

FIG 1 Production of IFNs in primary cultured kidney cells prepared from RIG-I- and MDA5-deficient mice. Kidney cells were pretreated with 100 U of IFN- β for 2 h and infected with PV at an MOI of 10. RNA was prepared from the infected cells at 6 hpi. The amounts of IFN- α mRNA (A) and IFN- β mRNA (B) were determined using quantitative real-time PCR. Cells were prepared in duplicate, and the experiments were repeated three times. Representative data are shown. The amount of IFN activity in the supernatant of infected kidney cells at 8 hpi was determined by the cytopathic effect dye uptake method using L929 cells (C). ND, not detected.

to the antiviral response to each viral infection. The type I IFN production that is induced by these sensors occurs in a virus-specific and cell-specific manner (21, 23). For example, RIG-I plays an important role in the antiviral response to Newcastle disease virus, influenza A virus, Sendai virus, vesicular stomatitis virus, Japanese encephalitis virus, and hepatitis C virus. However, MDA5 is important in the response to infection with picornaviruses, such as encephalomyocarditis virus (EMCV) (10, 23). Although RNA viruses produce dsRNA during the replication step, the protective effect of the TLR3-mediated pathway is not clear (9). In a previous study, TLR3 expression was found to cause severe encephalitis in West Nile virus (WNV) infection (50). How these sensor molecules contribute to the recognition of PV infec-

tion is not understood. The aim of the present study was to determine the role of these sensors in the response to PV infection in transgenic mice expressing human PVR. We generated PVR-tg mice deficient in these sensor and adaptor molecules. Our results demonstrate that the MDA5-, TRIF- and MyD88-mediated pathways contribute to the antiviral response against PV infection and that the TLR3-TRIF-mediated pathway plays a pivotal role in this response.

MATERIALS AND METHODS

Cells and viruses. An AGMK cell line, JVK-03 (24), was maintained in Eagle’s minimum essential medium containing 5% fetal bovine serum. PV type I Mahoney, a strain derived from the infectious cDNA clone pOM, was used in this study (45). The virus was propagated in JVK-03, and the viral titer was determined using the plaque assay. Primary cultured kidney cells were prepared from transgenic and knockout mice as previously described (54).

Transgenic and knockout mice and infection experiments. All experiments using mice were performed in accordance with the Guidelines for the Care and Use of Laboratory Animals of the Tokyo Metropolitan Institute of Medical Science. ICR-PVRTg21 mice (26) were mated with RIG-I^{-/-} and/or MDA5^{-/-} mice (21) in the ICR background because it is difficult to maintain RIG-I^{-/-} mice in other genetic backgrounds. We mated mice and obtained littermates with the genotypes RIG-I^{+/+} MDA5^{+/+}, RIG-I^{-/-} MDA5^{+/+}, RIG-I^{+/+} MDA5^{-/-}, and RIG-I^{-/-} MDA5^{-/-} to use in experiments. C57BL/6 (B6)-PVRTg21 mice were mated with MDA5^{-/-} mice, TRIF^{-/-} mice, MyD88^{-/-} mice, and TLR3^{-/-} mice (51) in the B6 background (backcrossed 7 to 10 times). IFNARI^{-/-} PVR-tg mice were previously described (19). Because all of the mice that were used in the present study were in the PVR-tg background, we omitted the notation “PVR-tg” for simplicity in this report. Six- to 7-week-old mice were used for infection experiments. The survival and clinical symptoms of the mice were observed daily for 3 weeks. At the first sign of severe neurological symptoms, the mice were sacrificed as a humane endpoint.

Measurement of IFN levels. IFN- α levels in the sera were determined using an enzyme-linked immunosorbent assay (ELISA). The ELISA kit for IFN- α was purchased from PBL Biochemical Laboratories. Mouse IFN activity in the supernatants of PV-infected kidney cells was measured by the cytopathic effect dye uptake method using L929 cells (54, 55). Recombinant mouse IFN- β (Toray) was used as the standard for unit definition.

Quantitative real-time reverse transcription (RT)-PCR. RNA was isolated from the tissues of infected mice or infected cells using the Isogen RNA extraction kit (Nippon Gene). DNase I treatment and cDNA synthesis were performed as previously described (54). The amounts of the mRNAs for IFN- α , IFN- β , OAS1a, and IRF-7 were determined using real-time RT-PCR with an ABI Prism 7500 (Applied Biosystems) as previously described (54).

RESULTS

IFN production in primary cultured kidney cells is dependent on MDA5. We examined whether, similar to EMCV infection, PV infection is recognized by MDA5 *in vitro*. We mated PVR-tg mice with MDA5-deficient and RIG-I-deficient mice to generate RIG-I^{+/+} MDA5^{+/+}, RIG-I^{-/-} MDA5^{+/+}, RIG-I^{+/+} MDA5^{-/-}, and RIG-I^{-/-} MDA5^{-/-} mice in the ICR background. We prepared primary cultured kidney cells from mice with these genotypes to determine the role of RLRs. After cultivation for approximately 1 week, the cells that became confluent were infected with PV at a multiplicity of infection (MOI) of 10. RNA was recovered from the infected cells at 6 hpi, and the amounts of the mRNAs for IFN- α and IFN- β were determined using real-time RT-PCR. Kid-

ney cells that were not pretreated with IFN- β before PV infection showed rapid cytopathic effect progression and did not produce IFN mRNA (data not shown). This result is consistent with our previous observations (54). We therefore pretreated cells with 100 U of IFN- β for 2 h and infected them with PV. As we reported previously, the IFN-treated kidney cells became resistant to PV infection, PV replication was severely inhibited, and IFN production was observed (54). Under this condition, we determined the sensor responsible for IFN production. We observed the induction of both IFN- α (Fig. 1A) and IFN- β mRNAs (Fig. 1B) in cells that were isolated from RIG-I^{+/+} MDA5^{+/+} mice and RIG-I^{-/-} MDA5^{+/+} mice but not from RIG-I^{+/+} MDA5^{-/-} mice or RIG-I^{-/-} MDA5^{-/-} mice. The induced IFN proteins were not detected by ELISA due to a very small amount of IFNs produced in the supernatants. However, IFN activity was detected in the supernatants of PV-infected kidney cells prepared from RIG-I^{+/+} MDA5^{+/+} mice and RIG-I^{-/-} MDA5^{+/+} mice but not from RIG-I^{+/+} MDA5^{-/-} mice or RIG-I^{-/-} MDA5^{-/-} mice using the cytopathic effect dye uptake method (Fig. 1C). These results suggest that PV infection is recognized by MDA5 but not RIG-I in primary murine kidney cells, which is consistent with previous reports demonstrating that MDA5 is essential for the detection of picornaviruses (10, 23). However, MDA5-mediated IFN production was observed only when cells had been primed with a low dose of IFNs.

IFN responses of MDA5-deficient mice are not significantly different from those of wild-type mice. We hypothesized that MDA5 plays an important role in the type I IFN response upon PV infection *in vivo*. We examined the serum IFN- α levels in PVR-tg mice intravenously infected with 2×10^7 PFU of PV using ELISA. Their serum IFN- α level was initially observed at 9 hpi, peaked at 12 hpi, and began to decline at 24 hpi (Fig. 2A). We then determined the serum IFN- α levels of the knockout mice at 12 hpi. Unexpectedly, similar serum IFN- α levels were detected in RIG-I^{+/+} MDA5^{+/+}, RIG-I^{+/+} MDA5^{-/-}, RIG-I^{-/-} MDA5^{+/+}, and RIG-I^{-/-} MDA5^{-/-} mice infected with PV (Fig. 2B).

We monitored the induction of mRNAs for the IFN-stimulated genes (ISGs), OAS1a (Fig. 3A) and IRF-7 (Fig. 3B), in the brain, spinal cord, liver, spleen, and kidney using real-time

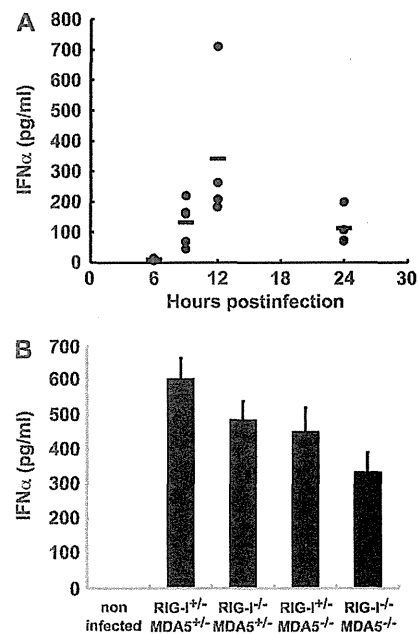


FIG 2 Production of serum IFN- α in RIG-I- and MDA5-deficient mice. (A) Time course of IFN- α levels in serum. PVR-tg mice in the B6 background ($n = 4$ or $n = 5$) were intravenously infected with 2×10^7 PFU of PV. Serum samples were collected at the indicated time points, and the concentration of IFN- α was determined using ELISA. (B) IFN- α levels of RIG-I- and MDA5-deficient mice in the ICR background ($n = 8$) at 12 hpi were compared. The experiments were repeated twice, and representative data are shown.

RT-PCR. Among the organs tested, the expression levels of these ISGs were the highest in the spleen. However, the expression profiles of these genes were essentially the same in all organs. In accordance with the elevated serum IFN levels, the induction of ISGs in various organs was observed in all mice (Fig. 3A and B). The results suggest that MDA5 does not play a critical role in IFN production and subsequent ISG induction in response to PV infection *in vivo*.

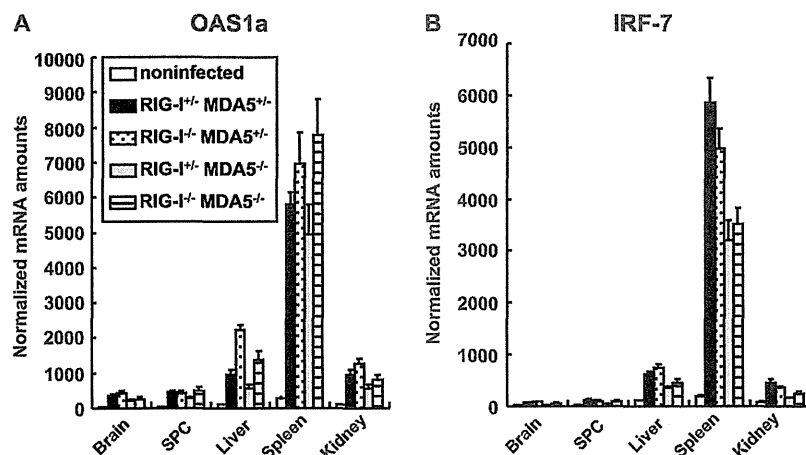


FIG 3 ISG induction in RIG-I- and MDA5-deficient mice. Mice ($n = 4$) were intravenously infected with 2×10^7 PFU of PV. At 12 hpi, RNA was isolated from the indicated tissues of the infected mice and OAS1a (A) and IRF-7 (B) mRNA levels were determined using quantitative real-time PCR. The experiments were repeated twice, and representative data are shown. SPC, spinal cord.

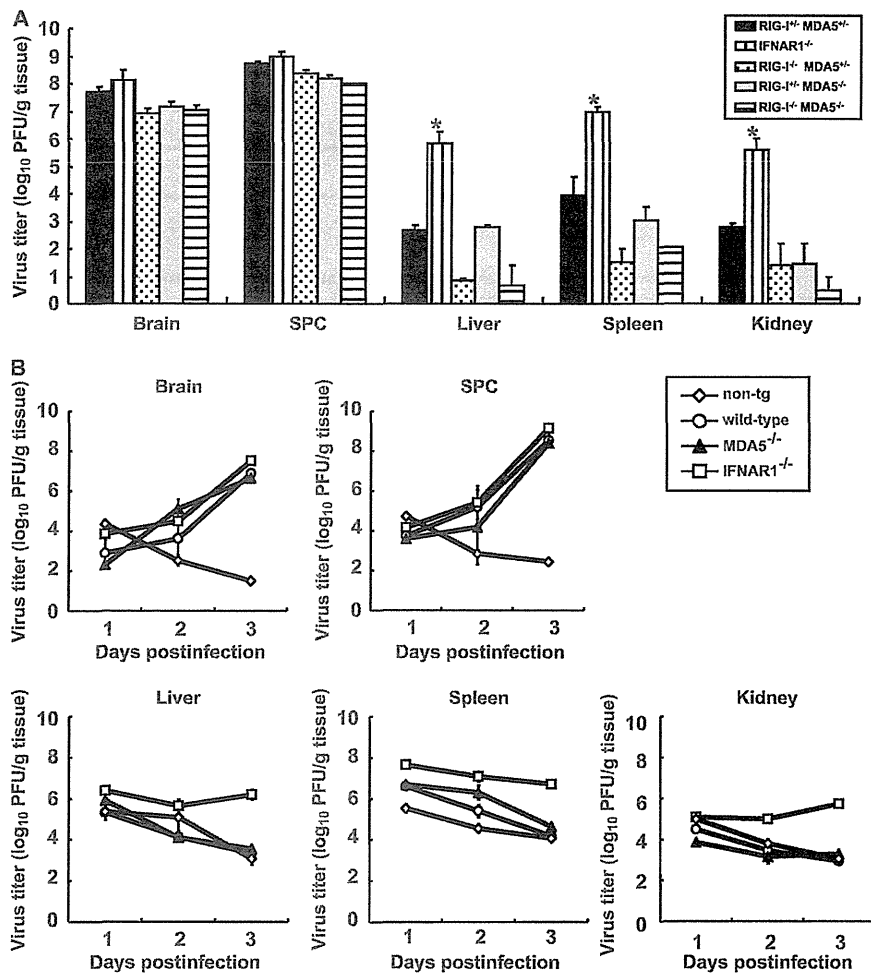


FIG 4 (A) PV replication in RIG-I- and MDA5-deficient mice. RIG-I^{+/+} MDA5^{+/+}, RIG-I^{-/-} MDA5^{+/+}, RIG-I^{-/-} MDA5^{+/-}, and RIG-I^{-/-} MDA5^{-/-} mice in the ICR background and IFNAR1^{-/-} mice in the B6 background ($n = 3$) were intravenously infected with 2×10^7 PFU of PV. Infected mice were paralyzed or dead at 3 to 5 days postinfection. The tissues of the paralyzed mice were collected, and the viral titers were determined using a plaque assay (*, $P < 0.01$ by t test compared to RIG-I^{+/+} MDA5^{+/+} mice). (B) PV replication kinetics in MDA5-deficient mice. Nontransgenic (non-tg) mice, wild-type mice, MDA5^{-/-} mice, and IFNAR1^{-/-} mice in the B6 background ($n = 3$) were infected as described above. Tissues were collected daily, and viral titers were determined. SPC, spinal cord.

