500ng of poly dI/dC or anti- β -catenin antibodies before adding the probes. (C) L929 cells transfected with plasmids containing luciferase reporter gene under the control of the IFN- β promoter either WT or mutated at the TCFA site (mutA), the TCFb site (mutB) or the TCFA and b sites (mutAB) were either non-treated (NT) or pre-treated with LiCl (LiCl) before infection with NDV. Cells were collected 7h p.i. and the luminescence was quantified with n=3. (D and E) L929 cells were either non-treated (NT) or treated with 20mM LiCl (LiCl) during 24h or 48h in the presence or absence of iCRT3 before being NDV-infected. IFN- β (D) or cyclin D1 (E) mRNA was analyzed by RT-qPCR and the corresponding fold inductions were calculated with respect to non-treated NDV-infected (D) or non infected (E) cells; in D (n=3). Student test: p-value less than 0.01 (**) and 0.05 (*).

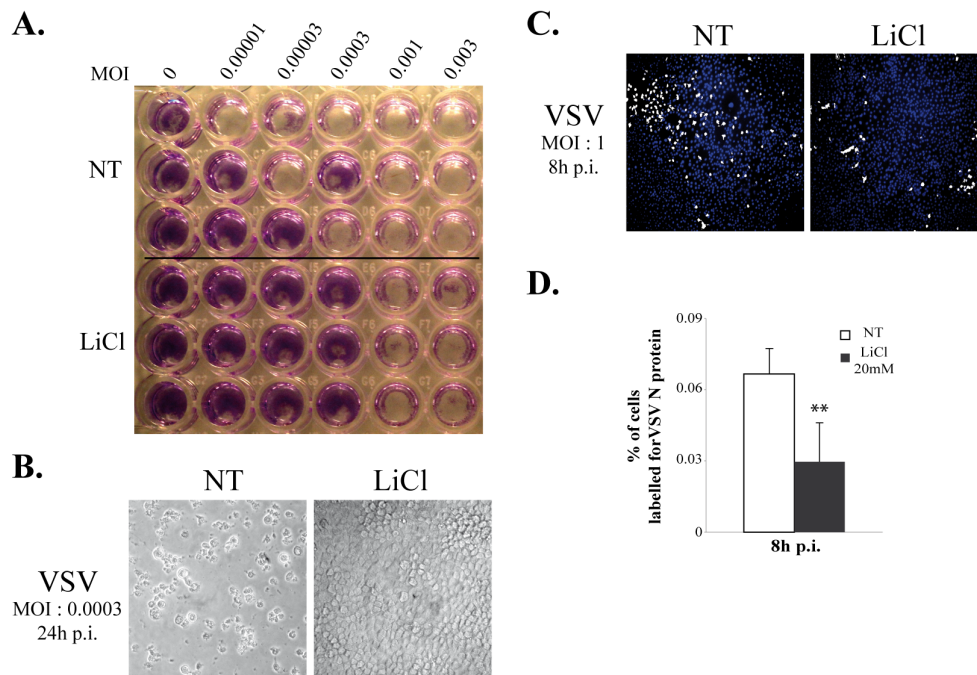


Figure 5. LiCl treatment confers an antiviral state. Monolayers of L929 cells either non-treated (NT) or pre-treated with LiCl 20mM for 24h were infected with VSV. **(A)** Cytopathic effect induced by increasing MOI of VSV was assayed by crystal violet dye staining 24h after infection; **(B)** Photographs of typical culture fields. **(C and D)** Cells were fixed 8h after infection (MOI=1), labeled with an antibody directed against the N protein of VSV (displayed in gray) and ToPro3 (blue); merge images of the corresponding culture fields are displayed in **(C)**. The % of infected cells, as determined by the presence of N protein encoded by VSV (fluorescence displayed in gray) was determined from a total of 7876 untreated and 9024 LiCl-treated cells counted with $n = 4$ **(D)**.

