IMMUNOLOGY

Mitofusin 2 Inhibits Mitochondrial Antiviral Signaling

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The innate immune response to viral infection involves the activation of multiple signaling steps that culminate in the production of type I interferons (IFNs). Mitochondrial antiviral signaling (MAVS), a mitochondrial outer membrane adaptor protein, plays an important role in this process. Here, we report that mitofusin 2 (Mfn2), a mediator of mitochondrial fusion, interacts with MAVS to modulate antiviral immunity. Overexpression of Mfn2 resulted in the inhibition of retinoic acid–inducible gene I (RIG-I) and melanoma differentiation–associated gene 5 (MDA-5), two cytosolic sensors of viral RNA, as well as of MAVS-mediated activation of the transcription factors interferon regulatory factor 3 (IRF-3) and nuclear factor κB (NF-κB). In contrast, loss of endogenous Mfn2 enhanced virus-induced production of IFN-β and thereby decreased viral replication. Structure-function analysis revealed that Mfn2 interacted with the carboxyl-terminal region of MAVS through a heptad repeat region, providing a structural perspective on the regulation of the mitochondrial antiviral response. Our results suggest that Mfn2 acts as an inhibitor of antiviral signaling, a function that may be distinct from its role in mitochondrial dynamics.

INTRODUCTION

Innate immunity is an essential and ubiquitous system that defends organisms from infectious pathogens. Initiation of the innate immune response is typically triggered by the recognition of broadly conserved elements of the invading pathogen known as pathogen-associated molecular patterns (PAMPs). The recognition of PAMPs by germline-encoded pattern recognition receptors ultimately activates intracellular signaling cascades that result in the clearance and killing of infectious microbes (*1*, *2*). Viral infection of host cells is detected by the cell's recognition of PAMPs such as double-stranded RNA (dsRNA), which initiates two distinct signaling pathways (*3*). The first, mediated by endosomal Toll-like receptor 3, recognizes viral dsRNA that enters the cell by endocytosis, whereas the second pathway detects cytoplasmic, virus-derived dsRNA through the involvement of two RNA helicases, retinoic acid–inducible gene I (RIG-I) and melanoma differentiation–associated gene 5 (MDA-5) (*3*). Although these two pathways differ with respect to their initiating stimuli and downstream effectors, they converge at the point of transcriptional activation, resulting in the rapid production of type I interferons (IFN-α and IFN-β) and other cytokines that promote the subsequent development of adaptive antiviral immunity (*4*, *5*).

Mitochondria, in addition to serving as the powerhouses of eukaryotic cells, are well characterized as crucial players in numerous cellular processes, including apoptosis (*6*), aging (*7*), and calcium homeostasis (*8*). Other studies, however, have revealed that mitochondria also play a fundamental role in antiviral immunity in mammals (*9*–*13*). Mitochondrial antiviral immunity depends on both the upstream activation of the RIG-I or MDA-5 pathway and the participation of mitochondrial antiviral signaling protein [MAVS (*9*), also known as IPS-1 (*14*), VISA (*15*), and Cardif (*16*)], a mitochondrial outer membrane protein that is a member of the caspase activation and recruitment domain (CARD) family. Cellular deficiency in MAVS abrogates the production of type I IFNs and prevents the activation of the transcription factors interferon regulatory factor 3 (IRF-3) and nuclear factor κB (NF-κB) after viral infection (*17*, *18*), thus underscoring the importance of the linkage between antiviral immunity and mitochondria. Although several cytoplasmic proteins have been functionally linked to the MAVS-dependent antiviral signaling pathway (*3*), the importance of other mitochondrial integral membrane proteins that potentially cooperate with MAVS has remained unclear. Here, we describe our findings that mitofusin 2 (Mfn2), a mediator of mitochondrial fusion, negatively regulates antiviral signaling through MAVS.

RESULTS

MAVS assembles into a high molecular mass complex on mitochondria

We reasoned that additional mitochondrial membrane proteins could functionally and physically interact with MAVS to regulate mitochondrial antiviral immunity. To test this hypothesis, we examined the molecular mass of endogenous MAVS by size exclusion chromatography. Despite having a predicted molecular mass of 56 kD, endogenous MAVS extracted from the mitochondrial fraction of human embryonic kidney (HEK) 293 cells eluted in a high molecular mass fraction that corresponded to ~600 kD at physiological pH (pH 7.2) (Fig. 1A). A similar result was obtained with N-terminal Myc-tagged MAVS that was stably expressed in HEK 293 cells (Fig. 1A). To verify that the observed molecular mass of the MAVS complex was not due to nonspecific aggregation under these experimental conditions, we analyzed Fis1, a C-terminal tail–anchored mitochondrial outer membrane protein that similarly forms higher-order complexes. Fis1 derived from mitochondrial extracts of HEK 293 cells eluted at a position corresponding to less than 230 kD (Fig. 1A), consistent with previous studies (*19*). These findings indicated that MAVS ordinarily forms a stable higher-order complex on the outer mitochondrial membrane, and they raised the possibility that unidentified mitochondrial components of this complex could be relevant to the mitochondrial antiviral response.

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MAVS associates with the mitochondrial outer membrane guanosine triphosphatase, Mfn2

We next attempted to determine whether MAVS associated with previously unidentified cellular components by analyzing immunoprecipitated samples derived from HEK 293 cells stably expressing Myc-tagged MAVS. Analysis of samples immunoprecipitated with an antibody against the Myc tag by liquid chromatography with tandem mass spectrometry (LC/MS/MS) identified several mitochondrial proteins (table S1). Plasmids encoding these proteins were individually coexpressed with a plasmid encoding MAVS by transient transfection of HEK 293 cells. Of these candidates, the mitochondrial outer membrane guanosine triphosphatase (GTPase) Mfn2, which mediates mitochondrial fusion (*20*), coimmunoprecipitated with MAVS (Fig. 1B). In addition, we confirmed that MAVS coimmunoprecipitated with endogenous Mfn2 in HEK 293 cells (Fig. 1C). The interaction between endogenous Mfn2 and MAVS was also observed in mouse embryonic fibroblasts (MEFs) (fig. S1). Consistent with this observation, MAVS and Mfn2 mRNAs showed similar expression patterns in human tissues (*15*, *21*), and the colocalization of both endogenous proteins to mitochondria was confirmed in MEFs by fluorescence microscopy (Fig. 1D). Although Mfn2 is a large transmembrane GTPase that is well known for mediating mitochondrial fusion, it has additionally been reported to act as an endoplasmic reticulum (ER)–mitochondrion tether (*22*), as a suppressor of cellular proliferation (*23*) and as a pathogenic factor in inherited peripheral neuropathy (*24*).