PV replication in nonneural tissues and mortality rates of mice deficient in RIG-I-like receptors. We have previously shown that the IFN- α/β response forms an innate immune barrier to prevent PV replication in nonneural tissues and PV invasion of the CNS (19, 25). Therefore, we evaluated PV replication in neural and nonneural tissues in RLR-deficient mice. The mice were infected with 2×10^7 PFU of PV, which is approximately 100 times higher than the 50% lethal doses for all mouse strains. The infected mice showed paralysis by 3 to 5 days postinfection. The brain, spinal cord, liver, spleen, and kidney of the paralyzed mice were recovered, and their viral titers were determined (Fig. 4A). PV was recovered from the CNS of the paralyzed mice almost equally among the genotypes. The viral titers recovered from the liver, spleen, and kidney of IFNAR1^{-/-} mice were significantly higher than those of wild-type mice, as previously described (19). However, PV titers that were recovered from these organs of RIG-I^{-/-} MDA5^{+/+}, RIG-I^{-/-} MDA5^{+/-}, and RIG-I^{-/-} MDA5^{-/-} mice were as low as or lower than those in the organs of RIG-I^{+/+} MDA5^{+/+} mice. We then examined virus replication kinetics us-

ing nontransgenic mice, wild-type mice, IFNAR1^{-/-} mice, and MDA5^{-/-} mice in the B6 background (Fig. 4B). The viral load in the CNS increased in a similar fashion among the transgenic mouse strains. However, the viral load kinetics in the liver, spleen, and kidney of wild-type and MDA5^{-/-} mice were similar to those of nontransgenic mice. The values for nontransgenic mice indicate the kinetics of clearance of inoculated virus. The results indicated that PV replication was severely inhibited in the liver, spleen, and kidney of wild-type and MDA5^{-/-} mice. This inhibition correlated well with the induction of serum IFNs in MDA5^{-/-} mice (Fig. 2). The PV antigen was detected in neurons in the CNS but not in other tissues in all knockout mice (Table 1). This result indicates that the lack of RLRs did not alter the tissue tropism of PV. These data suggest that inhibition of PV replication in nonneural tissues is not dependent on RLRs and that MDA5-independent mechanisms are the major contributors in controlling PV replication.

We examined the mortality rates of RIG-I^{+/+} MDA5^{+/+}, RIG-I^{-/-} MDA5^{+/+}, RIG-I^{+/+} MDA5^{-/-}, and RIG-I^{-/-} MDA5^{-/-}

TABLE 1 PV antigens in RIG-I- and MDA5-deficient mice

Organ or tissue	No. of PV antigen-positive mice/no. of mice tested			
	RIG-I ^{+/-} MDA5 ^{+/-}	RIG-I ^{-/-} MDA5 ^{+/-}	RIG-I ^{+/-} MDA5 ^{-/-}	RIG-I ^{-/-} MDA5 ^{-/-}
Brain	4/4	3/3	4/4	4/4
Spinal cord	4/4	3/3	4/4	4/4
Heart	0/4	0/3	0/4	0/4
Lung	0/4	0/3	0/4	0/4
Liver	0/4	0/3	0/4	0/4
Kidney	0/4	0/3	0/4	0/4
Spleen	0/4	0/3	0/4	0/4
Pancreas	0/4	0/3	0/4	0/4
Intestine	0/4	0/3	0/4	0/4
Adipose tissue	0/4	0/3	0/4	0/4

mice in the ICR background after intravenous infection with PV at 10^3 , 10^4 , and 10^5 PFU (Fig. 5A, B, and C). The mortality rates of these mice did not differ significantly from each other. We observed that the mortality rates of RIG-I^{+/-} MDA5^{-/-} mice that were inoculated with 10^4 PFU of PV was slightly higher than the mice of other genotypes. However, significant differences were not observed in mice that were inoculated with the other doses. Similar experiments were performed using MDA5^{-/-} and MDA5^{+/-} mice in the B6 background (Fig. 5D, E, and F). We did not observe significant differences between the MDA5^{-/-} and MDA5^{+/-} mice. The mortality rate of MDA5^{-/-} mice was slightly higher than that of MDA5^{+/-} mice that were inoculated with 10^5 PFU of PV. However, the opposite trend was observed when mice

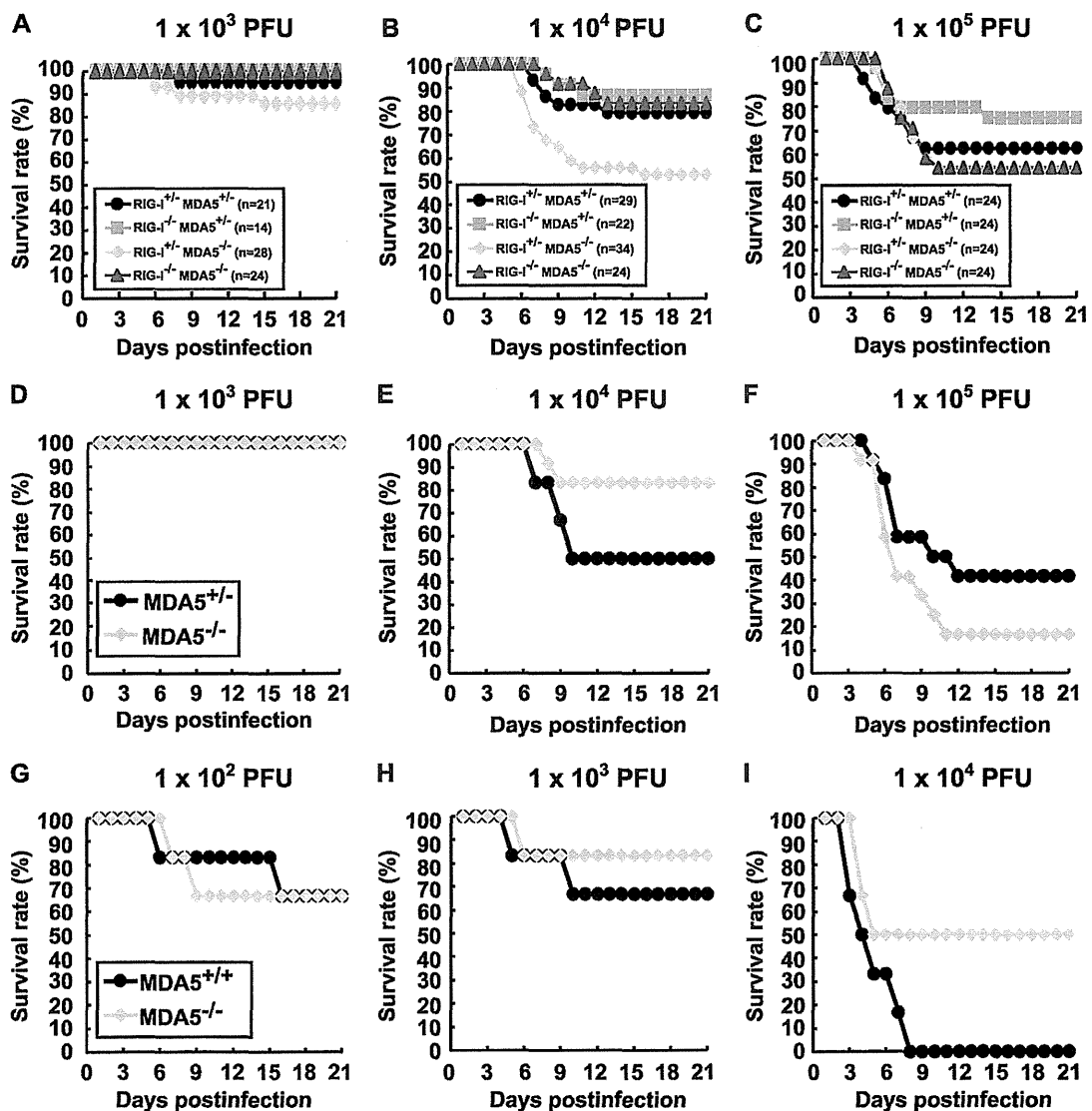


FIG 5 Mortality rates of RIG-I- and MDA5-deficient mice. Littermates of the genotypes indicated were obtained by mating RIG-I^{+/-} MDA5^{+/-} and RIG-I^{-/-} MDA5^{-/-} mice in the ICR background. The mice were infected intravenously with 10^3 (A), 10^4 (B), or 10^5 (C) PFU of PV. The results shown are the sums of several independent experiments. The total numbers of mice of the different genotypes that were used are boxed, and the doses used are shown at the top. Littermates of MDA5^{+/-} and MDA5^{-/-} mice were obtained in the B6 background. The mice ($n = 12$) were intravenously infected with 10^3 (D), 10^4 (E), or 10^5 (F) of PV. MDA5^{+/-} and MDA5^{-/-} mice ($n = 6$) were intracerebrally infected with 10^2 (G), 10^3 (H), or 10^4 (I) PFU of PV, respectively. We monitored the survival rates of the mice for 3 weeks after infection.

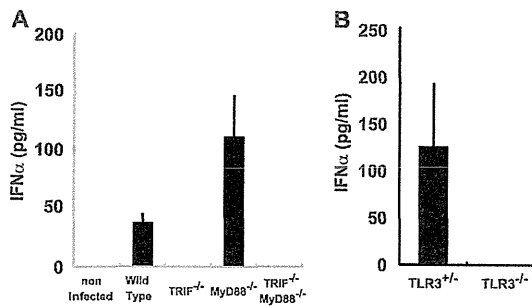


FIG 6 Production of serum IFN- α in TRIF-, MyD88-, and TLR3-deficient mice. Mice ($n = 3$ or 8) were intravenously infected with 10^7 PFU of PV. IFN- α levels of TRIF- and MyD88-deficient mice (A) and TLR3-deficient mice (B) at 12 hpi were compared. The experiments were repeated twice, and representative data are shown.

were inoculated with 10^4 PFU of PV. We suspect that the slight difference between the mortality rates of wild-type and MDA5^{-/-} mice was in the range of experimental fluctuation, and thus, the disruption of MDA5 did not significantly influence the mortality rate. In order to determine if the same is true when mice are infected by other routes, we inoculated wild-type and MDA5^{-/-} mice with PV intracerebrally and compared their mortality rates (Fig. 5G to I). Their mortality rates did not differ significantly. These results suggest that MDA5 does not make a great contribution to the protection of mice, at least after intracerebral and intravenous infections. Taken together, the MDA5-mediated response does not play a dominant role in IFN production, ISG induction, or inhibition of PV replication *in vivo*, unlike the MDA5-mediated effects on EMCV infection.

IFN response in TRIF- and MyD88-deficient mice. Because the experiments with MDA5-deficient mice suggested the existence of other protective mechanisms in PV infection, we investigated the role of TLRs using TRIF- and MyD88-deficient mice. PVR-tg mice were mated with TRIF^{-/-} and/or MyD88^{-/-} mice in the B6 background. Serum IFN- α of mice infected with 10^7 PFU of PV was measured using ELISA at 12 hpi (Fig. 6A). Interestingly, serum IFN production in response to PV infection was abrogated

in TRIF^{-/-} mice. Because TRIF acts as an adaptor for TLR3 and TLR4, we tested whether the same phenomenon occurs in TLR3^{-/-} mice. Serum IFN induction was not observed in TLR3-deficient mice (Fig. 6B). These results suggest that the TLR3-mediated pathway is essential for IFN production in response to PV infection.

