Simian Virus 40 Large T Antigen Induces IFN-Stimulated Genes through ATR Kinase

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Simian Virus 40 Large T Antigen Induces IFN-Stimulated Genes through ATR Kinase

Adriana Forero,*† Nicholas S. Giacobbi,‡ Kevin D. McCormick,*† Ole V. Gjoerup,*†,1 Christopher J. Bakkenist,‡ James M. Pipas,‡ and Saumendra N. Sarkar*†

Polymaviruses encode a large T Ag (LT), a multifunctional protein essential for the regulation of both viral and host cell gene expression and productive viral infection. Previously, we have shown that stable expression of LT protein results in upregulation of genes involved in the IFN induction and signaling pathway. In this study, we focus on the cellular signaling mechanism that leads to the induction of IFN responses by LT. Our results show that ectopic expression of SV40 LT results in the induction of IFN-stimulated genes (ISGs) in human fibroblasts and confers an antiviral state. We describe a LT-initiated DNA damage response (DDR) that activates IFN regulatory factor 1, causing IFN-β production and consequent ISG expression in human cells. This IFN-β and ISG induction is dependent on ataxia-telangiectasia mutated and Rad3-related (ATR) kinase, but independent of ATM. ATR kinase inhibition using a selective kinase inhibitor (ETP-46464) caused a decrease in IFN regulatory factor 1 stabilization and ISG expression. Furthermore, expression of a mutant LT that does not induce DDR also does not induce IFN-β and ISGs. These results show that, in the absence of viral infection, LT-initiated activation of ATR-dependent DDR is sufficient for the induction of an IFN-β-mediated innate immune response in human cells. Thus, we have uncovered a novel and critical role for ATR as a mediator of antiviral responses utilizing LT. The Journal of Immunology, 2014, 192: 5933–5942.

The polyomavirus (PyV) family consists of small dsDNA viruses that infect a wide variety of hosts. Infection with PyV is ubiquitous among the human population and generally results in subclinical infections in healthy hosts. However, upon the onset of AIDS-related, age-related, and iatrogenic immune suppression, manifestations of clinical diseases associated with viral infection become apparent (1–3). To date, there are few successful therapies for the treatment of human PyV-related diseases. Thus, understanding the interactions between the virus and the host response to viral infection is crucial for the development of new effective therapies.

The wealth of knowledge of PyV biology has stemmed from studies utilizing the prototypic virus, SV40. SV40 encodes early proteins, large T Ag (LT), small t Ag, 17k T (early region), and late proteins with structural and auxiliary functions. The SV40 LT is a well-studied multifunctional protein that controls viral DNA replication, host cell proliferation, and gene expression, thereby promoting cellular transformation. These functions are largely mediated by interactions between LT and numerous cellular proteins (4). Identifying the cellular processes targeted by LT is crucial for understanding the pathogenesis of PyV and their transformative phenotype.

Genotoxic stress triggers a signaling cascade, called DNA damage response (DDR), mediated by the kinases ataxia-telangiectasia mutated (ATM) and ATM and Rad3-related (ATR) (5). Activation of these kinases by dsDNA breaks and ssDNA gaps, respectively, results in the induction of the checkpoint proteins and modifications of many other proteins implicated in DNA repair to maintain genome integrity and cell survival (6). Multiple studies have provided evidence that infection with mouse PyV virus (7), JC PyV (8), BK PyV (9), and SV40 (10–14) causes the activation of DDR to augment viral genome replication. It has also been shown that expression of SV40 LT protein alone is sufficient to activate both ATM and ATR in cells (12). However, the cellular consequences of this DDR activation are not completely understood.

Detection of viral infection triggers cytoplasmic and nuclear sensors that initiate a signaling cascade that results in the induction of type I IFN and the expression of IFN-stimulated genes (ISGs). The ISGs have antiviral effector functions that limit the replication of viral genomes, inhibit protein synthesis, and promote cell death (15). Previously, using mouse genome-wide arrays, we reported that SV40 LT expression results in a tissue-specific induction of ISGs (16). Although this phenomenon was dependent on various domains of LT (17), it was surprising to find ISG induction in the absence of an active virus infection. Furthermore, the host factors responsible for this phenomenon remained elusive.

In this study, we have examined the cellular signaling pathways that are responsible for the SV40 LT-mediated induction of ISGs in human fibroblasts. LT expression induced upregulation of IFN regulatory factor (IRF)1 protein, causing transcription and secre-
tion of IFN-β and its downstream genes through IFN receptor signaling. Furthermore, we showed that the induction of DDR by LT is needed to induce the expression of IRF1, in an ATR kinase activity-dependent manner. Therefore, our data provide a clear mechanistic link between the DDR with the regulation of IFN responses and the induction of innate immune gene expression in the absence of viral infection.