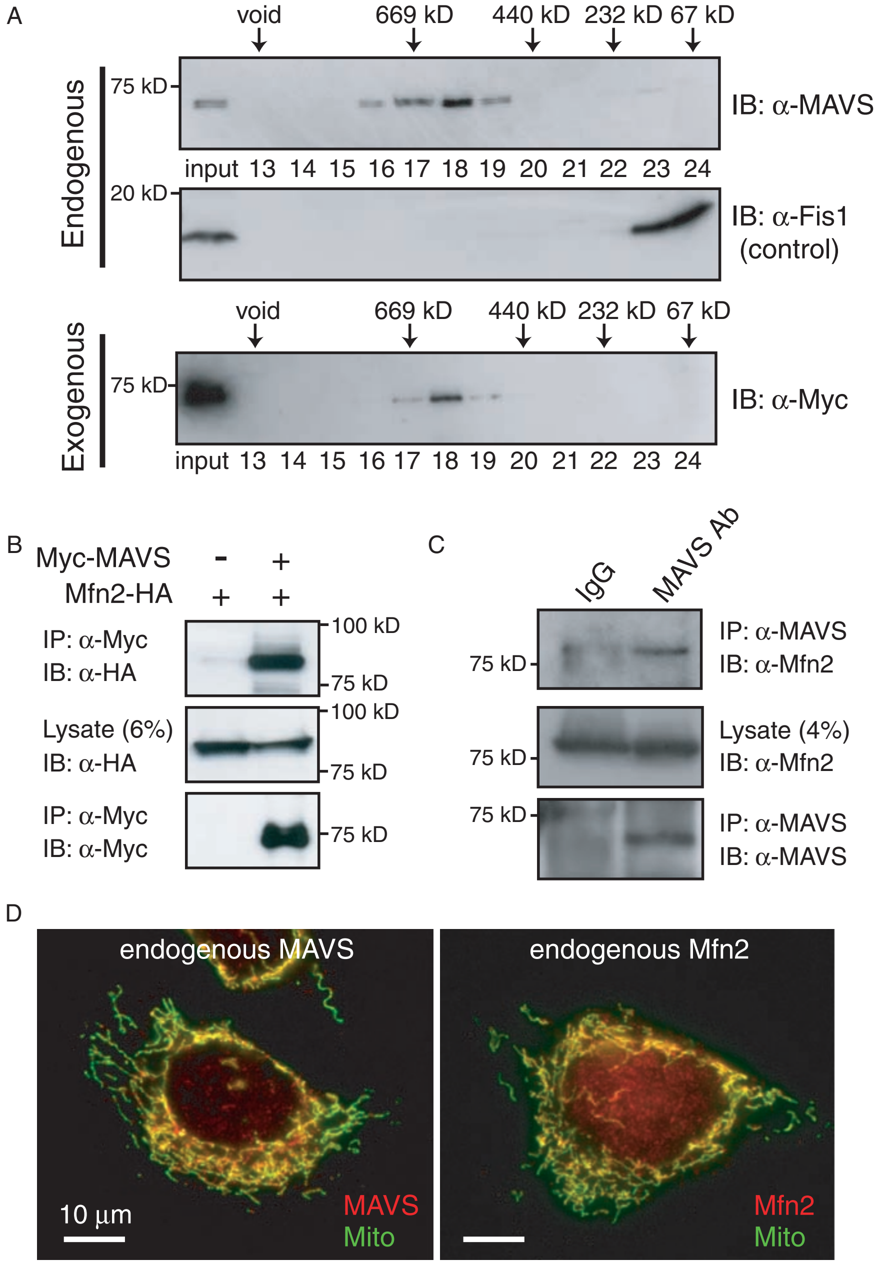

Fig. 1. MAVS is a component of a supramolecular protein complex. (**A**) Size exclusion chromatography (Superdex-200 HR-10/30 column) of endogenous and exogenous MAVS at pH 7.2. The positions corresponding to the elution of standard markers of molecular mass and the void volume are indicated. Fractions (numbered) were analyzed by Western blotting with a polyclonal antibody against hMAVS (to detect endogenous protein) or the 9E10 monoclonal antibody against Myc (to detect tagged protein), as well as with a polyclonal antibody against Fis1 for the control analysis. (**B**) HEK 293 cells were cotransfected with combinations of plasmids encoding HA-tagged Mfn2 and Myc-tagged MAVS, as indicated. Western blots of samples immunoprecipitated (IP) with an antibody against Myc or postnuclear cell lysates (lysate; 6% of the input) were analyzed by immunoblotting (IB) with either the monoclonal antibody HA.11 against HA or the monoclonal antibody 9E10 against Myc. (**C**) Interaction of endogenous Mfn2 with MAVS. Lysates of HEK 293 cells were subjected to immunoprecipitation with anti-MAVS polyclonal antibody or control IgG followed by the analysis of Western blots with an antibody against Mfn2. Lysate, 4% of the input. In (A) to (C), α denotes "anti-". (**D**) Endogenous MAVS (red) and Mfn2 (red) colocalize with mitochondria in MEFs. Mitochondria were stained with a monoclonal antibody against mtHsp70 (green). Scale bar, 10 µm.

Mfn2 inhibits MAVS-mediated activation of IRF-3 and NF-κB

Having identified Mfn2 as a component of the MAVS complex, we investigated whether this protein modulated MAVS-mediated activation of IFN-β and NF-κB reporter constructs. Although MAVS potently activated both IFN-β and NF-κB luciferase–based reporters, as seen previously (*9*, *14*–*16*), Mfn2 alone failed to activate either reporter construct (Fig. 2A). However, coexpression of Mfn2, but not the unrelated mitochondrial outer membrane protein Fis1, with MAVS was sufficient to inhibit MAVS-dependent activation of IFN-β and NF-κB reporters in a dose-dependent manner (Fig. 2B). This inhibitory activity was not observed with the Mfn2 homolog, Mfn1, despite the ~60% sequence identity between the two proteins (*21*), which indicated that the observed inhibitory activity toward MAVS-mediated signaling was specific to Mfn2 (Fig. 2C). The inhibition that resulted from the increased abundance of Mfn2 was not attributable to general mitochondrial dysfunction because most cells that contained both overexpressed MAVS and Mfn2 exhibited normal tubular mitochondrial morphology that was indistinguishable from that of untransfected cells (Fig. 2D).

Because MAVS-dependent antiviral signaling is potentiated by the recognition of viral dsRNA by the cytoplasmic RNA helicases RIG-I and MDA-5, we sought to determine the effect of Mfn2 on the ability of these sensor helicases and dsRNA to induce downstream activation of IRF-3 and the IFN-β reporter. Overexpression of the N-terminal CARD domains of RIG-I [designated as RIG-I(1–250) in this study] induces a robust intracellular antiviral response (*25*). Mfn2 dramatically reduced the ability of RIG-I(1–250) to activate the IFN-β reporter in a dose-dependent manner (Fig. 3A) and similarly reduced the production of endogenous IFN-β protein