We next assessed the induction of mRNAs for OAS1a (Fig. 7A) and IRF-7 (Fig. 7B) in various organs using real-time RT-PCR. The induction of OAS1a and IRF-7 was observed in all mice. Although serum IFN production was abrogated in TRIF^{-/-} mice and TRIF^{-/-} MyD88^{-/-} mice (Fig. 6), a significant level of ISG mRNA was induced. However, the induction levels were slightly lower than those in wild-type mice in some cases. The results suggest that the TRIF-mediated pathway contributes to ISG expression mainly through the induction of serum IFNs in response to PV infection and that some other mechanisms may also contribute to ISG expression.

PV replication in nonneural tissues and mortality rates of TRIF- and MyD88-deficient mice. The brain, spinal cord, liver, spleen, and kidney of paralyzed mice were recovered, and viral titers were determined (Fig. 8). PV was recovered from the CNS of TRIF^{-/-}, MyD88^{-/-}, and TLR3^{-/-} mice, and the titers were not different from those of wild-type mice. However, the viral titers of the liver, spleen, and kidney of TRIF^{-/-} and TLR3^{-/-} mice were significantly higher than those of wild-type mice but lower than those of IFNAR1^{-/-} mice. We then examined the virus replication kinetics in TRIF^{-/-} mice (Fig. 8B). The viral load in the CNS increased in TRIF^{-/-} mice similarly to that in other mice. In accordance to the absence of serum IFN (Fig. 2), the viral loads in the liver, spleen, and kidney of TRIF^{-/-} mice increased, while the viral loads in these organs of wild-type mice decreased. PV antigens were detected in the CNS of all of the knockout mice. In addition, PV antigens were detected in the adipose tissue, pancreas, and kidney of several TRIF^{-/-} and MyD88^{-/-} mice (Table 2). These results suggest that these tissues support viral multiplication in these knockout mice and that the TLR-mediated signaling pathways contribute to the regulation of PV replication in nonneural tissues.

The mortality rates of TRIF^{-/-}, MyD88^{-/-}, and TLR3^{-/-}

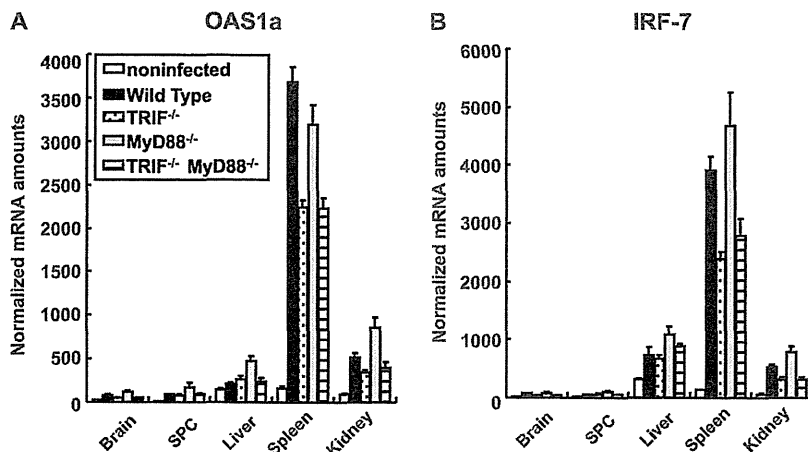


FIG 7 ISG induction in TRIF- and MyD88-deficient mice. Mice ($n = 4$) were intravenously infected with 10^7 PFU of PV. At 12 hpi, RNA was isolated from the indicated tissues of the infected mice and OAS1a (A) and IRF-7 (B) mRNA levels were determined by quantitative real-time PCR. The experiments were repeated twice, and representative data are shown. SPC, spinal cord.

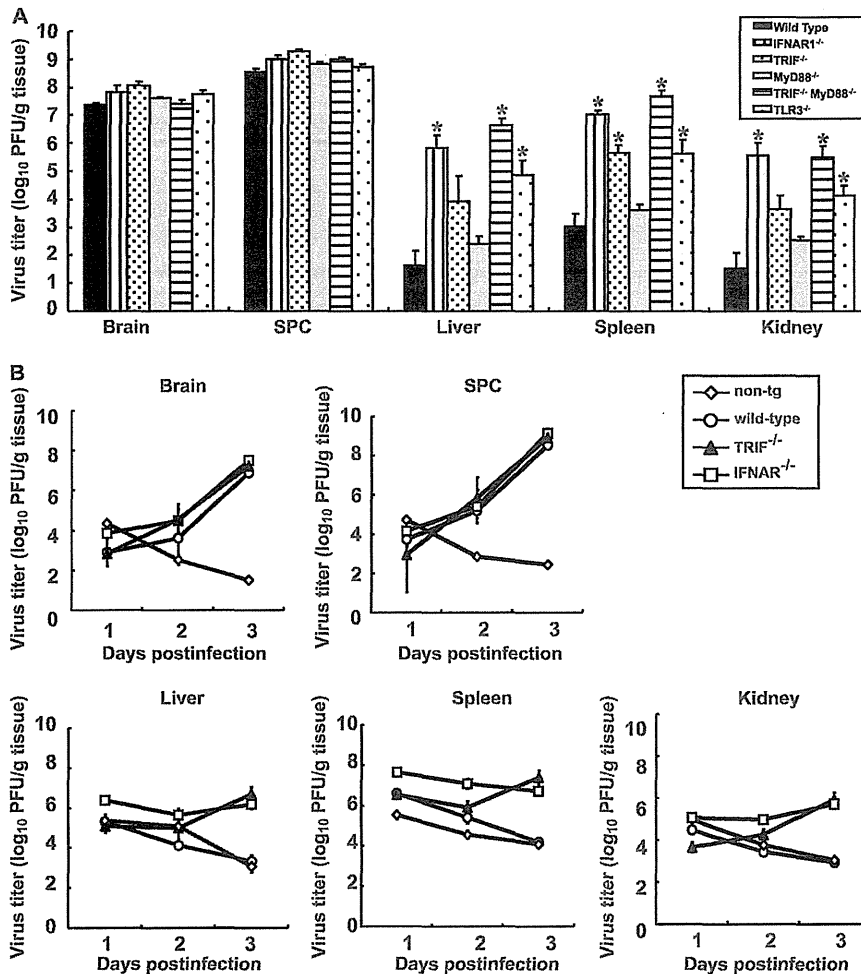


FIG 8 (A) PV replication in TRIF- and MyD88-deficient mice. Wild-type ($n = 4$), TRIF^{-/-} ($n = 4$), MyD88^{-/-} ($n = 6$), TRIF^{-/-} MyD88^{-/-} ($n = 4$), TLR3^{-/-} ($n = 5$), and IFNAR1^{-/-} ($n = 4$) mice were intravenously infected with 10⁷ PFU of PV. The infected mice were paralyzed or dead at 3 to 5 days postinfection. The indicated tissues were collected, and viral titers were determined using a plaque assay (*, $P < 0.01$ by t test compared to wild-type mice). (B) PV replication kinetics in TRIF-deficient mice. Nontransgenic mice, wild-type mice, TRIF^{-/-} mice, and IFNAR1^{-/-} mice ($n = 3$) were infected as described above. Tissues were collected daily, and viral titers were determined. The results for nontransgenic (non-tg) mice, wild-type mice, and IFNAR1^{-/-} mice are the same as those in Fig. 4B. SPC, spinal cord.

TABLE 2 PV antigens in TRIF- and MyD88-deficient mice

Organ or tissue	No. of PV antigen-positive mice/no. of mice tested			
	Wild type	TRIF ^{-/-}	MyD88 ^{-/-}	TRIF ^{-/-} MyD88 ^{-/-}
Brain	6/6	8/8	9/9	6/6
Spinal cord	6/6	8/8	9/9	6/6
Heart	0/6	0/8	0/8	0/6
Lung	0/6	0/8	0/8	0/6
Liver	0/6	0/8	0/9	0/6
Kidney	0/6	0/8	2/9	0/5
Spleen	0/6	0/8	0/9	0/6
Pancreas	2/6	0/8	7/9	4/6
Intestine	0/6	0/8	0/9	0/6
Adipose tissue	0/6	2/8	2/9	3/6

mice were compared (Fig. 9). Approximately 25% of the TRIF^{-/-} mice died after infection with 10² PFU of PV, and almost all of the mice died after infection with more than 10³ PFU of PV (Fig. 9A). Approximately 20% and 60% of the MyD88^{-/-} mice died after infection with 10³ and 10⁴ PFU of PV, respectively (Fig. 9B and C). TRIF^{-/-} MyD88^{-/-} mice were the most susceptible. In total, 70% of the mice died after infection with 10² PFU of PV (Fig. 9A). The mortality rate of TRIF^{-/-} MyD88^{-/-} mice was very close to that of IFNAR1^{-/-} mice (19). The mortality rate of TLR3^{-/-} mice was similar to that of TRIF^{-/-} mice (Fig. 9D, E, and F). These results suggest that the TRIF-mediated and MyD88-mediated antiviral responses contribute to the host's defense against PV infection and that the TLR3-TRIF-mediated response has the most dominant effect.

DISCUSSION

Each virus infects different cell types and has a characteristic mode of replication. In mammalian hosts, several viral RNA sensors,

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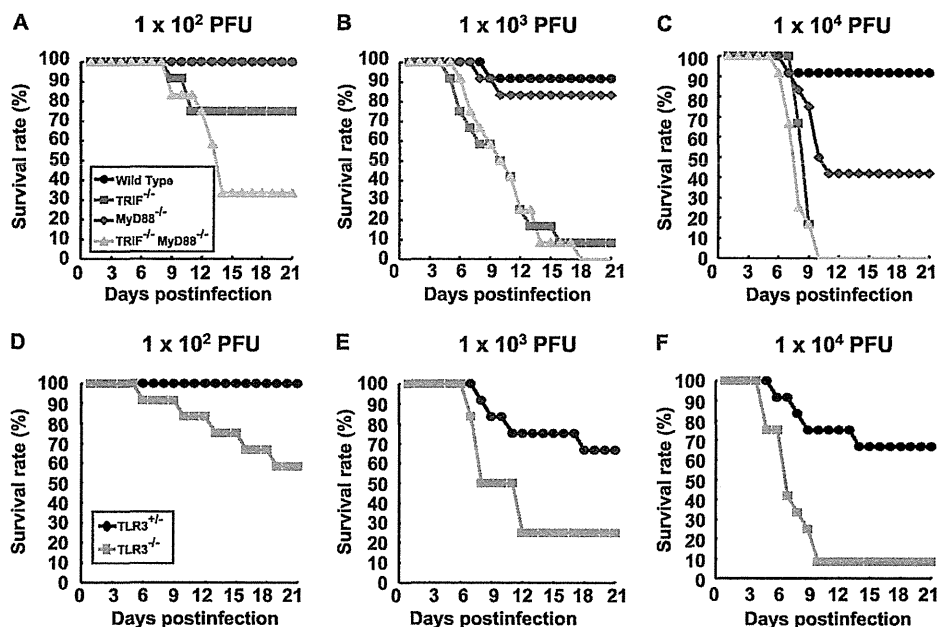


FIG 9 Mortality rates of TRIF^{-/-}, MyD88^{-/-}, and TLR3-deficient mice. (A) Wild-type, TRIF^{-/-}, MyD88^{-/-}, and TRIF^{-/-} MyD88^{-/-} mice ($n = 12$) were intravenously inoculated with the indicated doses of PV. (B) Littermates of TLR3^{+/-} and TLR3^{-/-} mice ($n = 12$) were used.

which are expressed in different cell types and recognize different molecular patterns, have evolved to counteract a variety of viruses. In the present study, we demonstrated that the MDA5-, TRIF-, and MyD88-mediated pathways contribute to the recognition of PV infection and that the TLR3-TRIF-mediated pathway plays the most important role in the antiviral response. Since all of the phenotypes shown after PV infection in the TRIF^{-/-} mice and TLR3^{-/-} mice are very similar to each other, we think that the contribution of the TLR3-mediated response is dominant and that of the TLR4-mediated response is negligible.

Previous reports have revealed that IFN is produced efficiently in EMCV-infected fibroblasts in an MDA5-dependent manner and that MDA5 contributes to the induction of serum IFNs and the protection of mice against EMCV (10, 23). Because EMCV belongs to the family *Picornaviridae*, we hypothesized that MDA5 also contributes to IFN induction in response to PV infection. However, the MDA5-dependent pathway did not play a dominant role in the defense against PV infection. Therefore, we speculate that PV uses mechanisms different from those of EMCV to strongly suppress IFN production *in vivo*. Indeed, IFN production in cultured cells in response to PV infection was observed only when the cells were pretreated with a low dose of IFNs. In addition, the amount of IFN produced was much lower than that produced in response to EMCV infection (Fig. 1). This result suggests that IFN induction in infected cells is suppressed and that this PV-mediated effect may be stronger than that of EMCV. Translational shutoff may be one of the reasons for this difference. PV 3A protein causes a change in membrane trafficking that prevents protein secretion and may also contribute to the suppression of IFN production (6). Caspase-dependent cleavage of MDA5 (3) and IPS-1 (39) in PV-infected cells has been reported. Through these possible mechanisms, PV may induce the suppression of IFN production in mice *in vivo*, and the MDA5-mediated pathway does not play an essential role in the host response, unlike in

EMCV infection. PV and EMCV seemed to use different strategies to counteract the host innate immune system, even though PV and EMCV belong to the same family. Thus, TLR3 became the sensor that functions most effectively for PV as a result of PV evolution. Although the TLR3-TRIF-mediated pathway plays a dominant role, the fact that significant ISG induction was observed in PV-infected TRIF^{-/-} and TRIF^{-/-} MyD88^{-/-} mice (Fig. 7) suggested that other mechanisms also operate in combination with this pathway.