Materials and Methods

Cells and reagents

HEK293T (Invitrogen, Carlsbad, CA; catalogue R700-07) cell lines were cultured in DMEM (Lonza, Basel, Switzerland) supplemented with 10% FBS (Atlanta Biologicals, Flowery Branch, GA) and 100 IU/ml penicillin and 100 mg/ml streptomycin (Pen/Strep; Lonza). BJ/TERT cells (12) and derived cell lines were cultured in DMEM with 20% medium 199 (Invitrogen, Carlsbad, CA), 10% FBS, and Pen/Strep. Primary human foreskin fibroblasts were purchased from Lonza and cultured, as per manufacturer’s instructions.

Hexydimethrine bromide (polybrene), cycloheximide (CHX), and Chk1 kinase inhibitor, UCN-01, were purchased from Sigma-Aldrich (St. Louis, MO). Blasticidin and puromycin were obtained from Inviogen (San Diego, CA). ATM kinase inhibitor, KU-60019, was obtained from Astra Zeneca (London, U.K.). ATR kinase inhibitor ETP-46464 was previously described (18). DMSO (Fisher Scientific, Pittsburgh, PA) was used as vehicle control.

The following Abs were used in this study for immunoblot analysis (19): SV LT (pAb 416 and 419) (12), ISG56 and ISG56 (20), Sendai virus C protein (21), and OASL (Abgent, San Diego, CA); IRF1, IRF7, IRF9, GFP, phospho-p53 (serine 15), p53 (DO1), actin, and tubulin (Santa Cruz, Dallas, TX); and total STAT1, phospho-STAT1 Y701, and phospho-STAT1 S727 (Cell Signaling, Danvers, MA).

Plasmids and viruses

Retroviral plasmids pLBNCX and pLBNCX-LT and plasmid pCMV-LT encoding SV40 LT cDNA have been previously described (12, 22). Plasmids pCDNA3.1/His/AhuIRF1, pCMV-FLAG-IRF7, and pCMV-p48 have been previously described (23, 24). Short hairpin RNA (shRNA) lentiviral vectors targeting IRF1 (TRCN0000014669), IFNAR1 (TRCN0000059017), and scrambled control were purchased from Sigma-Aldrich. Vesicular stomatitis virus (VSV)-GFP (25) was grown in BHK21 cells. Encephalomyocarditis virus (EMCV), obtained from American Type Culture Collection (VR-1479, Manassas, VA), and HSV-1 (K26) (26) were grown in vero cells. Sendai virus (Cantell strain) was purchased from Charles River Laboratories (Wilmington, MA). Multiplicity of infection (m.o.i.) and virus titer were determined in their respective producer cell lines.

Retroviral and lentiviral vectors

Retroviral vectors pLBNCX and pLBNCX-LT were transfected into (1 × 10^6) packaging cell line (293-Ampo) using Fugene 6 (Roche, Mannheim, Germany) following manufacturer’s guidelines and processed, as previously described (10). pLKO.1 shRNA delivery lentiviral vectors were packaged, as previously described (19). BJ/TERT-derived pLKO.1 cells were generated by overnight lentiviral infection with virus packaged from pLKO.1 vectors in the presence of 8 μg/ml polybrene. Forty-eight hours postinfection, cells were selected with 1 μg/ml puromycin for 7 d.

Luciferase reporter assays

HEK293T cells were used for luciferase assays, as previously described (19). BJ/TERT LT cells were transfected with 1 μg pGL3 basic or pLIFNβ2β+Luc plasmid using Lipofectamine 2000 (Invitrogen), and luciferase activity was assessed by dual luciferase assay (Promega, Madison, WI).

Quantitative PCR analysis of gene expression

Total RNA was extracted, and cDNA was prepared and subjected to real-time PCR, as previously described (19). Primers used for target gene amplification can be provided upon request.

Viruses and viral infections

For microscopy experiments, BJ/TERT vector or LT cells were seeded in a laboratory-tek II chamber slide (part 154534) and infected with VSV-GFP at 1 m.o.i. Cells were washed with PBS after 24 h infection and fixed in 4% paraformaldehyde, followed by washing mounting in Vectashield (Vector Laboratories, Burlingame, CA) containing DAPI. To determine viral protein expression and viral growth, BJ/TERT vector or LT cells were infected with VSV-GFP (m.o.i. 1), HSV-1 (K26) at a m.o.i. 5, or EMCV (m.o.i. 5). Infected cell supernatants were harvested at the indicated time points and kept at −80°C until further use. Infectious virus production was measured by plaque assay and reported as PFU/ml. Alternatively, BJ/TERT LT cells were pretreated with CHX (50 ng/ml), washed twice with PBS, and incubated with 4 μM ETP-46464 or DMSO for 3 h prior to infection with EMCV (m.o.i. 50). Virus growth was quantified by plaque assay on Vero cells and expressed as PFU/ml. Cellular viability was determined by crystal violet staining.

IFR3 dimerization assays

BJ/TERT, BJ/TERT VECTOR, and BJ/TERT LT cells (1 × 10^6) were plated in 10-cm plates. BJ/TERT cells were infected with 300 hemagglutinating units/ml Sendai virus (SeV) for 8 h. Cells were washed with PBS and lysed in 70 μl lysis buffer (50 mM Tris-HCl [pH 7.5], 150 mM NaCl, 1 mM EDTA, 1% Nonidet P-40, 2 mM NaVO3, 10 mM NaF, and 12 mM β-glycerophosphate). Lysates were then diluted in equal volumes of PAGE loading buffer (2×), resolved by native PAGE and blotted using anti-IRF3 Ab, as previously described (20).

