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STAT3 Negatively Regulates Type I IFN-Mediated Antiviral Response

Wei-Bei Wang,* David E. Levy, † and Chien-Kuo Lee*

Type I IFNs are crucial cytokines of innate immunity for combating viral infections. Signaling through type I IFN receptors triggers the activation of STAT proteins, including STAT1, STAT2, and STAT3. Although an essential role of STAT1 and STAT2 for type I IFN-induced antiviral response has been well established by studies of gene-targeted mice and human mutations, the role of STAT3 for this response remains unclear. Using gain-of-function and loss-of-function approaches, we demonstrated that STAT3 negatively regulates type I IFN-mediated response. STAT3 knockdown or knockout cells displayed enhanced gene expression and antiviral activity in response to IFN-α/β. Restoration of STAT3 to STAT3KO cells resulted in attenuation of the response. Upon viral infection, increased type I IFN production in STAT3KO cells resulted in enhanced STAT activation and ISG expression. One mechanism for the enhanced IFN production and response in the absence of STAT3 might operate through an MDA5-dependent manner. STAT3 also appeared to suppress IFN response directly in a manner dependent on its N-terminal domain and independent of its function as a transcriptional factor. Taken together, these results define STAT3 as a negative regulator of type I IFN response and provide a therapeutic target for viral infections.

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Type I IFNs, composed of an IFN-β and several IFN-α species, are critical cytokines of innate immunity for triggering antiviral response. Antiviral functions of type I IFNs are mediated by induction of ISG, including protein kinase R (PKR), 2',5'-oligoadenylate synthetase (OAS), RNase L, inducible NO synthase (iNOS), and IFN regulatory factors (IRFs), which interfere with virus replication or trigger cell apoptosis to avoid viral spread (1). The signaling pathways resulting in induction of the ISGs involve activation of STAT family members, including STAT1, STAT2, and STAT3, by tyrosine and serine phosphorylation (2). Activated STAT1, STAT2, and IRF9 form the ISGF3 complex, binding to the IFN-stimulated response element (ISRE) in the promoters of ISGs (3). Activated STAT1 and STAT3 form a homodimer, or heterodimer, and bind to IFN-γ-activated site. Whereas the homodimer of STAT1 or STAT3 and the heterodimer of STAT1-STAT3 can bind to similar cognate sites in vitro, the in vivo binding sites for these dimers are most likely to be different because the downstream targets of STAT1 and STAT3 and the phenotypes of STAT1- and STAT3-deficient mice are quite distinct (4–7).

STAT3 is a signaling mediator of IL-6 and IL-10 family members and other cytokines such as leptin and G-CSF (6, 8). Structurally, STAT3, similar to other STAT family members, consists of an N-terminal domain (NTD) for dimerization and tetramerization, a coiled-coil domain (CCD) for protein–protein interaction, a DNA-binding domain (DBD) for specific binding to IFN-γ-activated site element, a Src homology 2 domain for receptor recruitment and STAT dimerization, and a transactivation domain at the C terminus (6). Conventional knockout of STAT3 results in embryonic lethality, underscoring a critical role of STAT3 in embryonic development (9). Conditional targeting of STAT3 in distinct tissues or organs reveals versatile roles of STAT3 in vivo, including cell survival and/or apoptosis, migration, development, and differentiation (6). STAT3 also plays a key role in promoting tumor formation (10). Constitutive activation of STAT3 is found in tumors and immune cells in the tumor environment, serving as a mediator for crosstalk between tumors and immunological environment, leading to tumor-induced immunosuppression (11, 12).

Targeted deletion of STAT1 or STAT2 gene in mice (5, 7, 13) or mutation-associated STAT1 deficiency in humans (14) reveals a pivotal role of either molecule in antiviral response. Although a limited number of groups have studied the role of STAT3 in type I IFN-mediated biological response, its function has remained controversial (15–18). Using gain-of-function and loss-of-function approaches, we demonstrated that STAT3 inhibits antiviral activity of type I IFNs. Whereas knockdown or knockout of STAT3 resulted in enhanced antiviral response, restoration of STAT3 in STAT3KO mouse embryonic fibroblasts (MEFs) or hyperactivation of STAT3 in wild-type (WT) MEFs attenuated the response. Overexpression of WT or mutant STAT3 lacking DNA-binding or transactivation ability suppressed IFN-driven reporter activity. Interestingly, STAT3 NTD is sufficient to confer the suppressive effect. Therefore, these results support a negative role of STAT3 in type I IFN-mediated response.