The viral loads in the nonneural tissues of TLR3- and TRIF-deficient mice were much higher than those in wild-type mice, whereas the viral loads in the CNS were not significantly different in paralyzed mice (Fig. 8). These results suggest that the TLR3-TRIF-mediated pathway inhibits viral replication mainly before viral invasion of the CNS rather than after invasion and that this response plays an important role in preventing the viral invasion of the CNS. In the CNS, replication of PV was not effectively inhibited, even in wild-type mice. This result is consistent with our previous results obtained using IFNAR1^{-/-} mice and suggests that the antiviral response in the CNS is different from that in nonneural tissues upon PV infection (19). The cell tropism of PV may influence the efficiency of the immune response. For example, if PVR is expressed in TLR3-expressing cells, then PV replication would be detected immediately after infection. Alternatively, if PV infection *in vivo* occurs in the vicinity of TLR3-expressing immune cells such as DCs and macrophages, PV-infected cells may readily be captured by TLR3-expressing cells, thereby facilitating efficient cross-priming (27, 44) of PV RNA. PV infects neurons almost exclusively and not other cell types in the CNS. If neurons do not have the ability to induce a strong TLR3-mediated antiviral response upon PV infection, the CNS may be more defective in the innate immune response than nonneural tissues are. This may be one of the reasons why PV replicates preferentially in the CNS. Further studies on PV pathogenesis related to the innate

immune response will make a great contribution to elucidating the mechanisms of PV tissue tropism.

TLR3 recognizes dsRNA. However, the protective role of TLR3 in the response to many RNA viral infections is not clear (9, 29, 43). A previous study has demonstrated that WNV, which is an encephalitis virus belonging to the family *Flaviviridae*, causes more severe encephalitis in mice with intact TLR3 than in TLR3^{-/-} mice. Peripheral WNV infection leads to a breakdown of the blood-brain barrier (BBB) and enhances brain infection in wild-type mice but not in TLR3^{-/-} mice (50). In contrast, a protective role of the TLR3-mediated pathway in PV infection was clearly demonstrated in the present study. PV enters the CNS directly across the BBB via a PVR-independent mechanism (52) and from the neuromuscular junction via retrograde axonal transport (31–33). Because PV originally possesses two entry pathways into the CNS, the generation of a new entry pathway, even if it did occur, might not increase its deteriorative effect.

Interestingly, protective roles of the TLR3-mediated pathway have been reported for group B coxsackievirus (30, 41, 42), human rhinovirus (49), and EMCV (11) infections. Riad et al. (41) demonstrated that TRIF^{-/-} mice showed severe myocarditis after CVB3 infection and IFN- β treatment improved virus control and reduced cardiac inflammation. Richer et al. (42) reported that TLR3^{-/-} mice produced reduced proinflammatory mediators and were unable to control CVB4 replication at the early stages of infection, resulting in severe cardiac damage. They also showed that adoptive transfer of wild-type macrophages into TLR3^{-/-} mice challenged with CVB4 resulted in greater survival, suggesting the importance of the TLR3-mediated pathway in the macrophage. Negishi et al. (30) reported that TLR3^{-/-} mice showed vulnerability to CVB3 and that TLR3 signaling is linked to the activation of the type II IFN system. Since CVB3 does not induce robust type I IFNs, they suggested that the TLR3 type II IFN pathway serves as an “ace in the hole” in infections with such viruses. PV is similar to CVB3 because type I IFN production is low. However, in our preliminary experiments on PV infection in IFN- γ ^{-/-} PVR-tg mice, type II IFN did not make a significant contribution to the pathogenesis of PV. Taken together, these results suggest a critical role for the TLR3-mediated pathway, but the precise mechanisms leading to host protection are still controversial and the downstream events of TLR3 signaling after picornavirus infection remain to be elucidated.

Because the above-mentioned viruses are picornaviruses, picornavirus RNA may be easily detected by TLR3. There may be a common RNA structure in the genome or in the replication intermediates of these viruses that is detected by TLR3. Alternatively, picornavirus RNA may replicate in a compartment in which TLR3 can easily access the replicating dsRNA. To investigate these hypotheses, identification of the cells responsible for IFN production is an important step. Oshiumi et al. demonstrated that splenic CD8 α ⁺ CD11c⁺ cells, bone marrow-derived macrophages, and DCs are able to elicit IFN in response to PV infection (35). Further studies using this virus-cell system will elucidate the molecular recognition pattern in the PV genome, the precise mechanism of PV RNA recognition in TLR3-expressing cells, and the roles of these cells in the prevention of PV dissemination in the body.

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Cross-priming for antitumor CTL induced by soluble Ag + polyI:C depends on the TICAM-1 pathway in mouse CD11c⁺/CD8 α ⁺ dendritic cells

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Keywords: cross-presentation, dendritic cell, TLR3, TICAM-1 (TRIF), tumoricidal CTL

Abbreviations: APC, antigen-presenting cells; CTL, cytotoxic T lymphocytes; DAMP, damage-associated molecular pattern; DC, dendritic cells; IFN, interferon; IPS-1, IFN β promoter stimulator-1; MDA5, melanoma differentiation associated gene 5; Mf, macrophages; NK, natural killer; OVA, ovalbumin; PAMP, pathogen-associated molecular pattern; PRR, pattern-recognition receptors; PV, poliovirus; RIG-I, retinoic acid inducible gene-1; SL8, an OVA tetramer; TICAM-1, Toll-IL-1 receptor homology domain-containing molecule-1; TLR, Toll-like receptor; WT, wild-type

PolyI:C is a nucleotide pattern molecule that induces cross-presentation of foreign Ag in myeloid dendritic cells (DC) and MHC Class I-dependent proliferation of cytotoxic T lymphocytes (CTL). DC (BM or spleen CD8 α ⁺) have sensors for dsRNA including polyI:C to signal facilitating cross-presentation. Endosomal TLR3 and cytoplasmic RIG-I/MDA5 are reportedly responsible for polyI:C sensing and presumed to deliver signal for cross-presentation via TICAM-1 (TRIF) and IPS-1 (MAVS, Cardif, VISA) adaptors, respectively. In fact, when tumor-associated Ag (TAA) was simultaneously taken up with polyI:C in DC, the DC cross-primed CTL specific to the TAA in a syngenic mouse model. Here we tested which of the TICAM-1 or IPS-1 pathway participate in cross-presentation of tumor-associated soluble Ag and retardation of tumor growth in the setting with a syngenic tumor implant system, EG7/C57BL6, and exogenously challenged soluble Ag (EG7 lysate) and polyI:C. When EG7 lysate and polyI:C were subcutaneously injected in tumor-bearing mice, EG7 tumor growth retardation was observed in wild-type and to a lesser extent IPS-1^{-/-} mice, but not TICAM-1^{-/-} mice. IRF-3/7 were essential but IPS-1 and type I IFN were minimally involved in the polyI:C-mediated CTL proliferation. Although both TICAM-1 and IPS-1 contributed to CD86/CD40 upregulation in CD8 α ⁺ DC, H2K^b-SL8 tetramer and OT-1 proliferation assays indicated that OVA-recognizing CD8 T cells predominantly proliferated in vivo through TICAM-1 and CD8 α ⁺ DC is crucial in ex vivo analysis. Ultimately, tumor regresses > 8 d post polyI:C administration. The results infer that soluble tumor Ag induces tumor growth retardation, i.e., therapeutic potential, if the TICAM-1 signal coincidentally occurs in CD8 α ⁺ DC around the tumor.

Introduction

Cytotoxic T lymphocytes (CTL) and natural killer (NK) cells are two major effectors for antitumor cellular immunity. These effectors are driven through activation of dendritic cells (DC) and/or macrophages (Mf), which is mediated by pattern-recognition receptors (PRRs) for the recognition of microbial patterns.^{1,2} Antigen (Ag) presentation and upregulation of NK cell-activating ligands are major events induced in DC/Mf in response to PRRs, which link to evoking CTL- and NK-antitumor immunity, respectively. The immune-potentiating function of specific components of the classical adjuvants are largely attributable to the ligand activity of PRRs (CpG DNA/TLR9, polyI:C/TLR3, monophosphoryl lipid (MPL) A/TLR4, Pam2/TLR2, etc.).³ That

is, the DC/Mf competent to drive effectors are generated through PRR signal in inflammatory nest where affected cells and recruited immune cells encounter exogenous or endogenous PRR ligands. Since studying the functional properties of PRRs in tumor immunity is on the way using a variety of possible ligands and cell biological analyses, immune responses reflecting the total adjuvant potential around Ag-presenting cells (APC) in local inflammatory nests are not always elucidated even in mice.

RNA-sensing PRR pathways, including TLR3-TICAM-1, TLR7-MyD88 and RIG-I/MDA5-IPS-1 participate in driving Type I IFN induction and cellular immunity in DC subsets.^{1,4,5} Type I IFN and the IFNAR pathway in DC and other cells reportedly evoke and amplify T cell immunity.^{5,6} TLR7 resides exclusively in plasmacytoid DC⁷ whereas TLR3 mainly exists in

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myeloid DC/Mf and epithelial cells.⁸ They are localized on the membrane of the endosome and deliver the signal via their adaptors, MyD88 and TICAM-1.^{7,8} RIG-I and MDA5 are ubiquitously distributed to a variety of mouse cells and signal the presence of cytoplasmic viral products through IPS-1.⁹ Thus, TLR3 and RIG-I/MDA5 are candidates associated with DC maturation to drive effector cells.¹⁰ Indeed, viral dsRNA analog, polyI:C, is a representative ligand for TLR3 and MDA5 and induces polyI:C-mediated DC-NK reciprocal activation.^{11,12} These are also true in human DC.¹³

The point of this study is by which pathway antitumor CTL are induced for tumor regression in a mouse tumor-implant model. It has been postulated that DC present exogenous tumor Ag to the MHC Class I-restricted Ag-presentation pathway and proliferate CD8 T cells specific to the extrinsic Ag. When tumor cells provide soluble and insoluble exogenous Ag, this Class I Ag presentation occurs mostly TAP/proteasome-dependent, suggesting the pathway partly sharing with that for endogenous Ag presentation. This DC's ability to deliver exogenous Ag to the pathway for MHC Class I-restricted Ag presentation has been described as cross-presentation.¹⁴ DC cross-presentation leads to the cross-priming and proliferation of Ag-specific CD8 T cells in vivo and in vitro.¹⁴⁻¹⁸ A variety of PAMP^{15,16} and intrinsic DAMP¹⁷ as well as other factors including Type I IFN,^{5,18} CD4⁺ T cells¹⁹ and NKT cells²⁰ augment cross-priming in tumor-bearing mice. However, by what molecular mechanism polyI:C enhances CTL induction in tumor-bearing mice remains largely unsettled.

Here, we made an EG7 tumor-implant mouse system and treated the mice with s.c.-injected ovalbumin (OVA)-containing cell lysates (Ag) and polyI:C. Spleen CD8 α^+ DC turn CTL-inducible when stimulated with Ag and polyI:C. In either case of s.c., i.p., or i.v. injection of polyI:C, the TLR3/TICAM-1 pathway predominantly participates in CD8 α^+ DC cross-priming and antitumor CTL induction. Earlier studies using non-tumor models, suggested that both TLR3 and MDA5 appeared to participate in polyI:C-dependent CTL induction.²¹ TLR3 is predominantly involved in primary Ag response and Th1 skewing,²² while MDA5 participates in secondary Ag response.²³ Importance of TLR3 in induction of cross-priming was first suggested by Schulz et al., who used OVA/polyI:C-loaded or virus-infected xenogenic (Vero) cells and mouse DC.¹⁶ Here we demonstrate that the antitumor polyI:C activity is sustained by the TICAM-1 pathway in any route of injection in tumor-implant mice: antitumor CTL responses are mostly abrogated in TICAM-1^{-/-} but not IPS-1^{-/-} mice.

Results

Properties of EG7 tumor with high MHC in tumor-loading mice. The properties of the EG7 line we used are consistent with those reported previously.^{24,25} It expressed high MHC Class I (H2-Kb) and no Qa-1b or Rae-1 (Fig. S1). The expression levels of these proteins were barely changed before and after implantation of EG7 cells into mice. Cell viability was not affected by in vitro stimulation with polyI:C only (Fig. S1B).

However, a batch-to-batch difference of cell viability may have affected the rate of tumor growth in each mouse tumor-implant experiment.