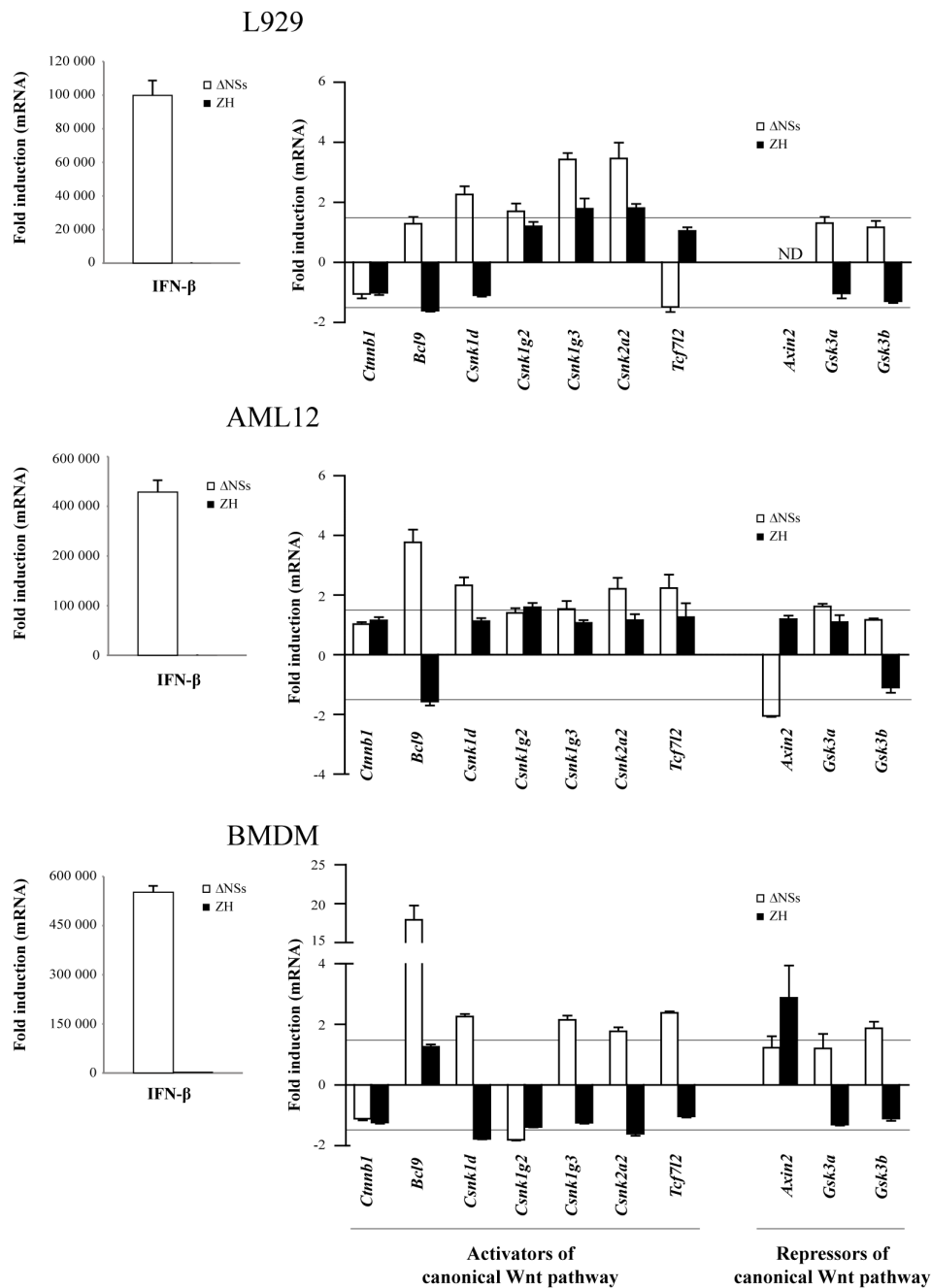


Figure 6. Infection with RVFV affects the Wnt/ β -catenin pathway at the transcriptional level.

The expression of genes associated to the Wnt/ β -catenin pathway previously identified as interacting with the NSs protein of RVFV (listed in Table II) was measured in three different cell types corresponding to fibroblast (L929), hepatocytes (AML12) and Bone Marrow Derived Macrophages (BMDM) either mock-, RVFZH548- (ZH) or RVFV Δ NSs- (Δ NSs) infected. RNAs purified from mock- or virus-infected cells (8h p.i.) were analyzed by RT-qPCR with primers specific for each gene of interest. The change in gene expression was calculated in ZH and Δ NSs-infected cells with respect to mock-infected cells. The horizontal broken lines indicate the cutoff value for upregulation (+1.5 fold) and downregulation (-1.5 fold). The effect of virus infection upon the expression of genes coding for WNT ligands as well as for antagonist of Wnt signaling (Apcc1, Dkk1 and Kremen2) could not be tested since the corresponding mRNA remained undetectable in the three cell types analyzed here. $n \geq 3$ for each cell line.