Results

SV40 LT induces ISG expression

Previous studies that examined global changes in gene expression induced by the SV40 early region identified a significant number of ISGs upregulated in mouse embryonic fibroblasts (17). To confirm whether LT alone can induce ISG without small t in human cells, we used retroviral transduction to generate immortalized human fibroblasts (BJ/TERT) stably expressing LT cDNA or empty vector (LBNCX). Expression of LT resulted in an increase in the protein levels of ISG60 (IFIT3) and the related protein ISG56 (IFIT1). Furthermore, another ISG, OASL, was upregulated in LT-expressing cells (Fig. 1A). The increase in protein synthesis was accompanied by an increase in ISG56, ISG60, and OASL mRNA transcription, suggesting that LT stimulates the transcription of these genes (Fig. 1B). Moreover, ISGs identified in the mouse genome arrays, Cig5, ISG15, and PKR, were also induced in human cells (Fig. 1B). To determine whether the ISG induction by LT is independent of telomerase (TERT) expression and immortalization, we expressed LT in primary human fibroblasts. Similar to BJ/TERT cells, ISG60 and OASL protein expression (Fig. 1C) and concomitant transcriptional upregulation (Fig. 1D) were observed with LT expression in primary human fibroblasts.

ISG expression generates an antiviral state

Given the strong upregulation of ISGs, we investigated whether LT expression protected fibroblasts from viral infection. BJ/TERT cells were infected at a m.o.i. of 1 with vesicular stomatitis virus (VSV-GFP), a (−) ssRNA virus, and incubated for 24 h following infection. Fluorescence microscopic analysis at 24 h post-infection showed readily detectable GFP expression in empty vector-expressing cells and VSV-induced cytopathic effects, but no detectable GFP expression or cytopathology in cells stably expressing LT (Fig. 2A). Similarly, immunoblot analysis of GFP expression in VSV-GFP–infected cells showed a marked decrease in GFP in cells expressing LT (Fig. 2B). The decrease in viral protein synthesis was also observed postinfection with SeV, another (−) ssRNA virus. BJ/TERT LT cells infected with SeV for 24 h failed to synthesize the major capsid protein (C protein), confirming that LT expression restricts viral protein synthesis upon RNA virus infection (Fig. 2B). To examine the overall effect on virus replication, BJ/TERT-expressing LT and vector control cells were infected with VSV and EMCV, a (+) ssRNA virus, and viral growth was assessed, as indicated. The growth of VSV (Fig. 2C) and EMCV (Fig. 2D) was severely impaired in cells expressing LT. We also tested LT-mediated inhibition of a dsDNA virus, HSV-1, and saw a 2-log reduction in virus production relative to control cells.
LT-mediated IFN synthesis pathway in contrast to the upregulation controlled by the same factor involved in the early phase of the right

Downregulation of IFNAR1 resulted in enhanced IFN-β protein is involved in the induction of ISGs in human cells. responsive gene, MxA mRNA (Fig. 3D), indicating that a type I IFNAR1 resulted in a decrease in ISG60, OASL, and the IFN-β expression of LT resulted in increased ISG mRNA expression in BJ/TERT cells, which fail to induce ISG expression after stimulation with type I IFN (Supplemental Fig. 1). As expected, in BJ/TERT cells stably expressing SV40 LT cDNA or empty vector. ISG60 and OASL mRNA was measured by qRT-PCR. Expression of mRNA was normalized to RPL32 and expressed as fold change compared with empty vector-expressing cells (value 1).

In the context of a viral infection, the induction of ISGs generally follows nucleic acid sensing by cytoplasmic and nuclear receptors, which activate IRF3 and induce IFN-β and ISGs. IFNs then bind to the IFN receptor, IFNAR1, activating the JAK/STAT signaling pathway. This results in the phosphorylation of STAT1 at Tyr 701 (Fig. 3B) and Ser 727 (Fig. 3C). These observations showed that LT cDNA is not only sufficient to induce STAT1 protein expression (Fig. 3A), but also enhances its phosphorylation at Tyr 701 (Fig. 3B) and Ser 727 (Fig. 3C). These observations suggest that the expression of LT induces IFN signaling. To confirm that the induction of ISGs in human fibroblasts is mediated by IFN signaling, we examined the effect of IFNAR1 knockdown in BJ/TERT cells, which fail to induce ISG expression after stimulation with type I IFN (Supplemental Fig. 1). As expected, expression of LT resulted in increased ISG mRNA expression in cells expressing a nontargeting shRNA. The downregulation of IFNAR1 resulted in a decrease in ISG60, OASL, and the IFN-responsive gene, MxA mRNA (Fig. 3D), indicating that a type I IFN protein is involved in the induction of ISGs in human cells.