CD8⁺ T cells are responsible for tumor retardation by polyI:C. EG7 cells (2×10^6) were inoculated into the back of C57BL/6 (WT), and the indicated reagents were subcutaneously (s.c.) injected around the EG7 tumor (Fig. 1A). Growth retardation of tumor was observed by treatment with polyI:C or polyI:C plus EG7 lysate (Fig. 1A). EG7 lysate only had no effect on tumor regression. When CD8 β^+ T cells were depleted before EG7 lysate/polyI:C treatment, polyI:C-mediated tumor growth suppression was cancelled (Fig. 1A), suggesting the participation of CD8 T cells in tumor growth suppression. The therapeutic potential of polyI:C appeared to be more reproducible in the presence of EG7 lysate than in the absence, judged from the increases of activated CD8⁺ T cells (Fig. 1B) and cytotoxic activity (Fig. 1C) of LN T cells isolated from the mice sacrificed after the last therapy. Yet, the EG7 Ag could be more or less supplied from the implant tumor. NK1.1⁺ cells did not participate in this EG7 tumor regression in this setting (data not shown).

Since EG7 lysate contains OVA, OVA-specific T cells in draining LN and spleen of the WT mice were counted by tetramer assay after the last therapy (Fig. S2A and B). The numbers of tetramer-positive cells were prominently increased in LN and spleen in mice with EG7 lysate and polyI:C. We confirmed the importance of simultaneous administration of Ag plus polyI:C for OVA-specific CTL induction as in Figure S2C, where pure Ag (OVA) was used instead of EG7 lysate for immunotherapy. The polyI:C adjuvant function appeared to be more efficient in the mixture of pure Ag than in polyI:C alone. Tumor regression (Fig. S2C) and OVA-specific CTL induction (Fig. S2D) were clearly observed in this additional experiment. To obtain reproducible data, we employed the EG7 lysate/polyI:C combination therapy as follows.

IFN-inducing pathways are involved in PolyI:C-derived EG7 growth retardation. We next inoculated EG7 cells (2×10^6) into the back of C57BL/6 (WT), TICAM-1^{-/-}, IPS-1^{-/-}, or TICAM-1/IPS-1 double-deficient (DKO) mice (Fig. 2). We s.c. administered EG7 lysate with or without polyI:C around the tumor. The EG7 lysate was the soluble fraction of EG7 which removed insoluble debris by centrifugation. The EG7 lysate contained unprecipitated micro-debris and soluble Ag. No other emulsified reagent was added for immunization. Thus, the adjuvant function of polyI:C per se is reflected in the tumor growth, although polyI:C had to be injected into mice twice a week. Retardation of tumor growth was observed > 8 d after immunization with EG7 lysate + polyI:C in WT mice, though no growth retardation without polyI:C (Fig. 2A). The polyI:C-mediated tumor growth suppression was largely abrogated in TICAM-1^{-/-} (Fig. 2B) and to a lesser extent in IPS-1^{-/-} mice (Fig. 2C), and completely in TICAM-1/IPS-1 DKO mice (Fig. 2D). Hence, TICAM-1 plays an important role in inducing polyI:C-mediated tumor growth retardation in the s.c. setting we employed.

CD8 T cell activation induced by the TICAM-1 pathway. CD8 T cell activation in the inguinal LN was tested with polyI:C + EG7 lysate in EG7 tumor-bearing mice using CD69 as

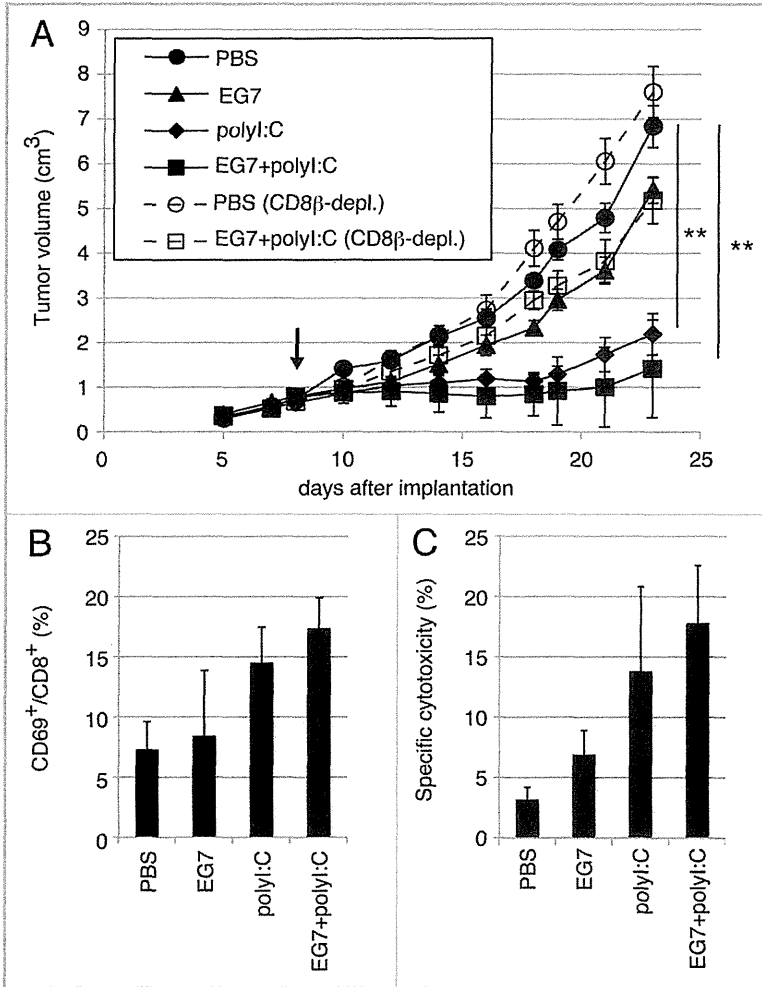


Figure 1. PolyI:C induces CTL-mediated tumor regression. (A) WT mice were challenged with EG7 cells and were treated with PBS (●), EG7 lysates (▲), polyI:C (◆) and EG7 lysates + polyI:C (■). The adjuvant therapy was started at the time indicated by the arrow and the indicated reagents injected twice per week. One of the two PBS groups (○) and one of the two EG7 lysates + polyI:C groups (□) were treated with anti-CD8β ascites in order to deplete CD8⁺ T cells once a week. Each group had 3–5 mice. (B) Draining inguinal LNs were harvested 24 h after the last treatment and the proportion of CD69-expressing CD8⁺ cells were counted. (C) LN cells were co-cultured with MMC-treated EG7 cells for 3 d and subjected to ⁵¹Cr release assay to evaluate CTL activity. E/T = 50. All error bars used in this figure show ± SEM. Data are representative of two independent experiments. One-way analysis of variance (ANOVA) with Bonferroni's test was performed to analyze statistical significance. **, p < 0.01.

an activating marker. Twenty-four hours after the last polyI:C + EG7 sec.c. treatment, cells were harvested from the LN excised (Fig. 3A). FACS profiles of total cells from each mouse group are shown in Fig. S3. By combination therapy with EG7 lysate and polyI:C, T cells were activated in WT and IPS-1^{-/-} mice, but the proportion of CD8 T cells was not affected by the therapy (Fig. S4A). Under the same conditions, T cells were barely activated in TICAM-1^{-/-} mice in response to polyI:C (Fig. 3A). The proportion of CD69⁺ cells are indicated in Figure 3B. IL-2 (Fig. 3C) and IFNγ (Fig. S4B) were highly induced in the

WT and IPS-1^{-/-} LN cells, while they were not induced in TICAM-1^{-/-} or DKO cells. IFNγ levels were upregulated only in polyI:C-treated tumor-bearing mice, although the WT > IPS-1^{-/-} profile for IFNγ production was reproducibly observed (Fig. S4B).

In vivo proliferation of CD8 T cells judged by tetramer assay and IFNγ induction. We next tested whether i.p. injection of polyI:C plus OVA induces CTL proliferation. PolyI:C and OVA were i.p. injected into mice and the polyI:C-dependent cross-priming of CD8 T cells were examined using the OVA tetramer assay. OVA-specific CD8 T cells were clonally proliferated in WT and IPS-1^{-/-} mice, but not in TICAM-1/IPS-1 DKO and IRF-3/7^{-/-} mice (Fig. 4A). Proliferation of OVA-specific CD8 T cells were severely suppressed in TICAM-1^{-/-} mice (Fig. 4A), suggesting that polyI:C-mediated cross-priming of CD8 T cells largely depends on the TICAM-1 pathway followed by IRF-3/7 activation in the i.p. route. The results were reproduced in additional experiments using more mice (Fig. 4B) and TLR3^{-/-} mice (Fig. S5A and B). The polyI:C cytokine response, where IFNα is IPS-1-dependent while IL-12p40 is TICAM-1-dependent, was also confirmed in serum level by polyI:C i.p. injection (Fig. S5E). Specific induction of IFNγ (Fig. 4C) was also observed in parallel with the results of Figure 4A.

Whether or not i.v. injection of polyI:C plus OVA induces Ag-specific CTL and cytotoxicity was next checked. OVA-specific OT-1 proliferation and cytotoxicity (Fig. 4D and E) were observed in in vivo analyses of WT and IPS-1^{-/-} CD8 T cells but not of TICAM-1^{-/-}, TICAM-1/IPS-1 DKO, and IRF-3/7^{-/-} mice in the i.v. setting.

Since TICAM-1 is the adaptor for TLR3 as well as cytoplasmic helicases,²⁴ we confirmed the level of cross-priming being decreased in TLR3^{-/-} mice and an expected result was obtained (Fig. S5A and B). Furthermore, in IFNAR^{-/-} mice, OVA-specific CTL induction was slightly reduced compared with that in WT mice, but higher than in TICAM-1^{-/-} mice (Fig. S5C and D). Hence, in vivo cross-presentation induced by polyI:C mostly depends on the TLR3-TICAM-1 pathway followed by transcriptional regulation by IRF-3/7 in any administration route, and is further promoted by Type I IFN presumably produced by the stromal cells through the IPS-1 pathway.²⁶

IPS-1 induces DC maturation but not cross-priming in vivo. Spleen DC maturation by i.v.-injected polyI:C was tested ex vivo using CD8α⁺ DC and CD8α⁻ DC isolated from WT or KO mice with no tumor as indicated in Figure 5A. The maturation markers CD86 and CD40 were upregulated on both CD8α⁺ and CD8α⁻

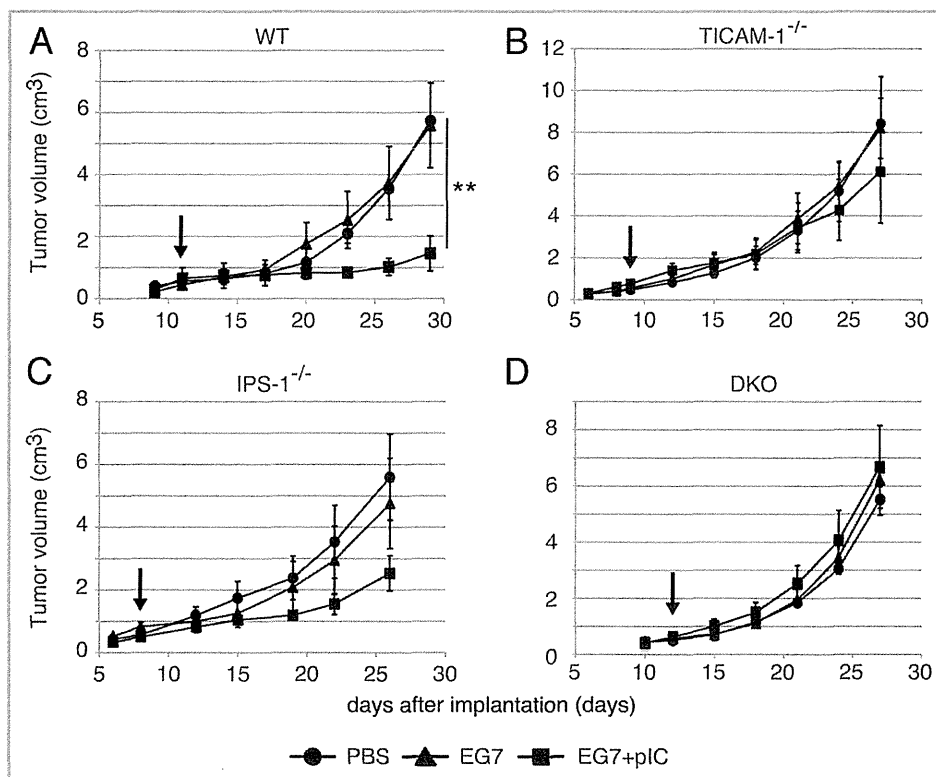


Figure 2. PolyI:C-induced tumor retardation is dependent on the TICAM-1 pathway. Antitumor effect of polyI:C on various KO mice were evaluated by using in vivo mouse tumor implant model. EG7 cells were inoculated to WT (A), TICAM-1^{-/-} (B), IPS-1^{-/-} (C) and DKO mice (D) on day 0. PBS (●), EG7 lysates (▲) or EG7 lysates + polyI:C (■) were s.c. administered around the tumor. The adjuvant therapies were started at the time indicated by the arrows and injected twice per week. Each group have 3–4 mice and error bar shows ± SEM. Data are representative of two independent experiments. **, $p < 0.01$

DC from WT mice when they were stimulated with OVA and polyI:C. Treatment of DC with OVA only did not induce upregulation of CD86 and CD40. Although the expression levels of CD86 and CD40 were a little less in CD8 α^+ and CD8 α^- DC from TICAM-1^{-/-} or IPS-1^{-/-} mice than those from WT mice, both CD86 and CD40 were sufficiently upregulated even in the abrogation of either one pathway in polyI:C-injected mice. The CD86 and CD40 shifts were completely abolished in DKO mice (Fig. 5A). Thus, the TICAM-1 pathway participates in both potent co-stimulation and cross-priming, while the IPS-1 pathway mainly participates only in integral co-stimulation in myeloid DC.