Materials and Methods

Animals and cells

Generation and mating of MxCre-STAT3ΔT mice and induction of STAT3 deletion have been described previously (19, 20). These animals were
maintained and housed in specific germ-free conditions in the Animal Core Facility at the National Taiwan University College of Medicine. Procedures and use of these animals were reviewed and approved by the Institutional Animal Care and Use Committee at National Taiwan University College of Medicine. WT, STAT1KO, and STAT3KO MEFs were generated, as described previously (21, 22).

Abs, cytokines, and DNA construct

The sources of the cytokines are as follows: recombinant human IFN-α (Roche), recombinant murine IFN-α (Merck), recombinant murine IFN-β (ProSpec). The sources of Abs are as follows: anti-β-actin (Chemicon), anti-actin (Sigma-Aldrich), anti-phospho-STAT1 (Y701) (Invitrogen), anti-STAT1 (homemade), anti-phospho-STAT2 (Y689) (Millipore), anti-STAT2 (homemade), anti-phospho-STAT3 (Y705), anti-STAT3 (Cell Signaling Technology), anti-MDA5 (Axaxxa), anti-IFNAR1 Ab (eBioScience), and anti-hemagglutinin (HA; 12CA5, homemade). Mouse IFN-α ELISA kit was purchased from PBL, WT STAT3 and DBD mutant carrying 5′ ACGGAGGGAGG 3′ IRES-STAT3 was a gift of H. Yu (Department of Cancer Immunotherapeutics & Tumor Immunology, Beckham Research Institute of City of Hope) (24). HA-tagged full-length STAT3 1–770 or truncated mutants of STAT3, including 1–134, 1–317, and 318–770 aa, were gifts of J.-Y. Chen (Institute of Biomedical Sciences, Academia Sinica, Taiwan) (25). Flag-MDA5 was a gift of T. Fujita (Institute for Virus Research, Kyoto University) (26).

Quantitative RT-PCR

Total RNA was prepared from MEFs or primary bone marrow-derived macrophages (BMMs) using a TRizol reagent (Invitrogen). A total of 1–3 μg RNA was subjected to reverse-transcriptase reaction, and cDNA was then subjected to quantitative PCR (QPCR) by iCycler IQ (Bio-Rad) using the following primer sets. Each sample was prepared in duplicate. OAS1, forward 5′-GCCATTCAGCAGCTCGACTATC-3′; reverse 5′-CTCTCCTGCCATCGGCTT-3′; PKR, forward 5′-TGGCCGACACA-ATGTATGTTAC-3′, reverse 5′-ATGTCGACAGCTGAAGATG-3′; iNOS, forward 5′-AGGCCTCATAACATCTG-3′, reverse 5′-GAC-GAGCCAAATACAGTCAGG-3′; GAC, forward 5′-GACGACAAACCTACACCCG-3′, reverse 5′-GAC-GAGCCAAATACAGTCAGG-3′; IRF1, forward 5′-ATAACCTCAGACTGCATCCGCTG-3′, reverse 5′-ATCCCTGTCTGTTGCGGCT-3′; IRF7, forward 5′-AGCGACAGCTGTTTACGAC-3′, reverse 5′-AGTTGCTGATCG-AGAC-3′. PCRs were conducted using Stratagene Brilliant II SYBR Green Master Mix (Merck), and the results were analyzed using Stratagene CFX Manager software. The 18S rRNA gene was used as an internal control for the different samples. At least three independent experiments were performed, and results were expressed as means ± SEM. To evaluate the level of specific mRNA expression, the 2^(-ΔΔCt) method was used, where 2^(-ΔΔCt) = 2^(-ΔCt(2A-2B))/2^(-ΔCt(ΔA-ΔB)).