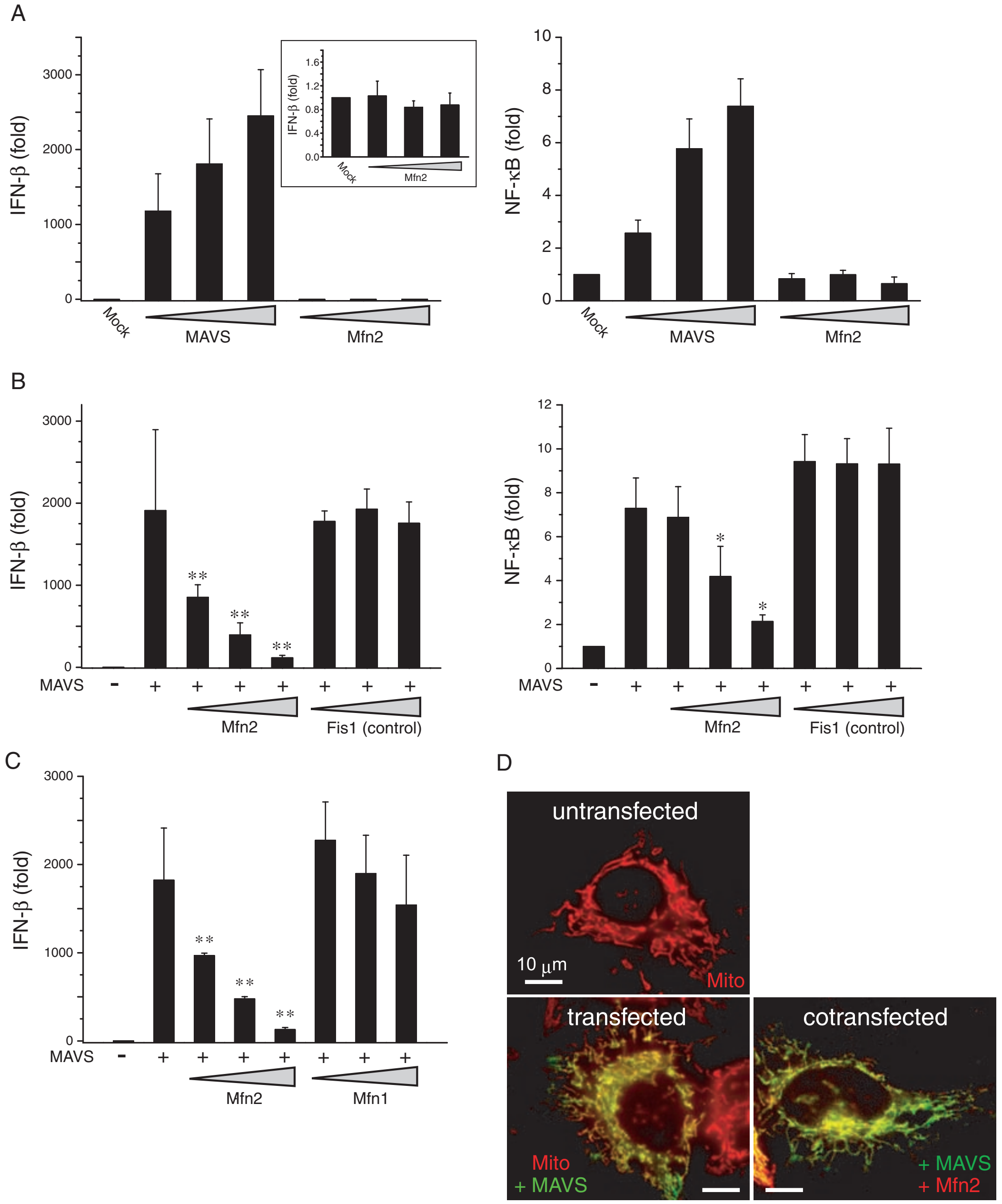

Fig. 2. Mfn2 inhibits MAVS-mediated activation of IFN-β and NF-κB reporters. (**A**) HEK 293 cells were transfected with empty vector (Mock) or increasing amounts (20, 50, and 100 ng) of plasmids encoding MAVS (positive control) or Mfn2 and with either IFN-β (left panel) or NF-κB (right panel) luciferase reporter plasmids. Inset: a magnified scale of Mfn2 result. (**B**) HEK 293 cells were cotransfected with 50 ng of a plasmid encoding MAVS and increasing amounts (20, 50, and 100 ng) of plasmids encoding Mfn2 or Fis1 (negative control) together with the same reporter plasmids used in (A). (**C**) The Mfn2 homolog, Mfn1, does not inhibit MAVS-mediated activation of IFN-β reporter. The resulting IFN-β reporter activity was determined as above. All data shown represent mean values ± SD (n = 3 experiments). *$P < 0.05$; **$P < 0.01$. (**D**) Immunofluorescence microscopy of untransfected HeLa cells, HeLa cells transfected with a plasmid encoding MAVS, or HeLa cells cotransfected with plasmids encoding MAVS and Mfn2. Cells were visualized with MAVS [enhanced green fluorescent protein; green], Mfn2 (Alex Fluor 568; red), and mitochondria (red fluorescent protein; red). Scale bar, 10 μm.

as determined by enzyme-linked immunosorbent assay (ELISA) (Fig. 3B). We additionally examined the activation of endogenous IRF-3 by performing gel-shift assays. Expression of RIG-I(1–250) promoted the hallmarks of IRF-3 activation, namely, its dimerization and phosphorylation (Fig. 3C), both of which were impaired by Mfn2 in a dose-dependent manner (Fig. 3C).

Overexpression of Mfn2 additionally abrogated the effect of MDA-5 in a dose-dependent manner (Fig. 3D). MDA-5 is the intracellular receptor for poly(I:C), a synthetic analog of viral double-stranded RNA (*26*, *27*). Consistent with previous findings, the delivery of poly(I:C) into HEK 293 cells by transient transfection stimulated the IFN-β response, which was suppressed by Mfn2 (Fig. 3E). In contrast, Mfn2 did not impair the IFN-β response to extracellular poly(I:C) (Fig. 3E). Taken together, these results indicate that Mfn2 acted as a negative regulator of RIG-I–, MDA-5–, and dsRNA-dependent antiviral signaling through MAVS and suggested that the association of MAVS and Mfn2 might underlie this inhibition.

Loss of endogenous Mfn2 results in enhanced RIG-I– and MDA-5–induced antiviral responses

The previous experiments showed that Mfn2 suppressed MAVS-dependent signaling. We therefore attempted to determine, through an RNA interference

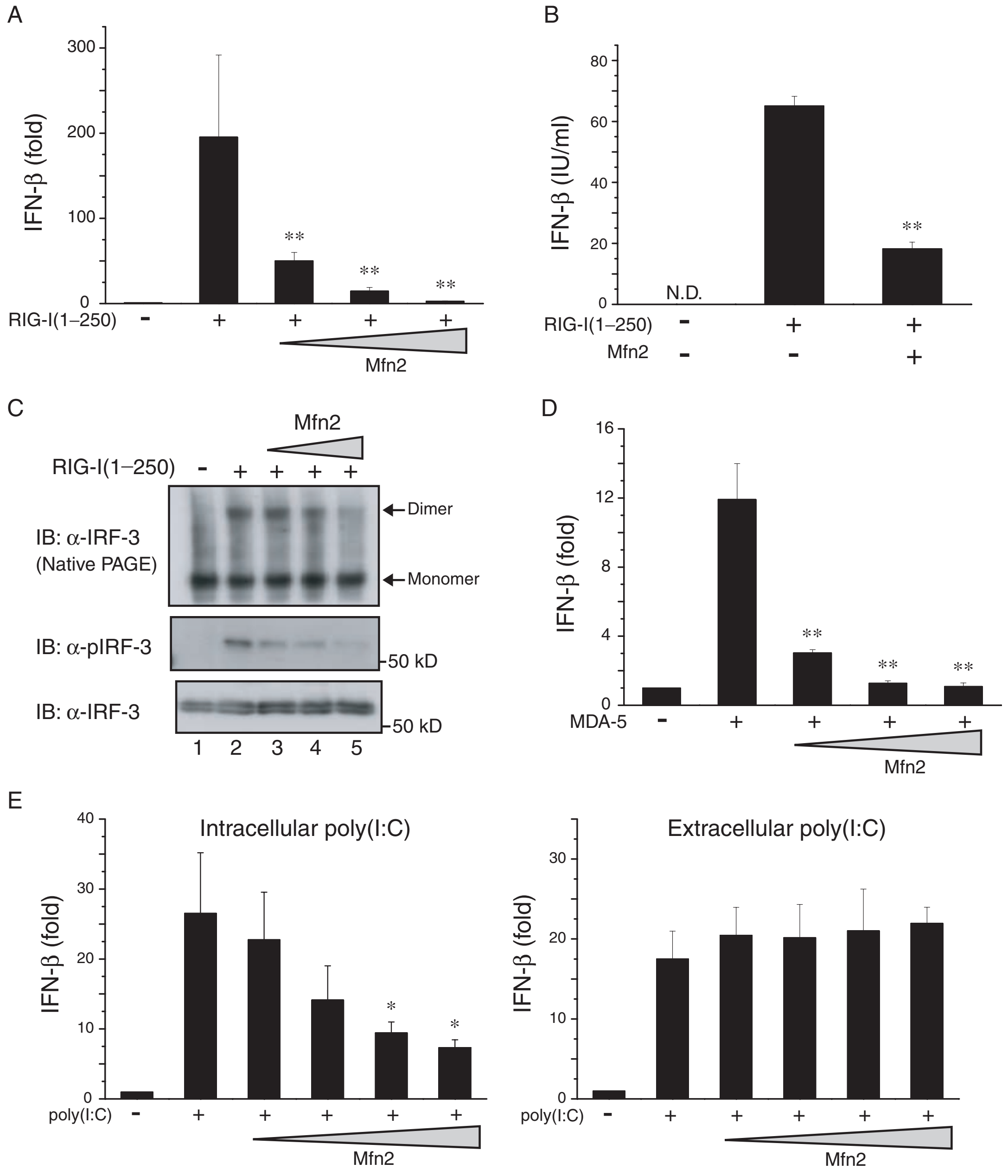

Fig. 3. Mfn2 suppresses IFN-β signaling mediated by RIG-I and MDA-5. (**A**) HEK 293 cells were cotransfected with 50 ng of plasmid encoding RIG-I(1–250) with increasing amounts (20, 50, and 100 ng) of a plasmid encoding Mfn2 together with the luciferase reporter plasmid p125luc. Transfected cells were analyzed 24 hours later for IFN-β–dependent luciferase activity. (**B**) HEK 293 cells were cotransfected with 200 ng of plasmid encoding RIG-I(1–250) and 200 ng of a plasmid encoding either pcDNA3.1 (negative) or Mfn2. Culture supernatants were harvested 24 hours after transfection and analyzed by ELISA to measure the production of IFN-β. (**C**) HEK 293 cells were cotransfected with 300 ng of a plasmid encoding RIG-I(1–250) and increasing amounts (100, 300, and 500 ng) of the plasmid encoding Mfn2. Cell lysates were resolved by electrophoresis under native (top panel) or denaturing conditions (middle and bottom panels) and then analyzed by Western blotting with the indicated antibodies. (**D**) Experiments were performed similarly to those in (A), except that the plasmid encoding MDA-5 was used in the transfections instead of the plasmid encoding RIG-I(1–250). (**E**) HEK 293 cells were transfected with various amounts (20, 50, 100, and 200 ng) of the plasmid encoding Mfn2 and were either cotransfected with poly(I:C) (left panel) or treated extracellularly with poly(I:C) (right panel). The resulting IFN-β reporter activity was determined as described earlier. All data shown represent mean values ± SD ($n = 3$ experiments). $^{*}P < 0.05$; $^{**}P < 0.01$.