The ectopic expression of LT resulted in the stimulation of IFN-β transcription in cells expressing the scrambled shRNA control. Downregulation of IFNAR1 resulted in enhanced IFN-β expression, most likely due to the lack of a negative feedback loop required to dampen its induction (Fig. 3E, left). The transcription of ISG15 followed the same pattern of expression as IFN-β (Fig. 3E, right), suggesting that transcriptional activation of both genes is controlled by the same factor involved in the early phase of the LT-mediated IFN synthesis pathway in contrast to the upregulation of ISG60, OASL, and MxA, which is largely dependent on IFNAR1-mediated signaling. Finally, we verified the downregulation of IFNAR1 expression in short hairpin IFNAR1 cells expressing either the empty vector or LT. Whereas the expression of LT led to a slight increase in IFNAR1 mRNA expression, targeting of IFNAR1 with shRNA led to nearly 90% decrease in mRNA expression in both LBNCX- and LT-expressing cell lines (Fig. 3F). Together, the data suggest that, in human fibroblasts, LT activates cellular factors involved in the transcriptional upregulation of IFN-β, consequently inducing ISGs through IFNAR1.

**FIGURE 1.** SV40 LT induces ISGs. (A) Induction of ISG protein expression in human fibroblasts. Lysates were prepared from BJ/TERT cells transduced by retrovirus infection with SV40 LT cDNA or empty vector (LBNCX) and probed with Abs against LT, OASL, ISG56, ISG60, and actin. (B) Transcriptional induction of ISG in human fibroblasts. Total RNA was extracted from BJ/TERT cells stably expressing SV40 LT cDNA or empty vector (described above). OASL, ISG56, ISG60, Cig5, ISG15, and PKR mRNA were assessed by qRT-PCR. Expression of mRNA was normalized to the housekeeping gene RPL32 and expressed as fold change compared with empty vector-expressing cells (value 1). (C) Induction of ISG protein expression in primary human fibroblasts (HFF). Lysates were prepared from primary HFF cells transduced by retrovirus infection with SV40 LT cDNA or empty vector and probed with Abs against LT, OASL, ISG60, and actin. (D) Transcriptional induction of ISG60 and OASL in primary human fibroblasts. Total RNA was extracted from primary HFF cells stably expressing SV40 LT cDNA or empty vector. ISG60 and OASL mRNA was measured by qRT-PCR. Expression of mRNA was normalized to RPL32 and expressed as fold change compared with empty vector-expressing cells (value 1).
to the induction of IFN-β transcription. To determine whether the expression of LT induces the activation of IRF3, we examined the presence of IRF3 dimers in LT- and SeV-infected cells. Whereas IRF3 dimers were readily detected in BJ/TERT cells 8 h after SeV infection, the expression of LT or vector control failed to promote IRF3 dimerization (Fig. 4C). With the exception of IRF3, the induction of IRF protein synthesis acts as a regulatory step of their transcriptional activities. Analysis of IRF protein expression showed a significant increase in IRF1, IRF7, and IRF9 in cells expressing LT (Fig. 4D). However, the induction of IFN-β promoter activity by using transient transfection of the IFN-β125-luc in BJ/TERT cells and recorded a 10-fold increase in luciferase activity relative to the luciferase activity observed in pGL3-basic–transfected cells (Fig. 4E). To examine the effect of these proteins on IFN-β promoter activation, we cotransfected HEK293T cells with IRF1, IRF7, or IRF9 cDNA and IFNβ125-luc and pRL-null as transfection controls. As expected, expression of IRF1 resulted in a 5-fold induction in promoter activity relative to vector control-transfected cells (Fig. 4F). Furthermore, the expression of IRF9 did not significantly activate the IFN-β promoter activity, excluding the possibility that IRF9 is involved in the direct activation of IFN-β transcription in BJ/TERT LT cells.

IRF1 is required for the induction of IFN-β by LT in human fibroblasts

To determine whether either IRF1 or IRF7 is required for the induction of IFN-β by LT, we knocked down the expression of these genes by transfecting small interfering RNA (siRNA) targeting IRF1 or IRF7 into BJ/TERT LT cells. The downregulation of IRF1, specifically, was accompanied by a decrease in the expression of ISGs, as determined by the loss of OASL and ISG60 protein expression. Furthermore, the loss of IRF1 expression led to a decrease of IRF7, which not only regulates ISG expression but is also an IFN-β–responsive ISG (30). Knockdown of IRF7 did not affect the expression of either ISGs or IRF1 (Fig. 5A). The loss of ISG expression was due to a decrease in transcriptional activation of these genes as determined by the decrease in mRNA expression.