Microarray analysis

Total RNA from WT or STAT3KO MEFs stimulated with or without 1000 U/ml IFN-α for 2 h was obtained using the TRizol reagent (Life Technologies), followed by cleanup and DNase I treatment with RQ1 RNase-free DNase (Fermentas), according to the manufacturer’s instruction. The quality of the RNA was evaluated using the Bioanalyzer 2100 (Agilent Technologies). The RNA samples were stored at −80°C until used for the microarray experiments. The CD1801A microarray (Agilent Technologies) was used to compare gene expression profiles at 2 h after IFN-α stimulation in the RNA samples. Gene expression was calculated using Illumina MouseWG-6 v1.1 Expression BeadChip. The complete dataset was available at National Center for Biotechnology Information GEO accession GSE25044 (http://www.ncbi.nlm.nih.gov/gds?term=GSE25044).

Western blot

Total cell lysates were prepared by lysing cells in lysis buffer (300 mM NaCl, 50 mM HEPES [pH 7.6], 1.5 mM MgCl2, 10% glycerol, 1% Triton X-100, 10 mM NaF, 20 mM Na3VO4, 1 mM EDTA, 0.1 mM PMSF, and 1 mM Na4VO3) at 4°C for 15 min. Lysates were first clarified by centrifugation at 12,000 × g for 20 min. Equal amounts of samples were resolved in 7–10% SDS-PAGE, followed by transferring to nitrocellulose or polyvinylidene difluoride membranes (Millipore) and blotting with indicated Abs.

In vitro antiviral assay and plaque formation assay

MEFs were pretreated with or without 2-fold serial dilution of IFN-α starting from 1000 to 1.8 U/ml for 24 h. EMCV at a multiplicity of infection (MOI) of 0.1 was added in the cells using serum-free DMEM for 45 min at 37°C. Viral supernatant was then removed, and the cells were washed and culture medium was added. Sixteen to 18 h postinfection, the medium was removed and cells were fixed with 10% formaldehyde solution for 20 min at room temperature. After fixation, cells were visualized with crystal violet. The excessive dye was then removed by immersing the plate in water. Each treatment was performed in duplicate. For plaque formation assay, different dilutions of supernatant from virus-infected cells (typically MEFs 16–18 h postinfection and BMMS 48 h postinfection) were used to infect vero cells in serum-free DMEM for 1 h, followed by overlaying 2% FBS in DMEM containing 1% SeaPlaque agarose (Lonza) to immobilize the virus. After 24 h, cells were fixed and visualized with crystal violet, and the plaques were enumerated.

Transfection and retroviral transduction of MEFs

Transfection of vector encoding different STAT3 into MEFs was done using Turbofect (Fermentas), according to manufacturer’s instruction. Retroviral transduction of MEFs was conducted, as described (28). Briefly, a retroviral vector Pallino encoding WT STAT3 and GFP, respectively, was cotransfected with a helper plasmid into HEK293T cells for 2 d before collecting the culture supernatant containing pseudotyped virus. MEFs were incubated with the viral supernatant in the presence of 8 μg/ml polybrene and spun at 1100 × g for 90 min at 30°C. Two days after the infection, GFP-positive cells were further purified up to 90–95% using the FACSAria cell sorting system (BD Biosciences).

Reporter assay

Luciferase assays for pISRE-luc (Strategene) containing 5′ ISRE from HLA4 gene were performed in duplicate by transfection into HEK293–TLR3 cells (a gift of K. Fitzgerald, University of Massachusetts) and STAT3KO MEFs in conjunction with different STAT3-expressing constructs using jetPEI (Polyplus-transfection) and Turbofect (Fermentas), respectively, according to manufacturer’s instruction. After transfection for 24–48 h, the cells were treated with or without various doses of human IFN-α2a (Roche) or mouse IFN-α (Merck) for 8 and 3 h, respectively, followed by measuring luciferase activities. Luciferase activities were measured according to manufacturer’s instructions (Promega) using Orion II microplate luminometer (Berthold).

Lentivirus-mediated knockdown of STAT3 and MDA5

The lentiviruses carrying short hairpin RNA (shRNA) targeting STAT3, MDA5, and luciferase were obtained from the National RNAi Core Facility located at the Institute of Molecular Biology/Genomic Research Center, Academia Sinica, Taiwan. The core facility is part of The RNAi Consortium. The sequence targeting mouse STAT3 is 5′-CGGTTGAGTT-TAATTCAGCTT-3′ (TRCN0000071456), MDA5 is 5′-CCACAGACAT- AGCACAAGTTG-3′ (TRCN0000103646), and a control construct targeting luciferase is 5′-GAGGAGGGAGG-3′. Viral supernatant was used to infect 1 × 105 MEFs at a MOI of 2. Lentivirus production and infection procedures were as described in the Web site (http://rnci.genmed.sinica.edu.tw/Protocols.asp). Following infection, the cells were cultured in a selection medium containing 5 μg/ml puromycin for 5 d to enrich infected cells before experiments were performed.