approach, whether endogenous Mfn2 was responsible for modulating the MAVS-dependent transcriptional activation of the gene encoding IFN-β. Consistent with our previous findings, HEK 293 cells that had been treated with Mfn2-specific small interfering RNA (siRNA), which efficiently knocked down the amount of endogenous Mfn2 protein by greater than 90% (Fig. 4, A and B), exhibited enhanced induction of the IFN-β reporter construct in response to RIG-I(1–250) relative to that of control siRNA–transfected cells (Fig. 4B). Moreover, reintroduction of Myc-tagged Mfn2 into HEK 293 cells that had been treated with Mfn2-specific siRNA restored the suppressive effect on RIG-I(1–250)–dependent induction of the IFN-β reporter (Fig. 4C). HEK 293 cells also exhibited a differential response to an increased abundance of MAVS when treated with the Mfn2-specific siRNA, with increased activation of the IFN-β reporter and production of endogenous IFN-β relative to that of cells treated with the control siRNA (fig. S2, A and B). Knockdown of endogenous Mfn2 by siRNA similarly enhanced the activation of the IFN-β reporter and the production of IFN-β

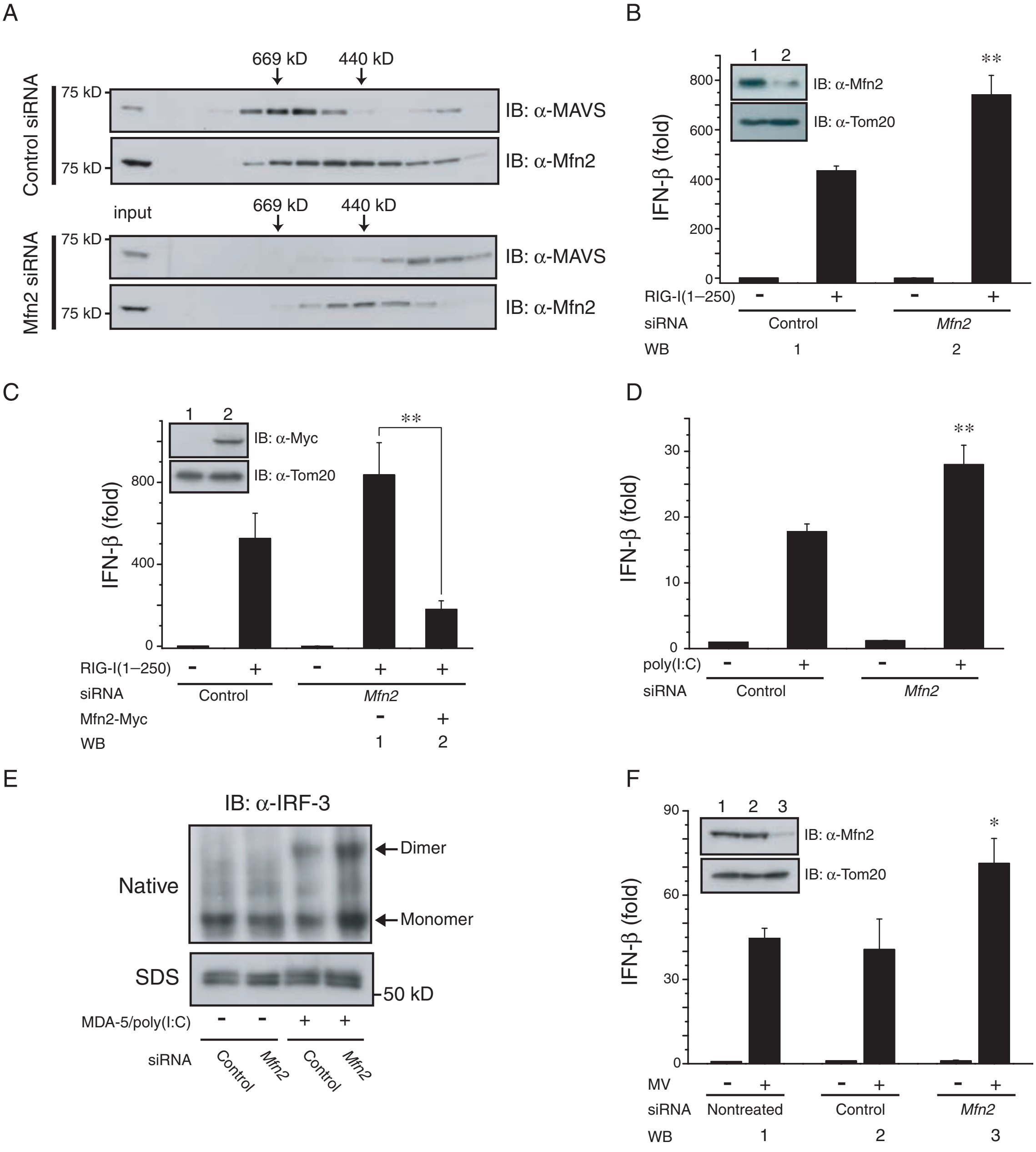

Fig. 4. Treatment with Mfn2-specific siRNA results in an enhanced antiviral response. (**A**) Gel filtration (Superose 6 HR-10/30) elution profiles of endogenous Mfn2 (as well as MAVS) extracted from the mitochondrial fraction of HEK 293 cells that had been treated with either control siRNA or siRNA specific for Mfn2. The positions corresponding to the elution of 669- and 440-kD molecular mass markers are indicated, and fractions were analyzed by Western blotting with antibodies against Mfn2 and MAVS. (**B**) HEK 293 cells were transfected with either control siRNA or siRNA specific for Mfn2 to evaluate the effect of knockdown of Mfn2 on the antiviral response. Twenty-four hours later, siRNA-treated cells were retransfected with the IFN-β reporter plasmid together with a plasmid encoding RIG-I(1–250). The efficiency of knockdown of Mfn2 (inset, lane 2) was confirmed by analysis of Western blots (WB) with a monoclonal antibody against Mfn2, and Tom20 was used as a loading control. (**C**) Experiments were performed similarly to those described in (B), except that IFN-β reporter-dependent luciferase activity was additionally measured after reintroduction of Myc-tagged Mfn2. Expression of the plasmid encoding Myc-tagged Mfn2 was confirmed by Western blotting analysis with an antibody (9E10) against Myc (inset, lane 2). (**D**) Experiments were performed similarly to those in (B), except that cells were transfected with poly(I:C) instead of the plasmid encoding RIG-I(1–250). (**E**) Knockdown of Mfn2 enhanced MDA-5–induced activation of IRF-3. (**F**) Activation of the IFN-β reporter in siRNA-treated HEK 293 cells infected with measles virus (MV) at an MOI of 2. All data shown represent mean values ± SD (*n* = 3 experiments). $^*P < 0.05$; $^{**}P < 0.01$.

protein in response to transfection with poly(I:C) (Fig. 4D and fig. S3), as well as increasing the amount of MDA-5–induced dimerized IRF-3 (Fig. 4E). Consistent with these findings, activation of the IFN-β reporter in response to infection with measles virus (MV), an RNA virus of the *Paramyxoviridae* family, was also enhanced in the cells treated with Mfn2-specific siRNA compared to that in control cells (Fig. 4F).