FIGURE 2. Expression of LT induces an antiviral state. (A) GFP expression in VSV-GFP–infected BJ/TERT cells. BJ/TERT cells expressing SV40 LT cDNA or vector control were infected with VSV-GFP (m.o.i. 1) for 24 h. GFP expression was detected by fluorescence microscopy (left), and cell morphology was examined by phase-contrast microscopy (middle). Nuclei were stained with DAPI (right). (B) Analysis of viral protein expression in infected BJ/TERT cells. BJ/TERT cells expressing SV40 LT cDNA or vector control were infected with VSV-GFP (m.o.i. 5) or SeV (200 hemagglutinating unit/ml) for 24 h. Lysates were prepared and probed with Abs against LT, GFP, and SeV C protein. (C) Analysis of VSV growth in BJ/TERT cells. BJ/TERT cells expressing SV40 LT cDNA or vector control were infected with VSV-GFP (m.o.i. 5). Supernatants were harvested at the indicated time points, and virus replication was measured by plaque assay on BHK21 cells. Virus growth is expressed as PFU/ml. (D) Analysis of EMCV growth in BJ/TERT cells. BJ/TERT cells expressing SV40 LT cDNA or vector control were infected with EMCV (m.o.i. 5). Supernatants were harvested at the indicated time points, and virus replication was measured by plaque assay on Vero cells. Virus growth is expressed as PFU/ml. (E) Analysis of HSV-1 growth in BJ/TERT cells. BJ/TERT cells expressing SV40 LT or vector control were infected with HSV-1 (K26-GFP) (m.o.i. 5). Supernatants were harvested at the indicated time points, and virus replication was measured by plaque assay on Vero cells. Virus growth is expressed as PFU/ml.
levels following the knockdown of IRF1. Downregulation of IRF1 in BJ/TERT LT cells also led to a reduction in IFN-β mRNA, explaining the concomitant loss of ISG expression. Again, IRF7 knockdown had no effect on the transcription of ISGs and resulted in a slight increase in IFN-β transcription. Cells were then selected with puromycin (1 μg/ml). Puromycin-resistant cells were then infected with a retrovirus encoding the SV40 LT cDNA or empty control (Vector) and selected for resistance to blasticidin (5 μg/ml). Total RNA was harvested, and expression of OASL, ISG60, and MxA mRNA was analyzed by qRT-PCR. Samples were normalized to RPL32 and expressed as fold change with respect to vector control cells (value 1). (E) Analysis of IFN-β and ISG15 induction in IFNAR1 knockdown cells. RNA was harvested from BJ/TERT cells expressing either empty vector or SV40 LT cDNA as well as a short hairpin targeting IFNAR1 (described above). Expression of IFN-β and ISG15 mRNA was analyzed by qRT-PCR. Samples were normalized to RPL32 and expressed as fold change with respect to vector control cells (value 1). (F) Validation of IFNAR1 knockdown in BJ/TERT cells. RNA was harvested from BJ/TERT cells expressing either empty vector or SV40 LT cDNA as well as a short hairpin targeting IFNAR1. Expression of IFNAR1 mRNA was analyzed by qRT-PCR. Samples were normalized to RPL32 and expressed as fold change with respect to vector control cells expressing the nontargeting shRNA (value 1).

ATR kinase activity is necessary for the induction of IRF1 and IFN-β

Expression of LT has been shown to induce DNA damage, and ATM and ATR kinase mediated DDR (8, 9, 12). Because the induction of a DDR has previously been associated with the accumulation of IRF1 protein (31), we examined whether the inhibition of either ATM or ATR kinase activity in cells stably expressing LT would cause a decrease in IRF1 and ISG expression. Treatment of BJ/TERT LT cells with a specific ATM kinase inhibitor, KU60019 (18, 32), did not affect the expression of either IRF1 or OASL as compared with controls. Treatment with ETP-46464, a specific ATR kinase inhibitor (18, 33), led to a dose-dependent decrease in OASL and IRF1 protein expression (Fig. 6A). Although LT is known to be phosphorylated by ATM (11), ATR kinase inhibition did not affect the LT protein stability (Fig. 6A, Supplemental Fig. 2). We validated ATM and ATR kinase inhibition by examining the phosphorylation p53 at Ser 15. Both KU60019 and ETP-46464 treatment led to a decrease in Ser15 phosphorylation without affecting the stability of p53 in BJ/TERT LT cells (Fig. 6B). To determine whether ATR kinase activity is involved in the transcriptional upregulation of IRF1, we quantified the levels of IRF1 mRNA after treatment of BJ/TERT