We next assessed in vitro proliferation of OT-1 cells. CD8 α^+ and CD8 α^- DC were prepared from PBS, polyI:C, OVA and OVA/polyI:C-treated mice, and mixed in vitro with CFSE-labeled OT-1 cells. WT, TICAM-1^{-/-} and IPS-1^{-/-} mice were used for this study. OT-1 proliferation was observed with CD8 α^+ DC but not CD8 α^- DC when OVA + polyI:C was injected (Fig. 5B). Furthermore, the OT-1 proliferation barely occurred in the mixture containing TICAM-1^{-/-} CD8 α^+ DC. Thus, OT-1 proliferation is triggered by the TICAM-1 pathway in CD8 α^+ DC. Again, IPS-1 had almost no effect on OT-1 proliferation with CD8 α^+ DC in this setting. In the mixture, IFN γ was produced in the supernatants of WT and IPS-1^{-/-} CD8 α^+ DC

but not TICAM-1^{-/-} DC by stimulation with OVA + polyI:C (Fig. 5C). No IFN γ was produced in the supernatants of CD8 α^- DC even from WT mice, which results are in parallel with those of OT-1 proliferation. In any case irrespective of tumor-bearing or not, Ag, polyI:C and the TICAM-1 pathway are mandatory for CD8 α^+ DC to cross-prime and proliferate OVA-specific CD8 T cells.

We checked the TICAM-1- or IPS-1-specific gene expressions related to Type I IFN and MHC Class I presentation using genechip and qPCR (Fig. S6). PolyI:C-mediated upregulation of *Tap1*, *Tap2* and *Tapbp* messages diminished in TICAM-1^{-/-} BMDC (Fig. S6A). The levels of these genes were hardly affected in IPS-1^{-/-} BMDC (data not shown). PolyI:C-mediated upregulation was observed with MDA5 (*Ifih1*) in CD8 α^- and CD8 α^+ DCs (Fig. S6B). Surprisingly, other factors including TLR3, TICAM-1 and MAVS messages were all downregulated in response to polyI:C in CD8 α^+ DC (Fig. S6B), for the reason as yet unknown.

Effect of TLR3-mediated IFN-inducing pathway on anti-tumor CTL induction. PolyI:C is a dsRNA analog capable of incorporating into the endosome and cytoplasm by exogenous administration in vitro.^{27,28} However, no evidence has been proposed that polyI:C is internalized into the endosome of

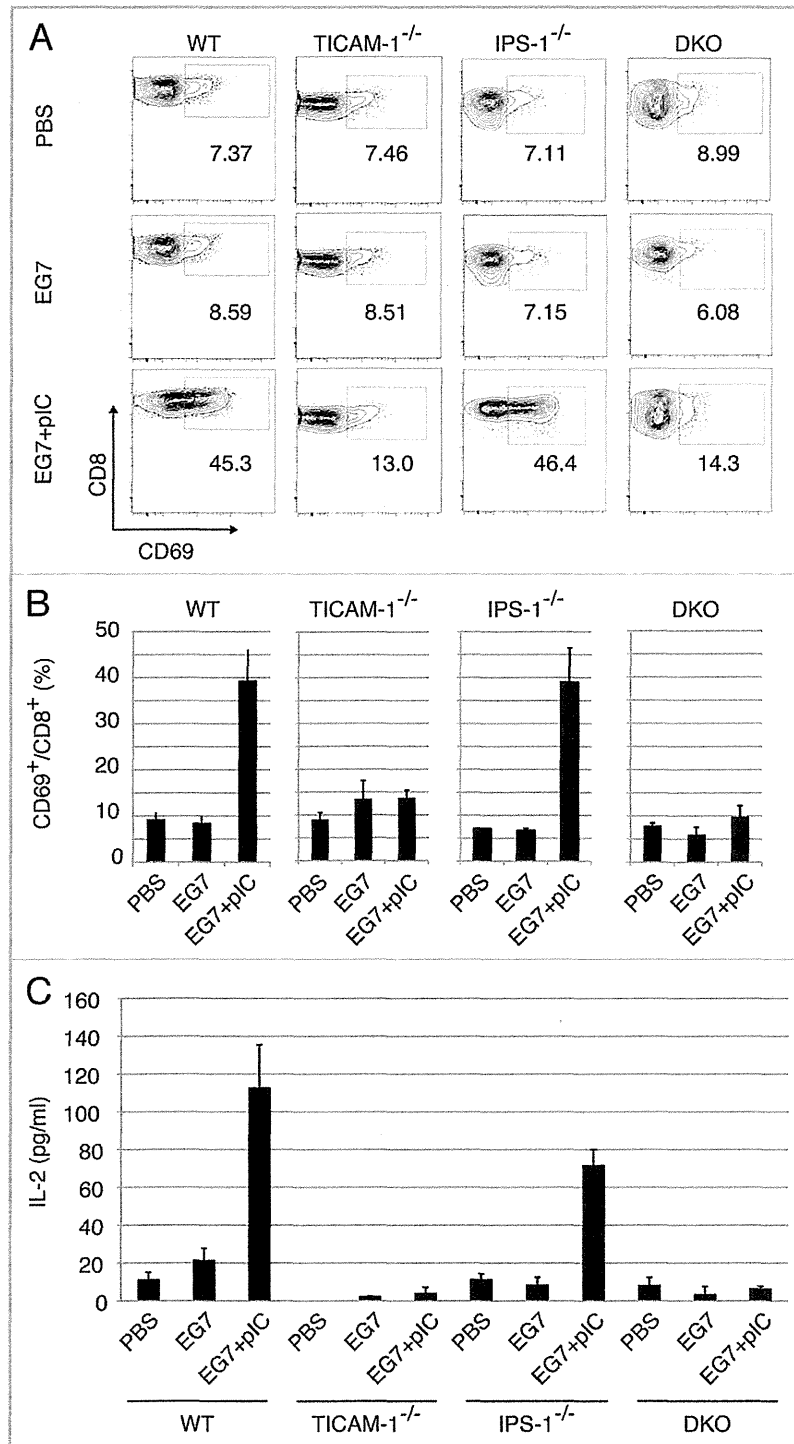


Figure 3. CD8 T cells in the draining LNs are activated through the TICAM-1 pathway by poly:I:C. Draining inguinal LNs were harvested from tumor-bearing mice 24 h after the last treatment. LN cells were stained with CD3ε, CD8α and CD69, and the cells gated on CD3ε⁺CD8α⁺ are shown (A). Spleen cells in each group of mice were stained separately, the CD8 levels in gated cells being variably distributed in FACS analyses. The average frequency of activated CD8 T cells defined by CD69 expression is shown (B). Alternatively, LN cells from the indicated mice were cultured for further 3 d in vitro and IL-2 production was measured by CBA assay (C).

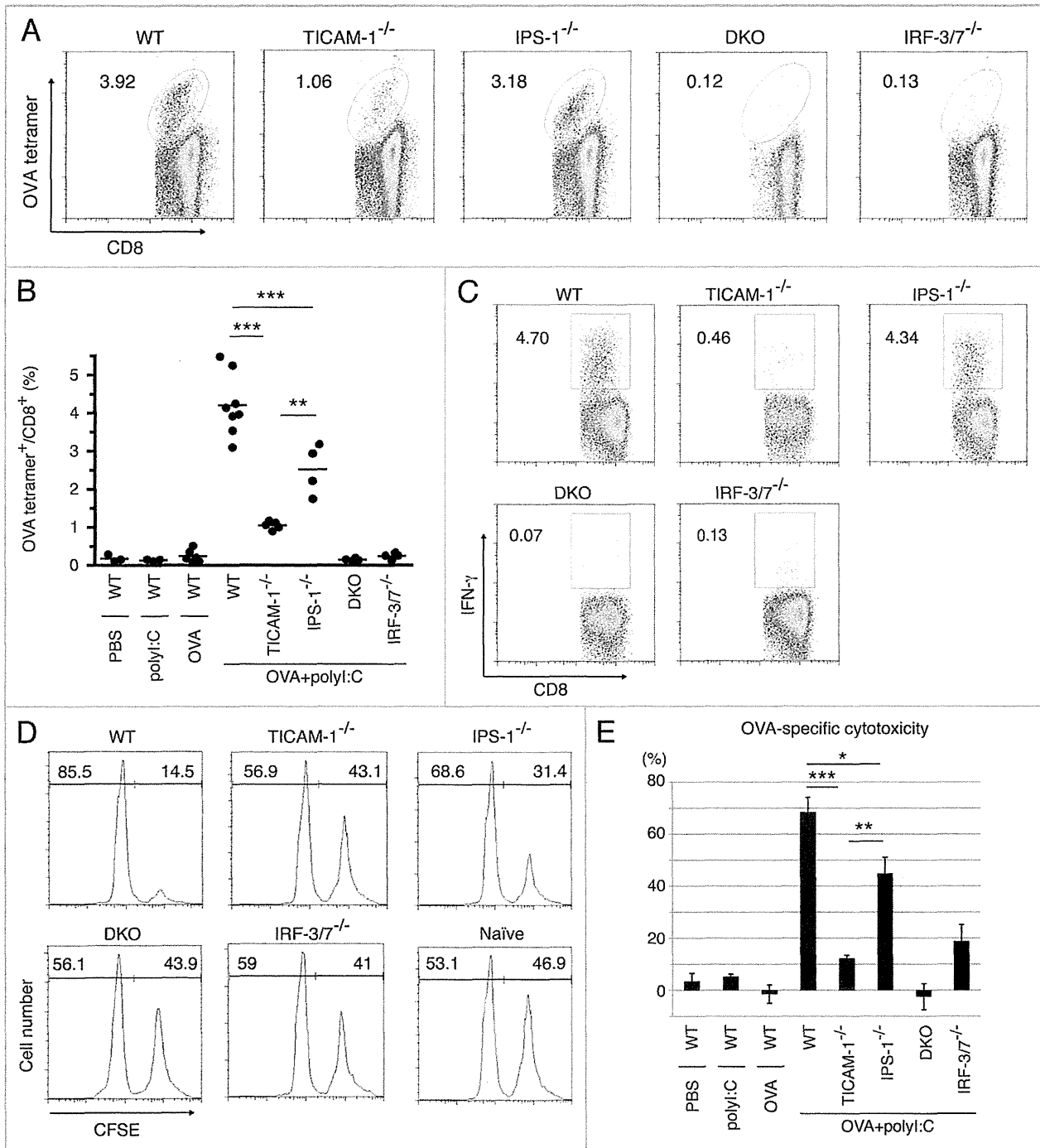


Figure 4. TICAM-1 and IRF-3/7 are essential for poly:I:C-induced antigen-specific CTL expansion. WT, TICAM-1^{-/-}, IPS-1^{-/-}, TICAM-1/IPS-1 DKO and IRF-3/7^{-/-} mice were i.p. administered with the combination of OVA and poly:I:C. After 7 days, splenocytes were harvested and stained with CD8 α and OVA tetramer (A). The average percentages of OVA-specific CTL are shown (B). Alternatively, splenocytes were cultured *in vitro* in the presence of SL8 for 8 h and IFN γ production was measured by intracellular cytokine staining (C). To assess the killing activity, *in vivo* CTL assay was performed. The combinations of OVA and poly:I:C were administered *i.v.* to each group of mice and 5 d later, cytotoxicity was measured (D). The data shown are collaborative or representative of at least three independent experiments. One-way analysis of variance (ANOVA) with Bonferroni's test was performed to analyze statistical significance. *, $p < 0.05$; **, $p < 0.01$; ***, $p < 0.001$.