Given that our knockdown experiments failed to completely deplete Mfn2 protein (the effects were relatively modest), we evaluated IFN-β responses in wild-type (WT) and *Mfn2*-deficient MEFs (*28*). MAVS- and RIG-I–dependent production of IFN-β was significantly enhanced (>4-fold) in the *Mfn2*-deficient cells compared to that of WT cells (Fig. 5A). In addition, reintroduction of Myc-tagged murine Mfn2, but not that of its homolog mMfn1, fully restored suppression of IFN-β production in MEFs from $Mfn2^{-/-}$ mice (Fig. 5B), underscoring the importance of endogenous Mfn2 for the modulation of MAVS-mediated antiviral responses. When the $Mfn2^{-/-}$ MEFs were infected with a recombinant vesicular stomatitis virus (VSV) expressing green fluorescent protein (GFP) (VSVΔG*-G) (*29*), the production of IFN-β protein was substantially increased relative to that of infected WT and *Mfn1*-deficient MEFs (Fig. 5C), and the number of cells expressing GFP was significantly reduced only in the *Mfn2*-deficient MEFs, indicating their increased resistance to VSV infection (Fig. 5D). Furthermore, induction of IFN-β production by a positive-stranded RNA virus of the *Picornavirus* family, encephalomyocarditis virus (EMCV), was also greater in the *Mfn2*-deficient MEFs relative to that of WT MEFs (Fig. 5E), consistent with a role for Mfn2 as an inhibitor of the MAVS-mediated antiviral response.

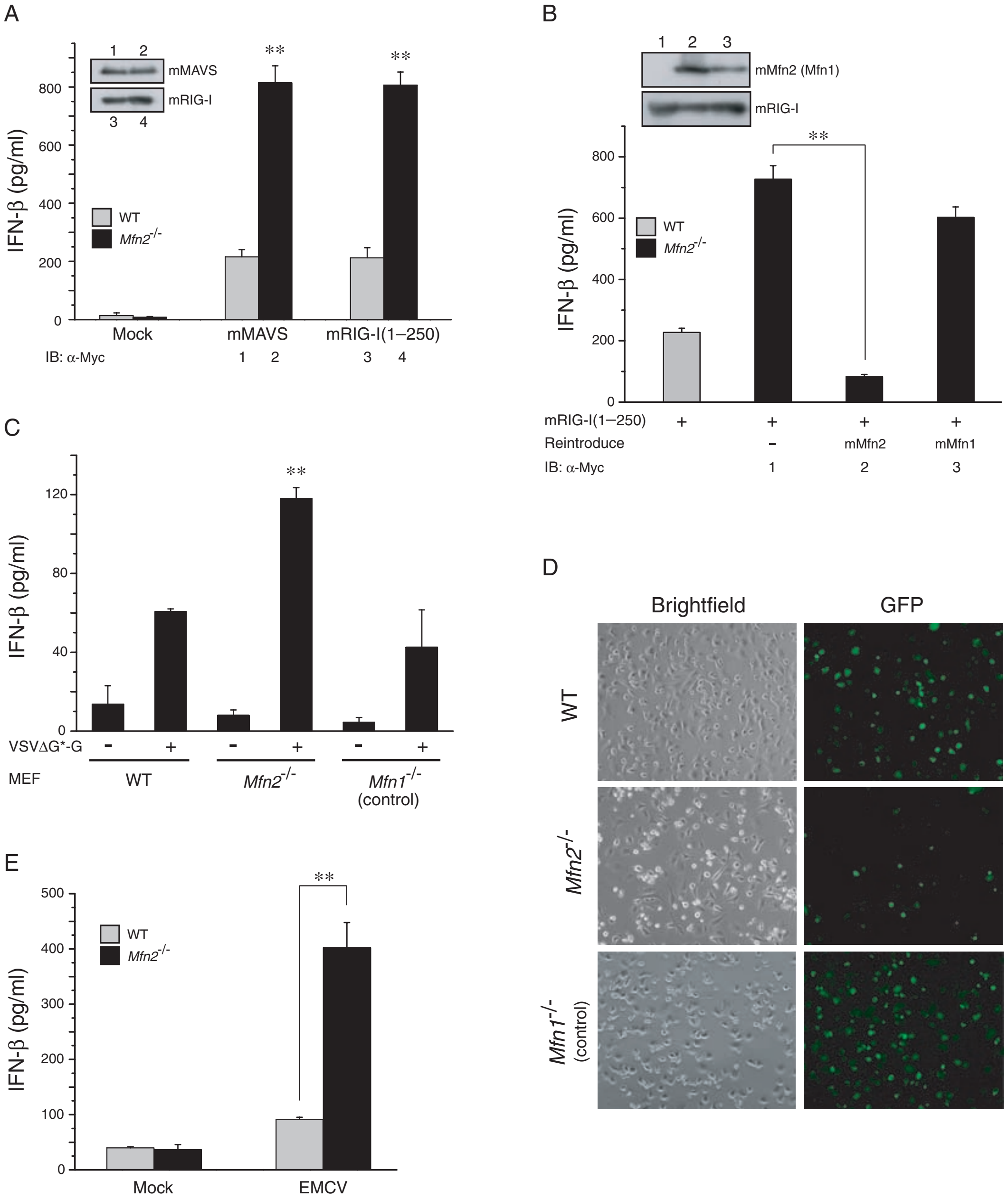

Fig. 5. The effect of Mfn2 deficiency on viral infection in MEFs. (**A**) WT and *Mfn2*-deficient MEFs were transfected with plasmids encoding either murine MAVS or mRIG-I(1–250), and the production of IFN-β was measured by ELISA 24 hours after transfection. Mock treatment of MEFs involved their transfection with equivalent amounts of pcDNA3.1(–). (**B**) Reconstitution of *Mfn2*-deficient MEFs with Mfn2 restores modulation of the IFN-β response. *Mfn2*-deficient MEFs were transfected with plasmids encoding mRIG-I(1–250) and either Myc-tagged mMfn2 or mMfn1, and culture supernatants were harvested 24 hours later for measurement of IFN-β production by ELISA. Expression of the plasmids encoding Mfn2 or Mfn1 was confirmed by analysis of Western blots with an antibody against Myc (inset, lanes 2 and 3). (**C**) This experiment was performed similarly to that described in (A) except that WT and *Mfn2*-deficient MEFs were infected with VSVΔG*-G at an MOI of 3. In this experiment, $Mfn1^{-/-}$ MEFs were also used as a control to evaluate the specificity of Mfn2 in modulating the antiviral response. (**D**) Fluorescence microscopy (GFP) of MEFs infected with VSVΔG*-G at an MOI of 3 for 24 hours. (**E**) WT and *Mfn2*-deficient MEFs were infected with EMCV at an MOI of 3, and the production of IFN-β was measured by ELISA. All ELISA data shown represent mean values ± SD ($n = 3$ experiments). $^{**}P < 0.01$.

The HR1 region of Mfn2 is critical for its interaction with MAVS

Through a coimmunoprecipitation approach, we mapped the region of Mfn2 that interacted with MAVS to a central 4,3 hydrophobic heptad repeat (HR1) region (Mfn2-HR1) (Fig. 6A). An analogous approach with deletion mutants of MAVS yielded results indicating that the C-terminal regions of MAVS (amino acid residues 201 to 540) were both necessary and sufficient for the interaction with Mfn2-HR1, and that both the CARD, which is important for the interaction between MAVS and cytoplasmic RNA helicases, and the proline-rich domain were dispensable for this interaction (Fig. 6B). The interaction between Mfn2-HR1 and MAVS was observed only with the transmembrane-anchored form of MAVS (C-term/TM), indicating that the Mfn2-HR1 fragment recognized a structural or topological element (or both) that was specific to the mitochondrial outer membrane–bound form of MAVS.