FIGURE 3. IFNAR-dependent and -independent induction of ISGs. (A–C) STAT1 activation in human fibroblasts by LT expression. BJ/TERT cells were transfected with SV40 early region or vector and placed under selection with puromycin (1 μg/ml) for 7 d. Whole-cell extracts were prepared from antibiotic-resistant cells. Lysates were probed with Abs against total STAT1 (A), STAT1 Y701 (B), STAT1 S727 (C), and GAPDH. (D) Analysis of ISG induction in IFNAR1 knockdown cells. BJ/TERT cells were infected with lentivirus encoding a short hairpin targeting IFNAR1 or scrambled control. Cells were then selected with puromycin (1 μg/ml). Puromycin-resistant cells were then infected with a retrovirus encoding the SV40 LT cDNA or empty control (Vector) and selected for resistance to blasticidin (5 μg/ml). Total RNA was harvested, and expression of OASL, ISG60, and MxA mRNA was analyzed by qRT-PCR. Samples were normalized to RPL32 and expressed as fold change with respect to vector control cells (value 1). (E) Analysis of IFN-β and ISG15 induction in IFNAR1 knockdown cells. RNA was harvested from BJ/TERT cells expressing either empty vector or SV40 LT cDNA as well as a short hairpin targeting IFNAR1 (described above). Expression of IFN-β and ISG15 mRNA was analyzed by qRT-PCR. Samples were normalized to RPL32 and expressed as fold change with respect to vector control cells (value 1). (F) Validation of IFNAR1 knockdown in BJ/TERT cells. RNA was harvested from BJ/TERT cells expressing either empty vector or SV40 LT cDNA as well as a short hairpin targeting IFNAR1. Expression of IFNAR1 mRNA was analyzed by qRT-PCR. Samples were normalized to RPL32 and expressed as fold change with respect to vector control cells expressing the nontargeting shRNA (value 1).
It has previously been reported that deletion (dl) of aa 89–97 in LT (dl89–97) results in the ablation of its binding to Bub1 and a reduction in the activation of DDR by LT (12). To provide genetic evidence to support the involvement of LT-mediated DDR in inducing IFN-β, we analyzed OASL and ISG60 protein expression in cells stably transduced with either full-length LT, dl89–97, or vector control (Fig. 6D). For dl89–97 mutant-expressing cells, we used two different batches of BJ/TERT cells, which were generated independently at two different times [dl89–97(I) and dl89–97(II)]. As previously observed, LT expression resulted in a robust induction of both ISG60 and OASL expression. However, dl89–97 expression resulted in attenuated ISG induction in both cell lines expressing dl89–97 (Fig. 6D, Suplemental Fig. 2). The reduction in ISG expression was accompanied by diminished IFN-β,

LT cells with KU60019 and ETP-46464. ATR kinase inhibition with ETP-46464 caused a decrease in the transcription of IRF1 mRNA, whereas ATM kinase inhibition with KU60019 had no effect on IRF1 mRNA expression. Likewise, ATR kinase inhibition led to a decrease in IFN-β mRNA levels, accounting for the decrease in both OASL mRNA and protein expression (Fig. 6C).

FIGURE 4. SV40 LT induces IFN-β expression. (A and B) SV40 LT induction of type I IFN mRNA. BJ/TERT cells were stimulated with 100 μg/ml poly(I:C) for 24 h or stably transduced with empty vector or SV40 LT cDNA by retroviral infection and blasticidin selection. Total RNA was extracted from 1 × 10^7 cells, and IFN-β (A) and Pan-IFN-α (B) mRNA levels were analyzed by qRT-PCR. mRNA expression was normalized to RPL32 and expressed as fold change relative to vector control-expressing cells (value 1). (C) IRS3 dimerization assay. Lysates were prepared from BJ/TERT cells stably expressing vector control, SV40 LT cDNA, or cells infected with 300 hemagglutinating units/ml for 8 h. Protein was resolved by native PAGE and probed with Abs against OASL, ISG60, SV40 LT, and tubulin. (D) SV40 LT mRNA levels were assessed by qRT-PCR. BJ/TERT LT cells (4 × 10^3) were transiently transfected with 1 μg IFN-β luciferase reporter construct or pGL3 basic vector control using Lipofectamine 2000 at a 1:2 DNA to transfection reagent ratio. Six hours posttransfection, fresh culture medium was added to cells and cells were incubated for 48 h prior to measurement of luciferase activity. Firefly luciferase was measured by dual-luciferase assay (Promega) and normalized to empty vector-expressing cells (value 1). (E) Induction of IFN-β promoter activity by IRF proteins. HEK293T (1.5 × 10^5) cells were cotransfected with pcDNA, IRF1, IRF7, and actin. (F) Analysis of IFN-β mRNA expression in IRF1 knockdown cells. BJ/TERT cells were stably transduced with a shRNA-targeting IRF1 or a nontargeting shRNA. Cells were then stably transduced with vector control or LT-encoding retrovirus. Total RNA was harvested, and cDNA was synthesized. Expression of target genes was determined by qRT-PCR analysis and normalized to RPL32 and control siRNA-transfected cells (value 1). (A–D) Induction of IFN-β transactivates IRF1 mRNA. HEK293T cells were transfected with IRF1 and IRF7, and actin. (A) Requirement for IRF1 in the induction of ISG protein synthesis. Briefly, BJ/TERT LT cells were plated in 60-mm dishes and transfected with 160 pmol siRNA pools targeting IRF1 (target sequences: 5′-CGTGTGACTTGGCAACTTG-3′ and 5′-CCCGTCTCTCTCTCATATT-3′), IRF7 (M-011810-02-0005; Thermo Fisher, Pittsburgh, PA), or control (D-001220-01-05; Thermo Fisher) using 6 μl Lipofectamine RNAiMAX (Invitrogen). After 48 h, lysates were prepared and probed with Abs against OASL, ISG60, SV40 LT, IRF1, IRF7, and actin.