Statistical analysis

Unless otherwise indicated, all experiments were performed in triplicates. A Student t test (two tailed) was performed for statistical analysis. *p < 0.05, **p < 0.01.

Results

STAT3 knockdown in WT MEFs results in enhanced type I IFN response

To study the role of STAT3 in type I IFN response, STAT3 was knocked down in WT MEF using lentivirus carrying shRNA to STAT3, shRNA to fireely luciferase was used as a control. As shown in Fig. 1A, following short hairpin STAT3 (shSTAT3) treatment, STAT3 protein levels were reduced to ~40% that of

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shLuc control. Moreover, basal and IFN-induced STAT3 phosphorylation at Y705 was also greatly reduced as compared with that of control, whereas the levels of pSTAT1 (pY701) and pSTAT2 (pY689) remained comparable. We next examined the effect of STAT3 knockdown on expression of ISGs. As shown in Fig. 1B–D, following stimulation, the expression of PKR, OAS, and IRF1 was increased in cells treated with shSTAT3 as compared with that of shLuc control. We next investigated whether IFN-mediated antiviral activity was affected or not by the treatment. As shown in Fig. 1E, antiviral response in STAT3 knockdown cells was greater than that of control cells, revealed by the increased resistance of lytic activity of EMCV following infection. Together, these results suggest that STAT3 may have a negative effect on IFN response.

STAT3KO MEFs and macrophages display enhanced type I IFN response

We next confirmed the suppressive effect of STAT3 using MEFs lacking STAT3. As shown in Fig. 2A and 2B, following IFN-α treatment, STAT3KO MEFs expressed higher basal and induced levels of PKR and OAS than did WT MEFs. A similar phenomenon was also observed in other IFN-α downstream genes, such as RNase L, IRF7, IRF1, and IP-10 (data not shown). We next employed DNA microarray to conduct a genome-wide expression profiling for WT and STAT3KO MEFs in response to IFN-α. Expression of a variety of ISGs was also increased in STAT3KO MEFs as compared with WT MEFs (Supplemental Table 1; GEO GSE25044, http://www.ncbi.nlm.nih.gov/gds/?term=GSE25044), suggesting that the hyperresponsiveness of IFN-α in STAT3KO MEFs and macrophages display enhanced type I IFN response.

FIGURE 1. STAT3 knockdown enhances type I IFN response. A. WT MEFs infected with lentivirus carrying shLuc or shSTAT3 were stimulated with or without 1000 U/ml IFN-α for 15 min. Total cell lysates were subjected to immunoblotting using Abs to pSTAT1, pSTAT2, pSTAT3, STAT3, and tubulin. Total RNA from the cells received the same treatments, as described in A, for different times was subjected to RT-QPCR using primers for PKR (B), OAS (C), IRF1 (D), and β-actin. Relative mRNA was calculated by normalizing the values of the indicated genes to that of β-actin. E. WT MEFs infected with lentivirus-shLuc (upper) or lentivirus-shSTAT3 (lower) were pretreated with or without 2-fold serial dilution of IFN-α starting from 125 U/ml. Following the treatment, the cells were infected with or without EMCV at a MOI of 0.1 for 16 h, followed by visualizing the viable cells with crystal violet. *p < 0.05, **p < 0.01.