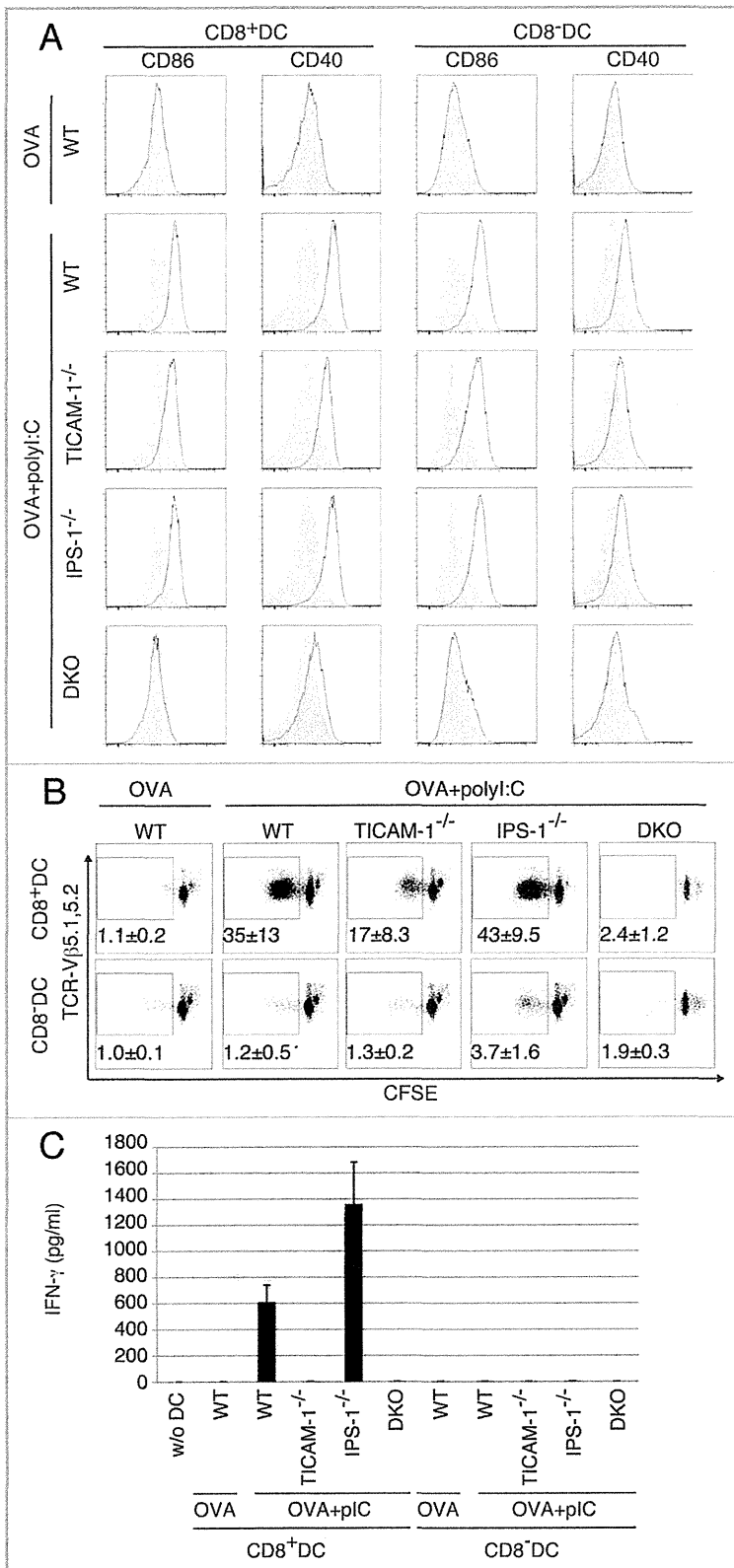


Figure 5. TICAM-1 in CD8 α^+ DC is more important than IPS-1 in polyI:C-induced cross-priming. OVA and polyI:C were administered i.v. and 4 h later, CD8 α^+ and CD8 α^- DC were isolated from the spleen. CD86 and CD40 expressions were determined by FACS (A). Filled gray and black line show isotype control and target expression, respectively. Alternatively, CD8 α^+ and CD8 α^- DC were co-cultured with CFSE-labeled RAG2^{-/-}/OT-1 T cells for 3 d. The cross-priming activity of each DC subset was determined with sequential dilution of CFSE (B) and IFN γ production (C). IFN γ was measured by CBA assay. The data shown are representative of two independent experiments. Err bar shows SD.

CD8 α^- DC where TLR3 is expressed in vivo. Peritoneal (PEC) M ϕ and bone marrow-derived DC²² usually phagocytose polyI:C and deliver them into the endosome. In mouse CD8 α^+ DC direct internalization of polyI:C has remain unproven. Using labeled polyI:C and anti-mouse TLR3 mAb, 11F8,²² we checked whether the exogenously-added polyI:C encountered with TLR3 in CD8 α^+ DC in vitro. TLR3 (green) was merged with TexasRed-polyI:C 30–120 min after polyI:C stimulation in the culture (Fig. 6A). The quantities of CD8 α^+ and CD8 α^- DC where FITC-polyI:C was incorporated were determined by FACS analysis (Fig. 6B). Thus, the process by which polyI:C injected reaches the endosomal TLR3 is delineated in the CD8 α^+ DC.

Discussion

PolyI:C is an analog of virus dsRNA, and acts as a ligand for TLR3 and RIG-I/MDA5. PolyI:C has been utilized as an adjuvant for enhancement of antitumor immunity for a long time.²⁹ However, the mechanistic background of the therapeutic potentials of polyI:C against cancer has been poorly illustrated. It induces antitumor NK activation through DC-NK cell-to-cell interaction when CD8 α^+ DC TLR3 is stimulated in the spleen.¹¹ Besides myeloid cells, however, some tumor cell lines express TLR3 and dsRNA targeting tumor cells may affect the growth rate of tumors,³⁰ where the receptor-interacting protein (RIP) pathway is involved downstream of TICAM-1.³¹ Here we showed evidence that polyI:C injection facilitates maturation of TLR3-positive CD8 α^+ DC (i.e., APC) to trigger CTL induction against exogenous soluble Ags including EG7 lysate or OVA. The TICAM-1 adaptor for TLR3 and IRF-3/7 are involved in the cross-presentation signal in CD8 α^+ DC, but the molecule/mechanism downstream of TICAM-1 that governs cross-presentation remains elusive. Since most of the tumor-associated Ags (TAA) are predicted to be liberated from tumor cells

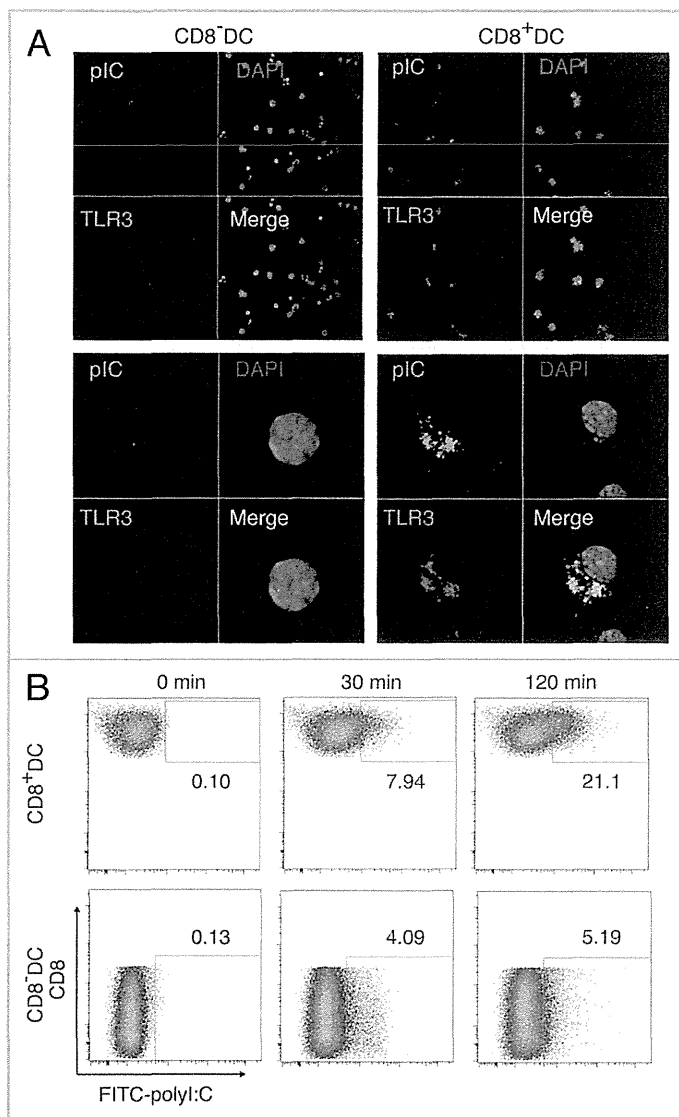


Figure 6. PolyI:C encounters TLR3 in CD8 α^+ DC. CD8 α^+ and CD8 α^- DC were isolated by FACS and stimulated with 20 μ g/ml TexasRed-polyI:C for 2 h. Then cells were stained with Alexa647-antiTLR3 and subjected to confocal microscopic analysis (A). Alternatively, splenic DC isolated by MACS were incubated with FITC-polyI:C for the time shown in figure and analyzed the degrees of polyI:C uptake by FACS (B). Data shown are the representative of three independent experiments.

as soluble Ags, the TICAM-1 pathway in CD8 α^+ DC would be crucial for driving of tumor-specific CTL around the tumor microenvironment. In any route of polyI:C injection, this is true as shown first in this study. Although TICAM-1 is an adaptor of other cytoplasmic sensors, DDX1, DDX21 and DHX36,³² the antitumor CTL responses are merely relied on TLR3 of CD8 α^+ DC in this system. Taken together with previous reports,^{11,12} TICAM-1 signaling triggers not only NK activation but also CTL induction.

TLR3 and MDA5 are main sensors for dsRNA and differentially distributed in myeloid cells.^{33,34} TLR3 is limitedly expressed in myeloid, epithelial and neuronal cells,³⁵ whereas MDA5 is ubiquitously expressed including non-myeloid stromal cells.³³ Several reports suggested that i.v. injection of polyI:C predominantly stimulate the stromal cells which express IFNAR,²⁶ thereby robust type I IFN are liberated from these cells to be a systemic response including cytokinemia and endotoxin-like shock.^{35,36} Both TLR3 and MDA5 link to the IRF-3/7-activating kinases leading to the production of IFN α/β .^{37,38} Once IFN α/β are released, IFNAR senses it to amplify the Type I IFN production,³⁹ and reportedly this amplification pathway involves cross-priming of CD8 T cells in viral infection.¹⁸ Tumor progression or metastasis can be suppressed through the IFNAR pathway.⁴⁰ These scenarios may be right depending on the conditions employed. Our message is related to what signal pathway is fundamentally required for induction of antitumor CTL in DC. The CTL response is almost completely abrogated in TICAM-1^{-/-} and IRF-3/7^{-/-} mice, but largely remains in IPS-1^{-/-} and IFNAR^{-/-} mice when Ag and polyI:C are extrinsically administered. The results are reproducible in some other tumor-implant models (data not shown), and even in IFNAR^{-/-} mice, TICAM-1-specific genes are upregulated to confer tumor cytotoxicity (Fig. S6, Azuma et al., unpublished data). In addition, the upregulation of these genes is independent of IPS-1 knockout in DC. Our results infer that the primary sensing of dsRNA in CD8 α^+ DC is competent to induce cross-presentation, which minimally involves the IPS-1 or IFNAR amplification pathway, at least at a low dose of polyI:C. Yet, subsequent induction of Type I IFN via the IFNAR may further amplify the cross-priming.^{18,41} Further studies are needed as to which of the TICAM-1-inducible genes link to the cross-presentation in CD8 α^+ DC.

The main focus of this study was to identify the pathway for transversion of immature DC to the CTL-driving phenotype by co-administration of polyI:C with soluble Ag. The IPS-1 pathway, although barely participates in antitumor CTL driving, can upregulate CD40/CD86 co-stimulators on the membranes of splenic CD8 α^+ and CD8 α^- DC in response to polyI:C, suggesting that MDA5 does function in the cytoplasm of splenic CD8 α^+ and CD8 α^- DC to sense polyI:C. However, effective CTL induction happens only in CD8 α^+ DC when stimulated with polyI:C. CD8 α^+ DC express TLR3 but CD8 α^- DC do not, and CD8 α^+ DC with no TLR3 fail to induce CTL, suggesting that integral co-stimulation by MDA5/IPS-1 is insufficient for DC to induce cross-priming of CD8 T cells: antitumor CTL are not induced until the TICAM-1 signal is provided in DC. At least, sole effect of the IPS-1 pathway and upregulation of co-stimulators on CD8 α^+ DC is limited for cross-priming and induction of antitumor CTL, which result partly reflects those in a previous report where IPS-1 and TICAM-1 harbor a similar potential for CD8 T cell proliferation when

polyI:C (Alum-containing) is employed as an adjuvant for CD8 α ⁺ DC to test proliferation of anti-OVA CTL.²¹

A question is why TICAM-1 is dominant to IPS-1 for response to exogenously-added polyI:C in CD8 α ⁺ DC. The answer is rooted in the difference of functional behavior between BMDC and CD8 α ⁺ DC. TLR3 levels are variable depending upon subsets of DC,²² which affects DC subset-specific induction of cellular immune response. The high TLR3 expression (partly surface-expressed) is situated in CD8 α ⁺ DC before polyI:C stimulation, which is distinct from the properties of F4/80⁺ Mf and presumably BMDC of low TLR3 expression. The polyI:C-uptake machinery¹⁵ appears to efficiently work in concert with the TLR3/TICAM-1 pathway in CD8 α ⁺ DC and this tendency is diminished when CD8 α ⁺ DC are pretreated with Alum + polyI:C.²¹ Furthermore, there are functional discrepancies between CD8 α ⁺ splenic DC and GM-CSF-induced BMDC, which appears to reflect the difference of their TLR3 levels.²² These results on CD8 α ⁺ DC encourage us to develop dsRNA adjuvant immunotherapy supporting TAA soluble vaccines for cancer applicable to humans, which possess the counterpart of CD8 α ⁺ DC.