These results prompted us to investigate the functional role of the HR1 region in the regulation of the antiviral response. In HEK 293 cells, expression of a plasmid encoding the Mfn2-HR1 fragment potently and dose-dependently suppressed IFN-β and NF-κB responses to the overexpression of MAVS-, RIG-I(1–250), and MDA-5 (Fig. 6C and fig. S4) in a manner similar to that observed with full-length Mfn2, indicating that the HR1 region could behave as a dominant-negative modulator of antiviral signaling. Mutations of the predicted *f* position in the HR1 region (E424G and R468H) (fig. S5), which is exposed on the surface of the protein, resulted in a severe loss of function when we evaluated the ability of the mutated protein to modulate the RIG-I–induced IFN-β response, whereas a GTPase mutant of Mfn2 (Mfn2^{K109A}) behaved nearly similarly to WT Mfn2 (Fig. 6D). Although the HR1 region has been characterized as an im-

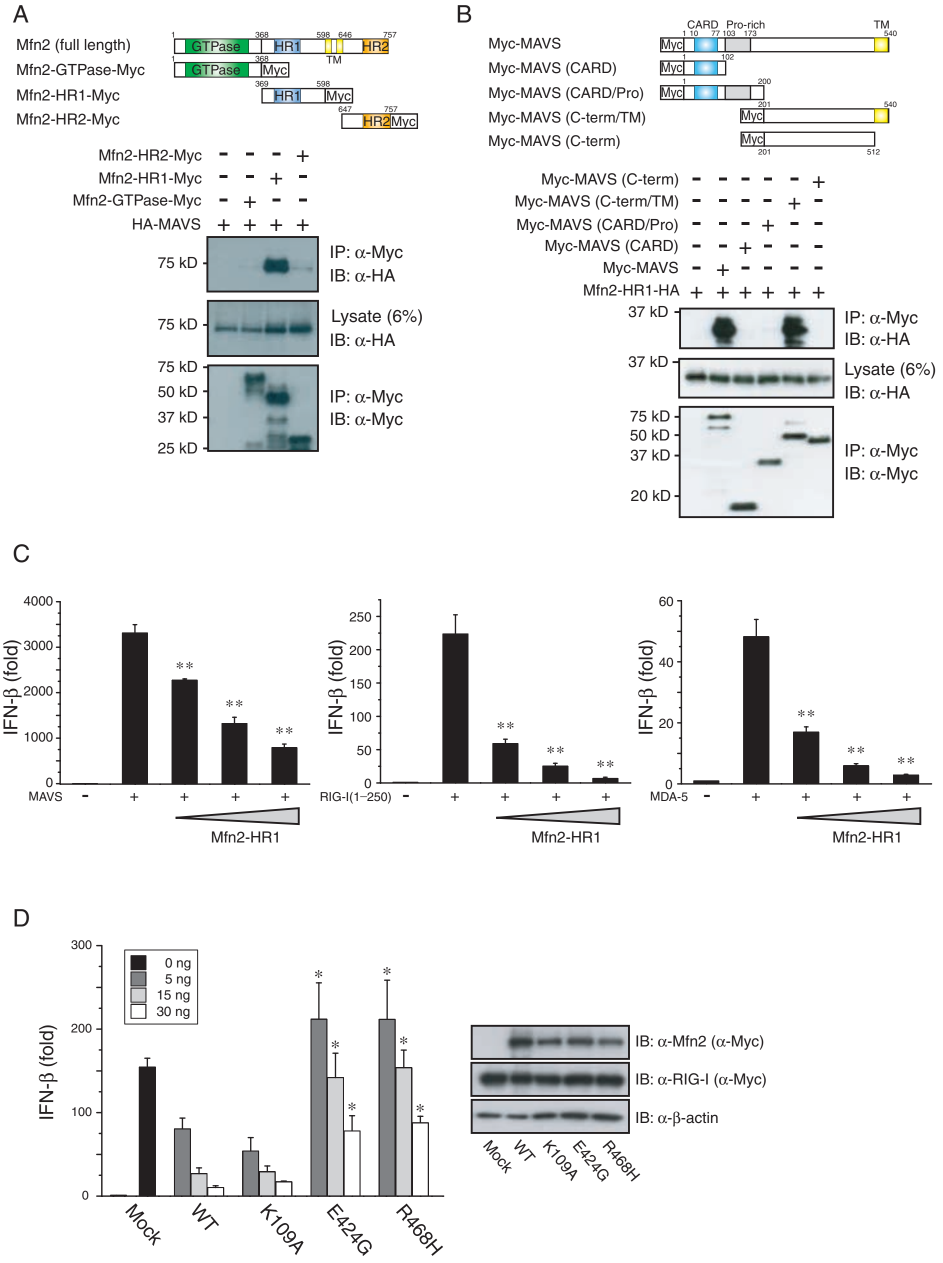

Fig. 6. The HR1 region of Mfn2 associates with MAVS and inhibits activation of the IFN-β reporter. (**A**) Interaction of HA-tagged MAVS and Myc-tagged Mfn2 variants (upper panel) was analyzed by coimmunoprecipitation assays, which were performed as described for Fig. 1B. The GTPase domain, hydrophobic heptad repeats (HR) 1 and 2, and transmembrane segment (TM) are depicted. (**B**) Interaction of truncated MAVS variants with the Mfn2-HR1 fragment. (**C**) HEK 293 cells were cotransfected with 50 ng of plasmids encoding either MAVS, RIG-I(1–250), or MDA-5 together with increasing amounts (20, 50, and 100 ng) of a plasmid encoding the Mfn2-HR1 fragment and the IFN-β luciferase reporter plasmid as described for Fig. 2. (**D**) HEK 293 cells were cotransfected with 50 ng of plasmid encoding RIG-I(1–250) and increasing amounts (5, 15, and 30 ng; inset) of plasmids encoding WT and mutant Mfn2 proteins together with the IFN-β reporter plasmid. Western blots showing the abundance of the WT and mutant Mfn2 proteins, as well as the abundance of stimulated RIG-I(1–250). All data shown represent mean values ± SD (*n* = 3 experiments). $^{*}P < 0.05$; $^{**}P < 0.01$.

portant domain for mitochondrial targeting (*30*) or fusion (*31*), its functional role in mitofusin homologs is still poorly understood. Our results indicate that the HR1 region of Mfn2 is critical for regulating the antiviral signaling pathway.

Mfn2 functions upstream of TRAF6 and TBK-1

Because Mfn2 was required for regulating antiviral signaling through MAVS, it was likely that Mfn2 acted downstream of (or at the same level as) MAVS in this pathway. In the course of examining the mechanism of its inhibitory activity, we found that Mfn2-specific siRNA had no effect either on the activation of the NF-κB reporter in response to tumor necrosis factor receptor-associated factor 6 (TRAF6) (Fig. 7A), an essential upstream regulator of the inhibitor of κB kinase complex, or on the activation of the IFN-β reporter in response to TANK-binding kinase 1 (TBK-1) (Fig. 7A), a kinase that targets IRF-3, even though both of these effectors act downstream of MAVS (*9*, *15*, *32*, *33*). Consistent with these findings, the production of the proinflammatory cytokine interleukin-6 (IL-6) by TRAF6 was also unaffected in *Mfn2*-deficient MEFs (Fig. 7B), suggesting that Mfn2 inhibited the RIG-I pathway downstream of MAVS and upstream of both TRAF6 (the NF-κB activation pathway) and TBK-1 (the IRF-3 activation pathway).

DISCUSSION

The mitochondrion is well known as the powerhouse of eukaryotic cells, and it is additionally involved in antiviral immunity in vertebrates (*9*–*13*). Despite the central role that the mitochondrial integral membrane protein MAVS plays in this pathway, few additional mitochondrial membrane proteins have been implicated in regulating its activity. In this study, we described our findings that Mfn2, a known mediator of mitochondrial fusion, interacted with MAVS to inhibit antiviral signaling pathways.

Our results show that MAVS forms a stable supramolecular assembly on the outer mitochondrial membrane at physiological pH. We propose that the MAVS complex is an Mfn2-dependent complex because knockdown of endogenous Mfn2 reduced the apparent molecular mass of MAVS, as determined by analytical size exclusion chromatography, from ~600 kD to a lower molecular mass (Fig. 4A). Because loss of endogenous Mfn2 also enhanced the MAVS-mediated antiviral response, it is possible that rearrangement of MAVS from a higher- to a lower-order complex is a prerequisite for the activation of MAVS in response to upstream signaling from RIG-I or MDA-5. Such a model would suggest that Mfn2 functions by stably sequestering MAVS in nonproductive higher-order complexes that are incapable of propagating a downstream antiviral response. A small portion of MAVS did not colocalize with Mfn2, as observed by both size exclusion chromatography (Fig. 4A) and immunofluorescence microscopy (Fig. 1D), raising the possibility that this fraction represents an available pool of MAVS that could be easily activated on viral infection. At present, it is unclear whether the lower-order state is more favorable for recruiting downstream molecules such as TRAF family members or whether it is preferentially competent for signaling to the IRF-3 or NF-κB activation pathways.