FIGURE 5. Induction of IRF1 transactivates IFN-β. (A) Requirement for IRF1 in the induction of ISG protein synthesis. Briefly, BJ/TERT LT cells were plated in 60-mm dishes and transfected with 160 pmol siRNA pools targeting IRF1 (target sequences: 5′-CGTGTGACTTGGCAACTTG-3′ and 5′-CCCGTCTCTCTCTCATATT-3′), IRF7 (M-011810-02-0005; Thermo Fisher, Pittsburgh, PA), or control (D-001220-01-05; Thermo Fisher) using 6 μl Lipofectamine RNAiMAX (Invitrogen). After 48 h, lysates were prepared and probed with Abs against OASL, ISG60, SV40 LT, IRF1, IRF7, and actin. (B–E) IRF1 and IRF7 requirement for the transcriptional induction of IFN-β and OASL. IFN-β (B), IRF1 (C), IRF7 (D), and SV40 LT (E) mRNA levels were assessed by qRT-PCR. BJ/TERT LT cells were transfected with siRNA against IRF1 and IRF7, as described above. Total RNA was harvested, and cDNA was synthesized. Expression of target genes was determined by qRT-PCR analysis and normalized to RPL32 and control siRNA-transfected cells (value 1). (F) Analysis of IFN-β mRNA expression in IRF1 knockdown cells. BJ/TERT cells were stably transduced with a shRNA-targeting IRF1 or a nontargeting shRNA. Cells were then stably transduced with vector control or LT-encoding retrovirus. Total RNA was harvested, and cDNA was synthesized. Expression of target genes was determined by qRT-PCR. Expression of target genes was normalized to RPL32 and reported relative to the enhancement observed over empty vector-expressing cells (value 1).
ISG60, and OASL mRNA induction in d89–97-expressing cells (Fig. 6E).

We then confirmed that the induction of DNA damage, in the absence of LT expression, could upregulate the expression of IRF1. BJ/TERT cells were UV irradiated and treated with ATM and ATR kinase inhibitors. UV irradiation resulted in the stabilization of p53 in all instances. The induction of IRF1 was comparable in BJ/TERT cells treated with KU60019 (ATM inhibitor) to the induction observed in DMSO-treated cells. ATR kinase inhibition with KU60019 resulted in a marked decrease in the induction of IRF1 protein synthesis (Supplemental Fig. 3A). Thus, activating ATR kinase signaling pathway is sufficient for the induction of IRF1.

To further dissect the mechanism of IRF1 induction, we examined the involvement of the ATR substrate Chk1. We treated BJ/TERT LT cells with the Chk1 inhibitor, UCN-01, and observed a decrease in IRF1 and OASL protein expression, relative to vehicle-treated cells. Similarly, the levels of phosphorylated p53 were reduced upon Chk1 kinase inhibition (Supplemental Fig. 3B).

Together, these results confirm that the activation of the ATR-Chk1 axis in response to DNA damage promotes the expression of IRF1.

Finally, we asked whether the inhibition of IFN-β expression, through the inhibition of ATR kinase activity, reversed the protection of fibroblast from viral infection afforded by LT expression. First, we treated BJ/TERT LT cells with CHX to inhibit IFN-β protein synthesis. Then, we preincubated cells with ATR kinase inhibitor, followed by adsorption of EMCV onto the cells and further incubation with either ETP-46464 or DMSO (Fig. 7A). ATR kinase inhibition decreased the LT protection of cells from virus-mediated cell death, as we observed a significant decrease (∼25%) in cell survival relative to the induction of cell death in DMSO-treated cells (Fig. 7B, left). The loss in viability was accompanied by a 25% increase in viral growth in BJ/TERT LT cells with inhibited ATR kinase activity (Fig. 7B, right). Taken together, our results suggest that ATR acts as a mediator of antiviral responses through the induction of IFN-β and ISG expression.
Discussion

We have defined a signaling mechanism through which stable expression of SV40 LT induces the expression of ISGs. Our results indicate that, depending on the particular gene, the induction of ISGs occurred in both an IFNAR1-dependent and IFNAR1-independent manner. This suggests that LT expression results in the induction of factors that control the expression of IFNs. Indeed, we observed a strong upregulation of IFN-β mRNA by LT accompanied by increased expression of regulators of IFN responses, as follows: IRF1, IRF7, and IRF9. Furthermore, we show that both LT expression and UV irradiation-induced DDR result in ATM kinase-dependent increase in IRF1 expression causing upregulation of IFN-β expression. Thus, our study uncovers a unique interface between the DDR and the IFN-β-mediated antiviral response that is largely mediated by ATR kinase.