FIGURE 2. STAT3 knockout enhances IFN-α response. Total RNA prepared from WT (filled) or STAT3KO (open) MEFs that were stimulated with or without 1000 U/ml IFN-α for 2 h was subjected to RT-QPCR using primers for PKR (A), OAS (B), and β-actin. Total RNA prepared from BMMs of WT (filled) or STAT3KO (open) mice that were stimulated with or without 100 U/ml IFN-α for 4 h was subjected to RT-QPCR using primers for PKR (C) and iNOS (D). Relative mRNA was calculated by normalizing the values of the indicated genes to that of β-actin. E. WT (upper), STAT1KO (middle), and STAT3KO (lower) MEFs pretreated overnight with 2-fold serial dilution of IFN-α from 1000 U/ml were infected with EMCV at a MOI of 0.1 for 18 h, followed by visualizing live cells with crystal violet. WT (filled) and STAT3KO (open) MEFs pretreated with the indicated doses of IFN-α were infected with EMCV (F) or vesicular stomatitis virus (G) at a MOI of 0.1 for 12 and 18 h, respectively, followed by measuring viral titers in the culture supernatant using plaque formation assay. *p < 0.05, **p < 0.01.
cells was a general phenomenon. We next examined IFN response in primary BMMs. As shown in Fig. 2C and 2D, STAT3KO BMMs also showed enhanced expression of PKR and iNOS following IFN stimulation. We next examined STAT activation in MEFs following IFN treatment. As shown in Supplemental Fig. 1, whereas activation of STAT1 and STAT2 was marginally increased in STAT3KO MEFs as opposed to WT MEFs, STAT1 activation was, however, comparable between STAT3KO and WT BMMs.

Due to STAT3KO MEFs showing a greater IFN response, we next investigated whether IFN-mediated antiviral activity was also enhanced. WT and STAT3KO MEFs were pretreated with or without 2-fold serial dilution of IFN-α, followed by infection with EMCV. Additionally, we also included STAT1KO MEFs as a control. As shown in Fig. 2E, increased doses of IFN-α reduced the lytic activity of EMCV in WT MEFs, indicating that IFN-α conferred antiviral response in a dose-dependent manner. However, the activity was dramatically abolished in STAT1KO MEFs, confirming a pivotal role of STAT1 for IFN-mediated innate immunity to viral infection (5, 7). By contrast, STAT3KO MEFs displayed an enhanced antiviral response, as revealed by increased resistance to EMCV-induced lytic activity. We next investigated whether the increased survival of STAT3KO MEFs was accomplished by reduced viral titers. Indeed, STAT3KO MEFs reduced EMCV viral titers before and after IFN-α treatment (Fig. 2F). This result was consistent with the enhanced antiviral state in STAT3KO MEFs. In addition to EMCV, STAT3KO MEFs also exerted a greater antiviral activity against vesicular stomatitis virus infection than did their WT counterparts (Fig. 2G) in response to IFN-α. Together, these results suggest that STAT3 suppresses type I IFN-mediated antiviral response.

Restoration of STAT3 reverses the otherwise enhanced type I IFN response in STAT3KO MEFs

To examine whether the enhanced IFN response in STAT3KO cells was intrinsic to the loss of STAT3, we restored STAT3 into STAT3KO MEFs by retroviral transduction. The levels of restored STAT3 were slightly lower than that of WT cells (data not shown). However, whereas re-expression of STAT3 did not change the levels of IFN-β-activated pSTAT1 or pSTAT2 (Fig. 3A), it attenuated IFN-α–stimulated expression of PKR and OAS (Fig. 3B, 3C).

We next determined the effect of gain of function of STAT3 in antiviral response. Compared with that restored with the empty vector, STAT3-restored cells showed increased lytic activity and viral titers (Fig. 3D, 3E). Similar results were also observed in WT MEFs when STAT3 was hyperactivated by cotreatment of IFN-α and IL-6 (data not shown). Taken together, these results suggest that enhanced gene expression and antiviral activity of type I IFN in STAT3KO MEFs are intrinsic to the loss of STAT3.