In conclusion, we propose a mechanism for the regulation of the cellular antiviral response in which signaling events at the mitochondrial outer membrane involving MAVS are modulated by Mfn2 through its HR1

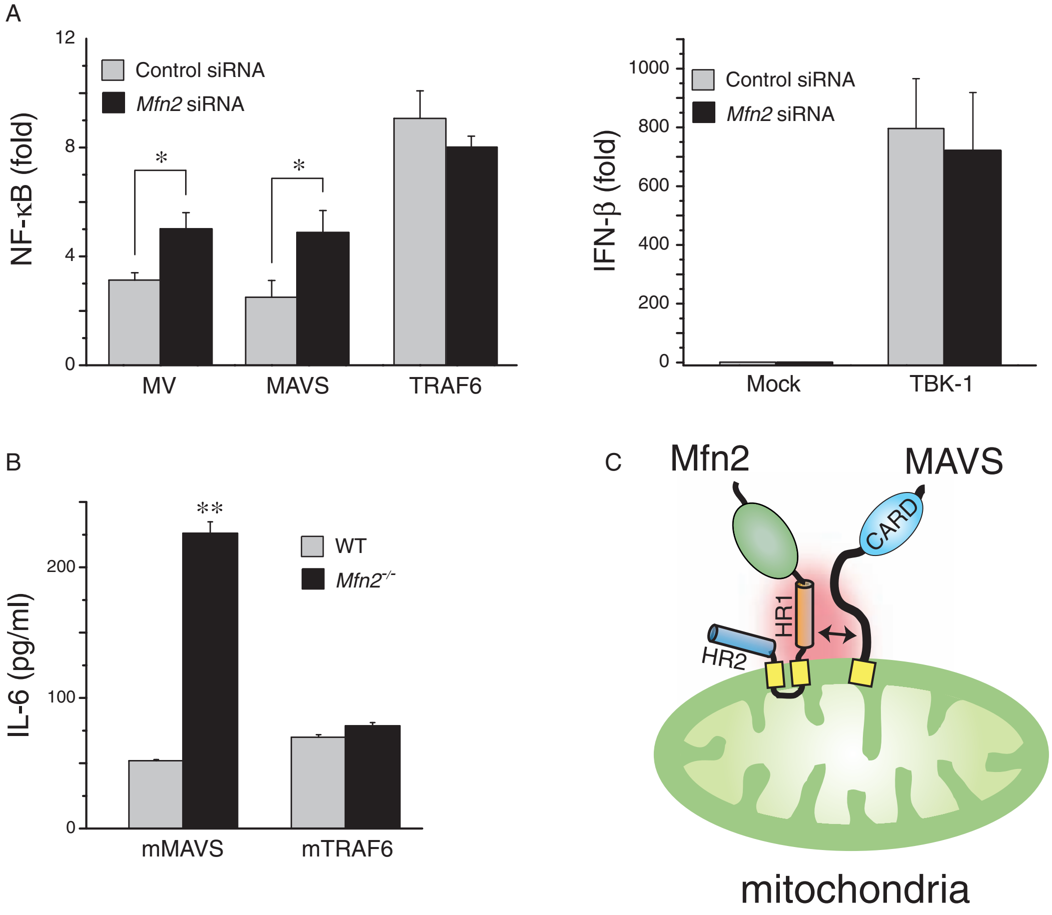

Fig. 7. The role of Mfn2 in antiviral signaling. (**A**) Activation of NF-κB (left panel) and IFN-β (right panel) reporters in siRNA-treated HEK 293 cells transfected with plasmids encoding MAVS, TRAF6, or TBK-1. In the control (left panel), cells were infected with measles virus (MV) at an MOI of 2. (**B**) WT and *Mfn2*-deficient MEFs were transfected with plasmids encoding either mMAVS or mTRAF6, and the subsequent production of IL-6 was measured by ELISA. All data shown represent mean values ± SD ($n = 3$ experiments). *$P < 0.05$; **$P < 0.01$. (**C**) Schematic representation of the MAVS-Mfn2 interaction on the mitochondrial outer membrane.

region (Fig. 7C) upon formation of a supramolecular complex. In this model, we speculate that Mfn2 inhibits the function of the C-terminal region (including the transmembrane domain) of MAVS rather than blocks its CARD, in contrast to previous findings with NOD-like receptor (NLR) family member X1 (NLRX1), a member of the cytoplasmic NLR family that also modulates MAVS-dependent antiviral signaling (*11*). Moreover, it is noteworthy that inhibition of MAVS-mediated antiviral signaling was not observed with Mfn1, which suggests that Mfn1 and Mfn2 are not functionally redundant and illustrates that Mfn2 has multiple specialized functions in the cell (*22*–*24*, *34*). A small amount of Mfn2 is thought to be present in the ER (*22*). In addition, stimulator of interferon genes (STING) [also termed MITA (*13*)], an essential mediator of the activation of IRF-3, is also present in the ER, mitochondria, or both and interacts with MAVS (*35*). Collectively, these findings raise questions about the interplay between the ER and mitochondria that control antiviral signaling and raise the possibility that Mfn2 may be involved.

MATERIALS AND METHODS

Cell culture

The HEK 293 and HeLa cell lines were maintained in Dulbecco's modified Eagle's medium (DMEM, GIBCO BRL) supplemented with 1% L-glutamine, 1% penicillin-streptomycin, and 10% bovine calf serum or 10% fetal calf serum, respectively, at 5% CO_2 and 37°C. WT, *Mfn1*$^{-/-}$, and *Mfn2*$^{-/-}$ MEFs were provided by D. Chan (Howard Hughes Medical Institute, Caltech) and maintained in standard medium (DMEM supplemented with 10% bovine calf serum) as described previously (*28*). Immunofluorescence microscopy to visualize mitochondria was performed as described previously (*19*, *28*).

Plasmid constructions and mutagenesis

Total messenger RNA (mRNA) from HEK 293 and MEFs was isolated with the TRIzol reagent (Invitrogen) and reverse-transcribed with moloney murine leukemia virus reverse transcriptase (Wako Pure Chemical Industries, Tokyo, Japan). Polymerase chain reaction assays were performed with PrimeSTAR DNA polymerase (Takara, Tokyo, Japan). The following primers (see Supplementary Materials for sequences) were used to generate the complete open reading frames of human MAVS: TK349/TK356; hMfn2: TK365/TK366; hMfn1: TK363/TK364; hFis1: TK367/TK368; hRIG-I(1–250): TK357/TK358; hMDA-5: TK442/TK443; hTBK-1: TK497/TK498; murine MAVS: TK300/TK307; and mRIG-I(1–250): TK310/TK345. Plasmids encoding epitope-tagged MAVS proteins were constructed by ligating the MAVS cDNA into Not I– and Eco RV–digested pcDNA3.1(−) vector (Invitrogen) that encoded either an N-terminal 3× Myc or 3× hemagglutinin (HA) tag. The hMfn2, hMfn1, hRIG-I(1–250), and hMDA-5 cDNAs were ligated into pcDNA3.1 that encoded either a C-terminal 7× Myc or a 3× HA tag.

Antibodies

Antibodies against human MAVS (hMAVS) and murine MAVS (mMAVS) were generated by immunizing rabbits with either recombinant N-terminal histidine-tagged hMAVS (amino acid residues 1 to 175) or mMAVS (amino acid residues 1 to 173), respectively. The recombinant proteins were overexpressed in *Escherichia coli* and purified from solubilized inclusion bodies. The immunoglobulin G (IgG) fractions were affinity-purified with the Econo-Pac Protein A Kit (BioRad). Monoclonal antibodies against Myc (9E10) and HA (HA.11) were purchased from Covance. Monoclonal antibodies against hMfn2, hTom20, IRF-3, and β-actin were obtained from Santa Cruz, and the rabbit monoclonal antibody (4D4G) against phosphorylated IRF-3 (at Ser^{396}) was from Cell Signaling. The Alexa Fluor 568–conjugated monoclonal antibody against mouse IgG was purchased from Molecular Probes. Polyclonal antibody against hFis1 was from ALEXIS Biochemicals. The monoclonal antibody against mitochondrial heat shock protein 70 (mtHsp70) was from Affinity BioReagents. The polyclonal antibody against rat Mfn2 was a gift from K. Mihara (Kyushu University, Japan).