There are two modes of dsRNA-mediated DC maturation, intrinsic and extrinsic modes that are governed by the IPS-1 and TICAM-1 pathways, respectively.^{9,34} It is important to elucidate the in vivo qualitative difference in the two pathways in tumor-loading mice. TLR3⁺ DC/Mf are responsible for CTL driving via an extrinsic route in viral infection.³⁴ Previous data suggested that dsRNA in infectious cell debris, rather than viral dsRNA produced in the cytoplasm of Ag-presenting cells or autophagosome formation, contribute to fine tuning of DC maturation through extrinsic dsRNA recognition.¹⁶ It is reported that dsRNA-containing debris are generated secondary to infection-mediated cell death,⁴¹ and DC phagocytose by-stander dead cells. Likewise, soluble tumor Ags released from tumor cells usually are extrinsically taken up by APC in patients with cancer.⁴² If CTL are successfully induced in therapeutic biotherapy targeted against cancer cells, this extrinsic TICAM-1 pathway must be involved in the therapeutic process.

Cross-presentation occurs in a TAP-dependent⁴³ and -independent fashions.^{44,45} The peptides are transported by TAP into the endoplasmic reticulum (ER) and loaded onto MHC Class I for presentation at the cell surface. ER and phagosome might fuse each other for accelerating cross-presentation.⁴⁶ Another possibility is that cross-presentation occurs in early endosomes where TLR3 resides. This early endosome cross-presentation does not always depend on TAP⁴²⁻⁴⁴ but requires TLR stimulation.³⁴ TLR4/MyD88 pathway is involved in the TAP-dependent early endosome model,⁴³ where recruitment of TAP to the early endosomes is an essential step for the cross-presentation of soluble Ag. These models together with our genechip analysis of polyI:C-stimulated BMDC suggested that some ER-associated proteins are upregulated in BMDC by polyI:C-TICAM-1 pathway. The results infer that the TLR3/TICAM-1 rather than the TLR4/MyD88 pathway more crucially participates in cross-presentation in response to dsRNA or viral stimuli and facilitates raising CTL antitumor immunity in APC.

Although multiple RNA sensors couple with TICAM-1 and signal to activate the Type I IFN-inducing pathway,²⁵ at least TLR3 in the CD8 α ⁺ DC are critical in CTL driving. CD8 α ⁺ DC are a high TLR3 expresser, while BMDC express TLR3 with only low levels.²² CD8 α ⁺ DC do not express it.²² The Ag presentation and TLR3 levels in CD8 α ⁺ DC appear reciprocally correlated with the phagocytosing ability of DC. Although the TLR3 mRNA level is downregulated secondary to polyI:C response after maturation, this may not be related to the CD8 α ⁺ DC functions. Yet, polyI:C might interact with other cytoplasmic sensors for DC maturation.^{32,47}

The route of administration and delivery methods may be important to culminate the polyI:C adjuvant function. The toxic problem has not overcome in the adjuvant therapy using polyI:C.^{35,36} and this is a critical matter for clinical introduction of dsRNA reagents to immunotherapy. The most problematic is the life-threatening shock induced by polyI:C. Recent advance of polyI:C study suggests that PEL-jet helps efficient uptake of polyI:C into peritoneal macrophages.⁴⁸ LC (poly-L-lysine and methylcellulose) has been used as a preservative to reduce the toxic effect of polyI:C.⁴⁹ Nanotechnological delivery of polyI:C results in efficient tumor regression.⁵⁰ There are many subsets of DC that can be defined by surface markers, and selecting an appropriate administration route can target a specific DC subset. The route for s.c. administration usually mature dermal/epidermal DC or Langerhans cells.^{51,52} Some DC subsets with unique properties specialized to CTL induction would work in association with the route of polyI:C administration. Attempting to develop more harmless and efficient dsRNA derivatives will benefit for establishing human adjuvant immunotherapy for cancer.

Materials and Methods

Mice. TICAM-1^{-/-} and IPS-1^{-/-} mice were made in our laboratory and backcrossed more than eight times to adapt C57BL/6 background.¹² IRF-3/7^{-/-} and IFNAR^{-/-} mice were kindly provided by T. Taniguchi (University of Tokyo, Tokyo, Japan). TLR3^{-/-} mice were kindly provided by S. Akira (Osaka University, Osaka, Japan). Rag2^{-/-} and OT-1 mice were kindly provided from Drs N. Ishii (Tohoku University, Sendai, Japan). Rag2^{-/-}/OT-1 mice were bred in our laboratory. All mice were maintained under specific pathogen-free conditions in the animal facility of the Hokkaido University Graduate School of Medicine. Animal experiments were performed according to the guidelines set by the animal safety center, Hokkaido University, Japan.

Cells. EG7 and C1498 cells were purchased from ATCC and cultured in RPMI1640/10% FCS/55 μ M 2-ME/1 mM sodium pyruvate and RPMI1640/10% FCS/25 ng/ml 2-ME, respectively. Mouse splenocytes, OT-1 T cell, CD8 α ⁺ DC and CD8 α ⁺ DC were harvested from the spleen and cultured in RPMI1640/10% FCS/55 μ M 2-ME/10 mM HEPES.⁴¹ B16D8 cells were cultured in RPMI/10% FCS as described previously.¹²

Reagents and antibodies. Ovalbumin (OVA) and polyI:C (polyI:C) were purchased from SIGMA and Amersham Biosciences, respectively. OVA₂₅₇₋₂₆₄ peptide (SIINFEKL: SL8)

and OVA (H2K^b-SL8) Tetramer were from MBL. Following Abs were purchased: anti-CD3 ϵ (145-2C11), anti-CD8 β (53-6.7), anti-CD11c (N418), anti-CD16/32 (93), anti-CD69 (H1.2F3) and anti-IFN γ (XMG1.2) Abs from BioLegend, anti-B220 (RA3-6B2), anti-CD4 (L3T4), anti-CD40 (1C10), anti-CD86 (GL1), and anti-MHC I-SL8 (25-D1.16) Abs from eBiosciences, anti-TCR-V β 5.1/5.2 Ab and ViaProbe from BD Biosciences. The Rat anti-mouse TLR3 mAb (11F8) was kindly provided by David M. Segal (National Institute of Health, Bethesda, MD). To rule out LPS contamination, we treated OVA or other reagents with 200 μ g/ml of Polymixin B for 30 min at 37°C before use. Texas Red- or FITC-labeled poly(I:C) was prepared using the 5' EndTagTM Nucleic Acid Labeling System (Vector Laboratories) according to the manufacturers instructions.

Tumor challenge and poly I:C therapy. Mice were shaved at the back and s.c. injected with 200 μ l of 2×10^6 syngenic EG7 cells in PBS. Tumor volumes were measured at regular intervals by using a caliper. Tumor volume was calculated by using the formula: Tumor volume (cm³) = (long diameter) \times (short diameter)² \times 0.4. A volume of 50 μ l of a mixture consisting of the lysate of 2×10^5 EG7 cells with or without 50 μ g of poly I:C (polyI:C) was s.c. injected around the tumor. We added no other emulsified reagent for immunization since we want to rule out the conditional effect of the Ag/polyI:C. The treatments were started when the average of tumor volumes reached at 0.4–0.8 cm³ and performed twice per week. EG7 lysate were prepared by three times freeze/thaw cycles (-140°C/37°C) in PBS, with removal of cell debris by centrifugation at 6,000 g for 10 min.⁵³ To deplete CD8 T cells, mice were i.p. injected with hybridoma ascites of anti-CD8 β mAb. The dose of antibody and the treatment regimens were determined in preliminary studies by using the same lots of antibody used for the experiments. Depletion of the desired cell populations by this treatment was confirmed by FACS for the entire duration of the study.

Evaluation of T cell activity in tumor-bearing mice. Draining inguinal LN cells were harvested from tumor-bearing mice after 24 h from the last polyI:C treatment. The activity of T cells was evaluated by CD69 expression and IL-2/IFN γ production. These cells were stained with FITC-CD8 α , PE-CD69, PerCP/Cy5.5-7AAD and APC-CD3 ϵ . To check cytokine production, LN cells were cultured for 3 d *in vitro* in the presence or absence of EG7 lysates and IL-2 and IFN γ productions were determined by Cytokine Beads Array (CBA) assay (BD). To assess the cytotoxic activity of CTL, standard ⁵¹Cr release assay was performed. For CTL expansion, 2.5×10^6 LN cells were co-cultured with 1.25×10^5 mitomycin C-treated EG7 cells in the presence of 10 U/ml IL-2 for 5 d. Then, LN cells were incubated with ⁵¹Cr-labeled EG7 or C1498 cells for 4 h and determined cytotoxic activity. The cell-specific cytotoxicity was calculated with subtracting the cytotoxicity for C1498 from for EG7 cells.

Antigen-specific T cell expansion *in vivo*. Mice were i.p. immunized with 1 mg of OVA and 150 μ g of poly I:C. After 7 d, spleens were homogenized and stained with FITC-CD8 α and PE-OVA Tetramer for detecting OVA-specific CD8 T cell

populations. For intracellular cytokine detection, splenocytes were cultured with or without 100 nM OVA peptide (SIINFEKL; SL8) for 8 h and 10 μ g/ml of Brefeldin A (Sigma-Aldrich) was added to the culture in the last 4 h. Then cells were stained with PE-anti-CD8 α and fixed/permeabilized with Cytofix/Cytoperm (BD Biosciences) according to manufacturer's instruction. Then, fixed/permeabilized cells were further stained with APC-anti-IFN γ . Stained cells were analyzed with FACSCalibur (BD Biosciences) and FlowJo software (Tree Star).

***In vivo* CTL assay.** The *in vivo* CTL assay was performed as described.⁵⁴ In brief, WT, TICAM-1^{-/-}, MAVS^{-/-} and IRF-3/7^{-/-} mice were i.v. administered with PBS, 10 μ g of OVA or OVA with 50 μ g of polyI:C. After 5 d, 2×10^7 target cells (see below) were i.v. injected to other irrelevant mice and 8 h later, the OVA-specific cytotoxicity was measured by FACSCalibur. Target cells were 1:1 mixture of 2 μ M SL8-pulsed, 5 μ M CFSE-labeled splenocytes and SL8-unpulsed, 0.5 μ M CFSE-labeled splenocytes. OVA-specific cytotoxicity was calculated with a formula: $\{1 - (\text{Primed } [\text{CFSE}^{\text{high}}(\%)/\text{CFSE}^{\text{low}}(\%)] / \text{Unprimed } [\text{CFSE}^{\text{high}}(\%)/\text{CFSE}^{\text{low}}(\%)])\} \times 100$.

DC preparation. DCs were prepared from spleens of mice, as described previously.⁵⁵ In brief, collagenase-digested spleen cells were treated with ACK buffer and then washed with PBS twice. Then splenocytes were positively isolated with anti-CD11c MicroBeads. CD11c⁺ cells were acquired routinely about $\geq 80\%$ purity. Further, to highly purify CD8 α ⁺ and CD8 α DCs, spleen DC were stained with FITC-CD8 α , PE-B220, PE/Cy7-CD11c and PerCP5.5-7AAD. CD8 α ⁺ or CD8 α CD11c⁺B220⁻ DCs were purified on FACSARIAII (BD). The purity of the cells was $\geq 98\%$.

OT-1 proliferation assay. Ten micrograms of OVA with or without 50 μ g of polyI:C were i.v. injected to WT, TICAM-1^{-/-}, IPS-1^{-/-} and DKO mice. After 4 h, CD8 α ⁺ or CD8 α DC were purified from the spleen. 2.5×10^4 CD8 α ⁺ or CD8 α DC were co-cultured with 5×10^4 1 μ M CFSE-labeled Rag2^{-/-}/OT-1 T cells for 3 d in 96-well round bottom plate. These cells were stained with PE-anti-TCR-V β 5.1,5.2 and APC-anti-CD3 ϵ and T cell proliferation was analyzed by CFSE dilution using FACSCalibur. Additionally, IFN γ in the culture supernatant was measured by CBA assay.

Statistical analysis. P-values were calculated with one-way analysis of variance (ANOVA) with Bonferroni's test. Error bars represent the SD or SEM between samples.

Disclosure of Potential Conflicts of Interest

No potential conflicts of interest were disclosed.

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Supplemental Materials

Supplemental materials may be found here:

<http://www.landesbioscience.com/journals/oncoimmunology/article/19893/>

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