Increased expression of type I IFNs in STAT3KO cells during viral infection

During viral infection, the binding of viral components to pattern recognition receptors triggers the production of type I IFNs, which in turn activates STAT proteins. Therefore, we next examined the role of STAT3 in viral infection in the absence of exogenous IFN-α. We first assessed STAT activation as an indicator of IFN-α signaling. As shown in Fig. 4A, at MOI of 0.1, EMCV infection failed to induce detectable tyrosine phosphorylation of STAT1 and STAT2 in WT MEFs, which might be due to an insufficient amount of type I IFN production. By contrast, the levels of pSTAT1 and pSTAT2 were increased in STAT3KO MEFs following the infection for 6 h. Concomitantly, infection-induced PKR expression was also augmented in STAT3KO MEFs as compared with WT MEFs (Fig. 4B). We next investigated whether the enhanced STAT activation in STAT3KO MEFs was due to increased production of type I IFNs during viral infection. As shown in Fig. 4C, STAT3KO MEFs expressed higher levels of IFN-β mRNA than did WT MEFs after the infection. A similar phenotype was also observed in primary BMMs. The levels of pSTAT1 (Fig. 4D) and the expression of ISGs, including PKR (Fig. 4E), OAS, iNOS, IRF1, IRF7, and TLR3 (Supplemental Fig. 2A–E), were also enhanced in STAT3KO BMMs after the infection. Additionally, STAT3KO BMMs also expressed significantly higher levels of IFN-β mRNA (Fig. 4F) and IFN-α protein (Fig. 4G) than did WT BMMs upon infection.

We next investigated whether the increased production of type I IFNs contributed to the enhanced activation of STAT1 and STAT2 in STAT3KO MEFs after the infection. STAT3KO MEFs were first pretreated with a neutralizing Ab to IFN-α/β receptor 1 (IFNAR1), followed by infection with EMCV. As shown in Supplemental Fig. 2H, the anti-IFNAR1 Ab attenuated pSTAT1 and pSTAT2 levels in STAT3KO MEFs, suggesting that virus-induced type I IFNs facilitate the enhancement of IFN-α signaling in STAT3KO cells.

MDA5 knockdown impedes enhanced antiviral response in STAT3KO cells

RIG-I and MDA5, two RLR family members of cytosolic sensors of viral RNA, are themselves IFN inducible (29, 30). We reasoned that STAT3 might indirectly regulate antiviral response through modulating the expression of these two molecules. As shown in Fig. 5, STAT3KO MEFs (Fig. 5A, 5B) and BMMs (Supplemental Fig. 2F, 2G) expressed higher levels of MDA5 and RIG-I than did FIGURE 3. Restoration of STAT3 to STAT3KO MEFs reduces type I IFN response. A, Empty vector (EV)- or STAT3-restored STAT3KO MEFs were treated with 20 ng/ml IFN-β for 30 min. Total cell lysates were then subjected to immunoblotting using Abs to pSTAT1, STAT1, pSTAT2, STAT3, and tubulin. Total RNA prepared from EV-restored (open) or STAT3-restored (filled) STAT3KO MEFs that were treated with or without 1000 U/ml IFN-α for 2 h was subjected to RT-QPCR using primers for PKR (B), OAS (C), and β-actin. Relative mRNA was calculated by normalizing the values of the indicated genes to that of β-actin. D, EV- or STAT3-restored STAT3KO MEFs pretreated overnight with 2-fold serial dilution of IFN-α from 1000 U/ml were infected with EMCV at a MOI of 1 for 24 h, followed by visualizing live cells with crystal violet. E, Supernatants of EV (open)- or STAT3-restored (filled) STAT3KO MEFs that were pretreated with the indicated doses of IFN-α, followed by EMCV infection for 24 h, were subjected to plaque formation assay to determine the viral titers. **p < 0.01.
WT controls following EMCV infection. Although MDA5 has been shown to play a critical role in clearance of EMCV infection (31), its effector function in the absence of STAT3 remained to be verified. Therefore, we first overexpressed MDA5 in STAT3KO MEFs. As shown in Fig. 5C–E, increased MDA5 accentuated infection-induced IFN-α expression and antiviral activity. We next confirmed the role of MDA5 in STAT3KO MEFs by a knockdown approach using lentivirus carrying shRNA to MDA5. To rule out off-target effects, shRNA to luciferase was used as a control. As shown in Fig. 5F, whereas the expression of MDA5 was further induced by IFN-α treatment, short hairpin MDA5 (shMDA5), but not shLuc, greatly reduced the protein levels of MDA5. Interestingly, shMDA5 treatment resulted in decreased IFN-α expression (Fig. 5G), increased EMCV infection, as revealed by elevated viral RNA (Fig. 5H), and increased lytic activity of EMCV (Fig. 5I) in STAT3KO MEFs. These results suggest that increased MDA5 expression contributes to enhanced type I IFN response in STAT3KO MEFs.