Analytical size exclusion chromatography

Three 10-cm dishes of confluent HEK 293 cells were washed once with cold 1× phosphate-buffered saline (PBS) (pH 7.2), and cells were scraped off and lysed in 1 ml of homogenization buffer [20 mM Hepes (pH 7.5), 70 mM sucrose, and 220 mM mannitol] by 30 strokes in a Dounce homogenizer. The homogenate was centrifuged at 800*g* for 5 min to precipitate nuclei, and the resulting supernatant was further centrifuged at 10,000*g* for 10 min at 4°C to precipitate the crude mitochondrial fraction. After the pellet was washed once with homogenization buffer, the mitochondrial extracts were prepared by solubilization with lysis buffer [50 mM tris-HCl (pH 7.2), 200 mM NaCl, 10% glycerol, and 1% digitonin] and clarification by centrifugation at 12,000*g* for 5 min. Size exclusion chromatography of mitochondrial extracts was performed on Superdex-200 HR-10/30 or Superose 6 HR-10/30 columns (GE Healthcare) equilibrated with 50 mM tris-HCl (pH 7.2) containing 200 mM NaCl, 10% glycerol, and 0.1% NP-40. Extracts were loaded onto the column at a flow rate of 0.3 ml/min at room temperature. Fractions (600 μl each) were collected, resolved by 8% SDS–polyacrylamide gel electrophoresis (SDS-PAGE), and analyzed by Western blotting with either a polyclonal antibody against hMAVS (see above) or a monoclonal antibody against hMfn2. For the analysis of Fis1, fractions were resolved by 15% SDS-PAGE followed by Western blotting analysis with a polyclonal antibody against hFis1. The following molecular weight standards (GE Healthcare) were used: Blue Dextran-2000 (2000 kD), thyroglobulin (669 kD), ferritin (440 kD), catalase (232 kD), and bovine serum albumin (67 kD).

Immunoprecipitation of the hMAVS complex

HEK 293 cells were transfected with the expression plasmid encoding 3× Myc-tagged hMAVS (see above) by the calcium phosphate method. Transfected cells were selected in DMEM medium supplemented with hygromycin B (200 μg/ml; Wako Pure Chemical Industries) for 2 weeks. Stably transfected cells were grown to confluence on five 15-cm dishes. Cells were washed three times with 1× PBS (pH 7.2) and lysed with 10 ml of lysis buffer [20 mM Hepes (pH 7.5), 150 mM NaCl, 10% glycerol, 1 mM EDTA, 1 mM DTT, and 1% digitonin] supplemented with Complete Mini Protease Inhibitor Cocktail (Roche). The clarified supernatant was incubated with monoclonal antibody against the Myc tag (9E10) at 4°C for 2 hours, after which 60 μl of protein A–Sepharose beads (GE Healthcare) was added. After incubation for 5 hours at 4°C, the beads were washed three times with lysis buffer, and immunoprecipitates were resolved by 10% SDS-PAGE. Silver-stained bands were analyzed by LC/MS/MS (Medical Institute of Bioregulation, Kyushu University, Japan).

Coimmunoprecipitations

Coimmunoprecipitation experiments were performed as described previously (*36*) with minor modifications. HEK 293 cells at 80% confluence were transiently transfected with the appropriate plasmids (2 μg each) in a six-well plate by the calcium phosphate method. Two days after transfection, cells were lysed with 1 ml of lysis buffer [50 mM tris-HCl (pH 7.4), 150 mM NaCl, 10% glycerol, and 1% NP-40], and the clarified supernatants were incubated overnight at 4°C with 20 μl of agarose beads (Sigma-Aldrich) conjugated to a polyclonal antibody against *c*-Myc. After four washes with 1× PBS (pH 7.2), immunoprecipitates were resolved by 8 or 12% SDS-PAGE and analyzed by Western blotting with a monoclonal antibody (HA.11) against the HA tag followed by a horseradish peroxidase (HRP)-conjugated antibody against mouse IgG (Jackson ImmunoResearch). To immunoprecipitate endogenous MAVS, HEK 293 cells and MEFs were lysed with 1% digitonin lysis buffer, and the clarified supernatants were incubated with 10 μg of antibody against hMAVS or mMAVS, followed by incubation overnight at 4°C with 20 μl of protein A–Sepharose beads. The beads were washed four times with lysis buffer, and immunoprecipitates were resolved by 8% SDS-PAGE, analyzed by Western blotting with a monoclonal antibody against hMfn2, and detected with a HRP-conjugated antibody against mouse IgG.

Luciferase assays

HEK 293 cells (2×10^5 cells per well) were plated in 24-well plates. The following day, cells were cotransfected with 100 ng of a luciferase reporter plasmid (p125luc or pELAM), 2.5 ng of the *Renilla* luciferase internal control vector phRL-TK (Promega), and each of the indicated plasmids with the Lipofectamine 2000 reagent (Invitrogen). Empty vector [pcDNA3.1(−)] was used to maintain equivalent amounts of DNA in each well. Cells were harvested 24 hours after transfection and analyzed by a dual-luciferase reporter assay on the GloMax 20/20n luminometer (Promega). Each experiment was replicated at least three times. The p125luc reporter plasmid was provided by T. Taniguchi (University of Tokyo, Japan).

Native PAGE

Native PAGE experiments were performed as described previously (*37*).

RNA interference

For RNA interference–based knockdown experiments, a 25-nucleotide siRNA was purchased from Invitrogen (Stealth Select RNAi). HEK 293 cells were transfected with 50 nM siRNA (final concentration) with Lipofectamine RNAiMAX (Invitrogen). The following day, cells were transfected with luciferase reporter plasmids and then harvested after an additional 24 hours. The designation and sequence (sense strand only) of the Stealth Select RNAi oligonucleotides used in the study were hMfn2 (HSS115028) and 5′-ggaccuccaugggcauucuuguugu-3′, respectively. Stealth RNAi Negative Control Medium GC Duplex #2 (Invitrogen) was used as the control.

ELISA

Production of IFN-β by HEK 293 cells and MEFs was measured with species-specific ELISA reagents for human and murine IFN-β from Kamakura Techno-Science Inc. (Kanagawa, Japan) and PBL Biomedical Laboratories, respectively. The ELISA kit for murine IL-6 was purchased from R&D Systems.

Viral infections

The siRNA-treated HEK 293 cells, which were also cotransfected with reporter plasmids, were plated in 12-well plates and incubated overnight. When the cells were 50% confluent, the culture medium was aspirated and the cells were infected with 200 μl of the Edmonston strain of measles virus (*38*) at 37°C at a multiplicity of infection (MOI) of 2. One hour after infection, cells were supplemented with 800 μl of standard DMEM, then incubated for another 48 hours before the performance of luciferase assays. MEFs were infected with either VSVΔG*-G (*29*) or EMCV (*25*) at an MOI of 3 and incubated for 24 hours before analysis by ELISA, as described above.

SUPPLEMENTARY MATERIALS

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Materials
Fig. S1. Interaction between endogenous mMfn2 and mMAVS in MEFs.
Fig. S2. Knockdown of Mfn2 with specific siRNA results in enhanced MAVS-mediated activation of the IFN-β reporter.
Fig. S3. Treatment of HEK 293 cells with Mfn2-specific siRNA increased the production of endogenous IFN-β in response to transfection with poly(I:C).
Fig. S4. Mfn2-HR1 is a dominant-negative modulator of MAVS-mediated activation of NF-κB.
Fig. S5. Sequence alignment of Mfn2 homologs within HR1.
Table S1. List of mitochondrial proteins, other than Mfn2, that were identified by LC/MS/MS.
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