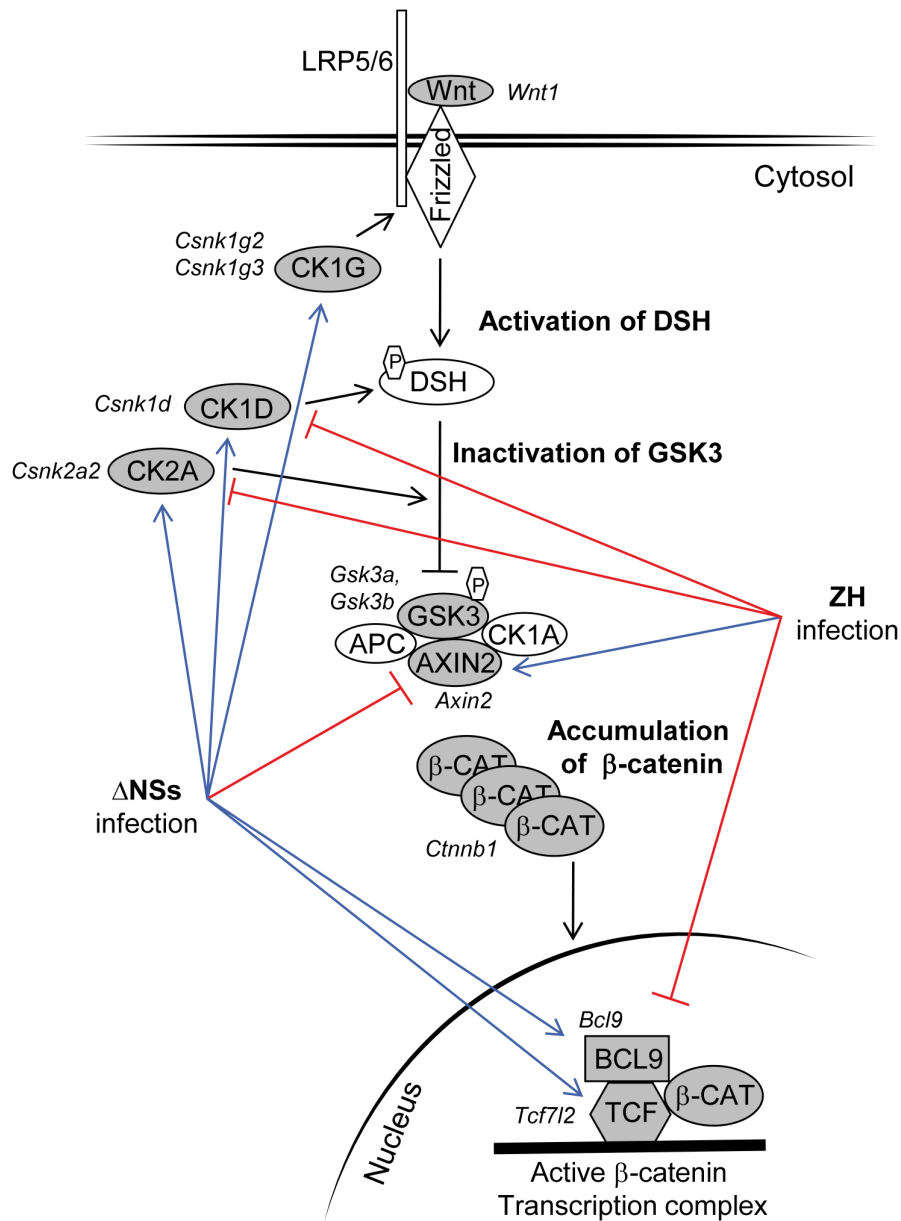


Figure 7. Non-pathogenic and pathogenic strains of RVFV have opposite effects on the Wnt/β-catenin pathway. Genes participating in the Wnt/β-catenin pathway whose promoter regions were identified as significantly interacting with RVFV NSs protein during ChIP-on-chip experiments, listed in Table II, are shown in gray. Genes whose expressions were affected after infection with either the non-pathogenic ΔNSs or the pathogenic ZH strain of RVFV with respect to mock-infected cells are indicated by blue (upregulated) or red (downregulated) arrows.