**STAT3 suppresses type I IFN response independent of its DNA-binding and transactivation ability**

To investigate whether the suppressive effect of STAT3 on IFN-α response requires de novo protein synthesis, we pretreated cells with cycloheximide (CHX). As shown in Fig. 6, CHX pretreatment could not block the enhanced expression of PKR and OAS in STAT3KO MEFs (Fig. 6A,6B) and elevated expression of PKR and iNOS in STAT3KO BMMs (Fig. 6C,6D) in response to IFN-α. Although these results suggest that the suppressive effect of STAT3 is independent of its downstream effector molecules, we still cannot rule out the possibility of involvement of CHX-sensitive inhibitors of IFN-α response. Therefore, we next...
performed reporter assays to examine whether STAT3 was able to suppress IFN-driven transactivation activity. Expression of WT STAT3 suppressed IFN-driven ISRE reporter activity in a dose-dependent manner (Fig. 6E). Interestingly, both DBD mutant of STAT3 and STAT3β were also capable of suppressing the reporter activity (Fig. 6F), suggesting that DNA-binding and transactivation ability of STAT3 were not required for the suppressive effect. To dissect further the functional domains of STAT3 required for the effect, different truncation mutants of STAT3 were used. As shown in Fig. 6G, 1–134 aa (NTD only) or 1–317 aa of STAT3 (NTD and CCD) remained the inhibitory activity, whereas the activity was almost abolished in cells expressing STAT3 318–770 aa lacking NTD and CCD. These results suggest that STAT3 NTD is sufficient to confer the suppressive activity. These results are also consistent with the dispensable role of DNA-binding and transactivation ability of STAT3. Taken together, these results suggest that STAT3 may directly suppress type I IFN response, and the effect is independent of its DNA-binding and transcriptional function.

**NTD of STAT3 is sufficient to suppress type I IFN response**

To further confirm the antagonistic effect of STAT3 1–134 aa, we restored HA-tagged WT or STAT3 1–134 aa into STAT3KO MEFs. As shown in Fig. 7A, the expression of WT or mutant STAT3 was detected by anti-HA Ab. STAT3 1–134 aa exerted almost the same inhibitory activity as did WT STAT3 in reporter...
Discussion

This work highlights a previously unappreciated role of STAT3 in type I IFN response. Using loss- and gain-of-function approaches, we demonstrated that STAT3 negatively regulates type I IFN-mediated responses. Whereas knockdown or knockout of STAT3 resulted in enhanced ISG induction and antiviral activity in response to type I IFNs, restoration of STAT3 in STAT3KO MEFs attenuated the response. Interestingly, viral infection of STAT3KO cells induced higher levels of type I IFN expression and activation of STAT1 and STAT2, leading to the expression of elevated levels of ISGs, including a viral sensor MDA5. The results of MDA5 overexpression and knockdown experiments suggest a positive role of MDA5 in regulating type I IFN production and antiviral response in the absence of STAT3. In addition, our truncation experiment showed that STAT3 1–134 aa is sufficient to confer antagonism of IFN response, demonstrating that the inhibitory effect of STAT3 on type I IFN response is independent of its DNA-binding and transcriptional activity. Taken together, we demonstrated that STAT3 suppresses antiviral response through directly regulating IFN response and inducing viral sensors and IRFs during viral infection.

A negative role of STAT3 in type I IFN response is reported recently. Ho and Ivashkov (15) showed that overexpression of STAT3 in THP-1 cells downregulated IFN-α-activated, STAT1-dependent genes such as IRF-1, CXCL9, and CXCL10, and knocking down STAT3 led to elevated expression of the same set of genes. Conversely, IFN-α-activated STAT3 supported ISRE-driven genes such as OAS and Mx2. Enhanced STAT3 expression did not affect tyrosine phosphorylation or nuclear translocation of STAT1; instead, it sequestered STAT1 and suppressed the formation of DNA-binding STAT1 homodimers. Contrary to their findings, we showed that STAT3 negatively regulated ISRE-driven genes, including OAS, PKR, and IRF7. The discrepancy between our system and theirs remains unclear. It could be that we addressed the role of STAT3 in mouse MEFs and BMMs, whereas Ho and Ivashkov studied STAT3 in human monocytic cell line. The advantage of studying STAT3 in mouse cells is that we could apply both knockdown and knockout technologies to ensure consistent results. Concerning the suppressive mechanism of STAT3, we showed that STAT3 1–134 aa is sufficient to antagonize IFN response, suggesting that competition for dimer formation with STAT1, requiring Src homology 2 domain, is not involved. Therefore, the sequestration mechanism does not seem to operate in our system.