Classic IFN induction has been viewed as being almost exclusively caused by virus infection and sensing of viral nucleic acid. However, recent studies point to several other situations when infection-independent IFN–ISG induction has been reported (34, 35). In this study, we show a unique mechanism for LT-mediated induction of IFN that is distinct from previous mechanisms and provide a mechanistic connection between DDR and IFN induction. The DDR is a complex cellular network involved in the detection of genotoxic stress, which triggers cell-cycle arrest and DNA repair or triggers apoptosis if the insult fails to be repaired. Early studies have connected DDR to IRF1 in a different context (31, 36–38). Discovered as an important mediator of IFN responses (39–41), the role of IRF1 in the regulation of other stress responses is still not clearly understood. Studies have implicated IRF1, along with p53, in the induction of genes involved in the regulation of cell growth, susceptibility to transformation by oncogenes, and the induction of apoptosis (36). Mechanistic studies examining the regulation of IRF1 expression have linked ATM as well as NF-κB with the induction of IRF-1 in various cells (31). Other studies have also identified NF-κB as a crucial factor involved in the induction of IRF1 and IRF7 expression in human epithelial cells (35, 42). Interestingly, the activation of ATR in Arabidopsis serves to potentiate plant immunity (43). Thus, it is likely that the triggering of DDR is an evolutionarily conserved mechanism to protect genome integrity and to some extent induce an antiviral response against pathogen infection.

In the context of virus infection, much attention has been devoted toward understanding the complex molecular interactions between DNA viruses and the DDR [reviewed in (44, 45)]. Detection of viral genomes as damaged DNA, the expression of viral oncogenes that deregulate cell-cycle checkpoints and promote replicative stress, and the induction of reactive oxygen species are all triggers for a response that can have potentially deleterious consequences for both the virus and the infected cell. In contrast, other studies have elucidated ways in which invading pathogens hijack these pathways during the course of infection to promote efficient replication of their genomes (45). HSV-1 relies on the induction of both ATM and ATR activity early in infection to stimulate the replication of viral genomes, while effectively degrading ATR at later time points to successfully complete the infectious cycle (46, 47). Similarly, the PyV (7–10, 12, 48) and human papillomaviruses (49) also induce the DDR machinery for viral replication while countering these responses during the late phases of viral replication for the completion of the infectious cycle. In this study, we have shown that, whereas the induction of ATM- and ATR-triggered signaling cascades leads to the activation of proteins that benefit viral replication and immune evasion, the ATR signaling arm specifically acts as a sensor of virus-induced replicative stress and potentially promotes viral elimination through the induction of IFN responses in human fibroblasts. Using a virally encoded oncogene and investigating the apical kinases of the DDR, ATM, and ATR, we were able to distinguish the signaling pathways and shed light on the connection between DDR and antiviral IFN responses.

Interestingly, RNA viruses, such as HIV-1 (50), avian infectious bronchitis virus (51), hepatitis C virus (52), and Rift Valley fever (53), have also been shown to trigger DDR. Thus, it is likely that these viruses have developed strategies to overcome the blockade imposed by the induction of DDR-mediated IFN induction. Indeed, studies provide evidence that Rift Valley fever virus nonstructural proteins induce replicative stress that triggers the ATM signaling pathway and enhances viral replication. In contrast, nonstructural proteins target ATR signaling, specifically, to further...
promote viral growth (53). Although we and others have provided evidence that the ATR signaling pathway is involved in the regulation of immune responses, the overall role of ATR in mediating antiviral responses still remains to be further explored.

DNA tumor viruses not only benefit from the induction of effector genes that can promote genome replication, but also have developed strategies to prevent the arrest in cellular replication, cellular death, and other potential antiviral effects mediated by DDR (44). In particular, SV40 LT can efficiently abrogate the transcriptional antiviral responses still remains to be further explored.

The overall role of ATR in mediating immune responses, the replication fork integrity during SV40 chromatin replication. ATR- and ATR-mediated G2 checkpoint signaling. ATR kinase activation in G1 phase facilitates the repair of ionizing radiation-induced DNA damage. Nuclear Acids Res. 41: 10334–10344.


References


Supplementary Figure 1: Loss of IFN signaling in BJ/TERT shIFNAR1 expressing cells.
BJ/TERT cells stably expressing either control (shCTRL) or IFNAR1-targeted shRNA (shIFNAR1) were treated with IFNα as indicated followed by immunoblotting with indicated antibodies.
**Supplementary Figure 2: Densitometric Analysis of protein expression in Figure. 6**

(A-C) Densitometric analysis was done (Fig. 6A) for protein expression using Image J. Band intensity for IRF1, OASL, and SV40 LT was measured and normalized to Actin band intensity. Ratios were then expressed relative to DMSO treated cells (value 1).

(D-F) Densitometric analysis was done (Fig. 6D) in the same way as above. Band intensity for ISG60 (D) OASL (E) and SV40LT (F) was measured and normalized to Actin band intensity. Ratios were then expressed relative to LT expressing cells (value 1).
Supplementary Figure 3: DNA-damage induction of IRF1 requires ATR and Chk-1 kinase activity

(A) Induction of IRF1 expression by UV damage. BJ/TERT cells were treated with KU60019 or ETP46464 for 2hrs prior to UV irradiation (20J/m²). Cells were kept under inhibitor treatment for an additional 22 hrs. Lysates were prepared and probed with antibodies against IRF1, p53, and actin.

(B) Requirement for Chk1 kinase activity in LT-mediated IRF1 induction. BJ/TERT LT cells were treated with 100nM UCN-01 for 24 hrs. Lysates were prepared and probed with antibodies against IRF1, OASL, phosho-p53 (S15), and actin.