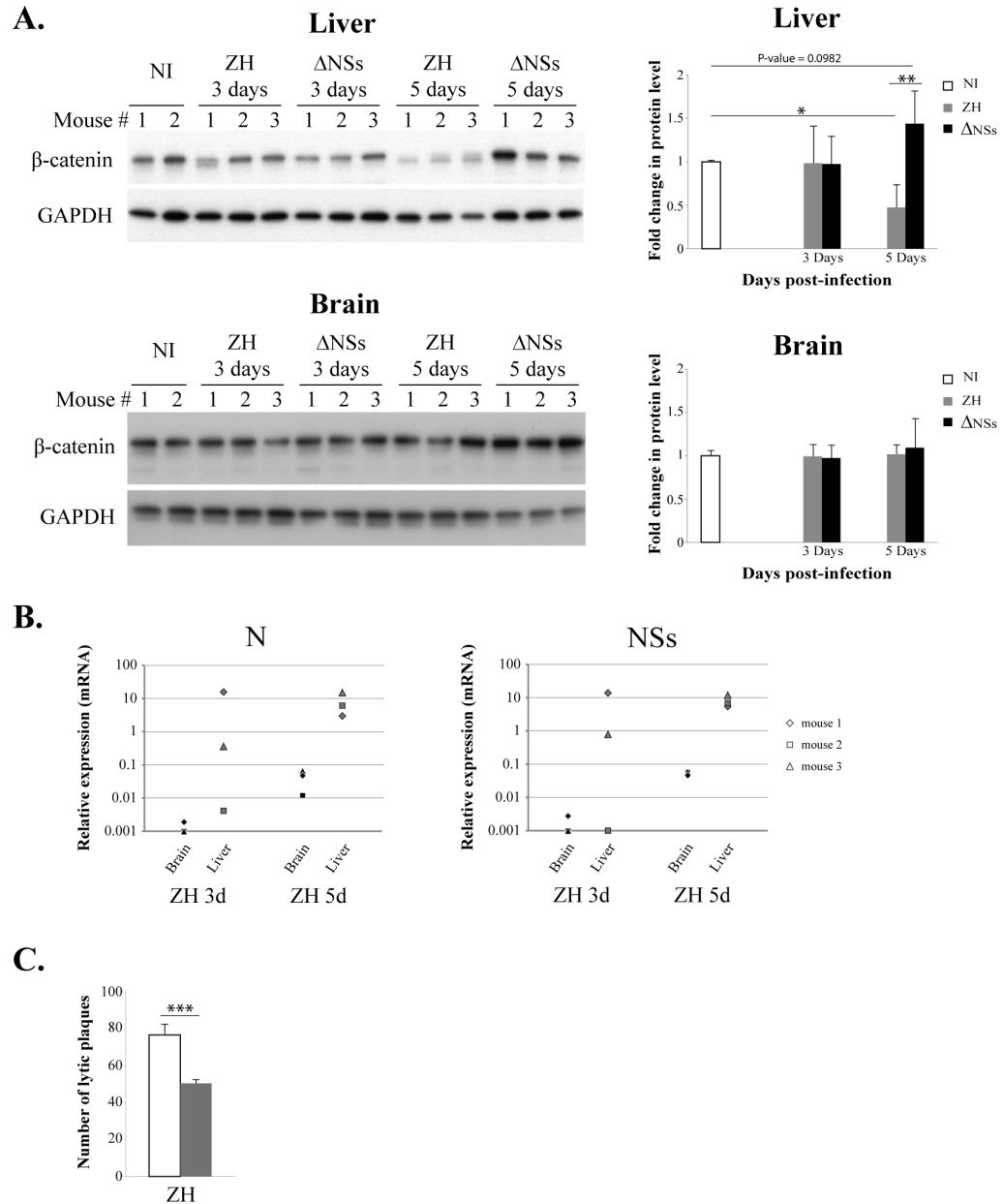


Figure 8. A physiological relevance for β -catenin protein level during RVFV infection. (A and B) β -catenin protein and viral N and NSs RNA levels were evaluated in liver and brain of mice either non-infected (NI) or at days 3 and 5 p.i. with RVFVZH548 (ZH) or RVFV Δ NSs (Δ NSs). (A) β -catenin protein level was analysed by Western blot and estimated densitometrically by comparison with the band intensity of GAPDH; fold changes in protein level were calculated by comparison of the relative β -catenin level in infected versus non-infected (NI) samples. Values were averaged from (n) independent samples per time point with n=3 mice (NI), n=6 mice (ZH 3 days and Δ NSs 3 and 5 days) and n=4 mice (ZH 5 days). (B) The relative level of viral N and NSs mRNA were estimated by comparison with the expression of three reference genes (Ppib, Hprt1 and Utp6c). (C) Number of lytic plaques formed in monolayers of L929 cells either non-treated or pre-treated with LiCl 20 mM during 24h and infected with RVFVZH548. Cells were fixed and stained with crystal violet 3 days p.i. (n=4). Student test: p-value less than 0.001 (***) 0.01 (**) and 0.05 (*).