In most biological responses, STAT3 acts as a positive regulator (6). However, we and others have shown that STAT3 also acts as a negative regulator for G-CSF–mediated granulopoiesis (19, 32). As such, excessive granulocytes are produced in the bone marrow and periphery in mice lacking STAT3 in the hematopoietic system. Reduced expression of suppressor of cytokine signaling 3, a potent negative regulator, in STAT3KO bone marrow in response to G-CSF is shown to account for the hyperproliferative activity of the cells (33, 34). STAT3 also functions as a negative regulator of TLR-mediated inflammatory response (35–37). Mice devoid of STAT3 in macrophages and neutrophils are highly susceptible to LPS-induced endotoxic shock with increased production of inflammatory cytokines. This is due to the lack of suppressive effect of IL-10 on cytokine production from macrophages and neutrophils in the absence of STAT3 (38). The results of this study define a new negative role of STAT3 in IFN-mediated functions and provide another mechanism to fine-tune type I IFN response. Additionally, they underscore a potential therapeutic target of STAT3 for viral infections.

Acknowledgments

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Disclosures

The authors have no financial conflicts of interest.

References


Corrections


In *Materials and Methods*, the primer sequences of IFN-β provided in the *Quantitative RT-PCR* section should read “forward 5’-ATGAGTGGTGTTGCAGGC-3’, reverse 5’-TGACCTTTCAATGCAGTAGATTCA-3’”.

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Table 1. List of genes with greater than 3-fold changes (in STAT3KO MEF) in response to IFNα*

<table>
<thead>
<tr>
<th>Gene name</th>
<th>Fold change (ST3KO/IFN vs ST3KO)</th>
<th>Fold change (WT/IFN vs WT)</th>
<th>Description</th>
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<tr>
<td>VIPERIN</td>
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<td>16.8</td>
<td>IFN-inducible antiviral protein</td>
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<td>44.9</td>
<td>8.1</td>
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<td>ISG15-specific protease</td>
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<td>MX2</td>
<td>30.3</td>
<td>3.2</td>
<td>Antiviral GTPase</td>
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* RNA prepared from WT or STAT3KO MEFs that were treated without or with IFNα 1000 U/ml for 2 h was subjected to expression microarray analysis using Illumina MouseWG-6 v1.1 Expression BeadChip.

The microarray data has been deposited to GEO accession # GSE25044.

Fig. S1

Fig. S1 Activation of STATs in WT and STAT3KO cells in response to IFN. WT (left) or STAT3KO (right) MEFs (A) or BMMs (B) were treated with IFNα 1000 U/ml and 100 U/ml, respectively, for the indicated times. Total cell lysates were subjected to immunoblotting using antibodies to pSTAT1, pSTAT2, pSTAT3, STAT1, STAT2, STAT3 and tubulin for MEFs and pSTAT1, STAT1 and tubulin for BMMs.
Fig. S2

A. OAS

B. iNOS

C. IRF1

D. IRF7

E. TLR3

F. MDA5

G. RIG-I

H. IFNAR1 Ab

Fig. S2 Increased expression of IFN downstream genes in STAT3KO BMMs after EMCV infection. WT (solid) or STAT3KO (empty) BMMs were infected with EMCV at an MOI of 10 for the indicated times. RNA prepared from the cells was subjected to RT-QPCR using primers for OAS(A), iNOS(B), IRF1 (C), IRF7(D), TLR3(E), MDA5(F), RIG-I(G) and β-actin. Relative mRNA was calculated by normalizing the values of specific genes to that of β-actin. (H) STAT3KO (right) MEFs were pretreated without or with anti-IFNAR1 antibody 1 µg/ml, followed by infection with EMCV at an MOI of 0.1 for the indicated times. Total cell lysates were then subjected to immunoblotting using antibodies to pSTAT1, pSTAT2 and tubulin. h.p.i. hour post-infection