STING inhibitors target the cyclic dinucleotide binding pocket

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Significance

cGAS (cytosolic DNA sensor cyclic AMP-GMP synthase)-STING (stimulator of interferon genes) signaling is critical for sensing cytosolic DNA to initiate host immune responses against invading pathogens and cancer. However, inappropriate activation of STING signaling causes severe and often fatal autoimmune or autoinflammatory diseases. Hence, STING is an attractive drug target for the treatment of STING-driven autoimmune and inflammatory disorders. Therefore, there is a need to identify lead compounds that effectively inhibit human STING for further drug development. Here, we identified and characterized a STING-specific inhibitor SN-011 with high efficiency, specificity, and safety, paving the way for therapeutically manipulating STING-mediated clinical diseases.

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Cytosolic DNA activates cGAS (cytosolic DNA sensor cyclic AMP-GMP synthase)-STING (stimulator of interferon genes) signaling, which triggers interferon and inflammatory responses that help defend against microbial infection and cancer. However, aberrant self-DNA leads to chronic IFN expression, which has been implicated in the development of some autoimmune disorders (25). Genetic mutations of genes that cause cytosolic accumulation of nucleic acids, including the DNase TREX1, RNASEH2A-C, SAMHD1, ADAR, and MDA5, cause a broad spectrum of inflammatory and autoimmune phenotypes, including Aicardi–Goutières syndrome (AGS), familial chilblain lupus, and systemic lupus erythematosus (SLE) (26–28). Trex1 deficiency in mice causes inflammatory myocarditis, progressive cardiomyopathy, and circulatory failure. Trex1-deficient mice lacking STING are completely protected from otherwise lethal inflammatory diseases, indicating the central role of STING in disease pathogenesis. Moreover, gain-of-function (GOF) mutations in STING cause early-onset vasculopathy and pulmonary inflammation in patients, known as STING-associated vasculopathy with onset in infancy (SAVI) (29, 30). In addition, in some IFN or inflammation-driven disorders, including senescence, lethal sepsis, acute pancreatitis, Parkinson’s...
SN-011 is a Potent STING Inhibitor. To identify more potent inhibitors, a structure–activity relationship (SAR) study of SN-001 was performed using a set of seven SN-001 analogs, SN-005 to SN-011 (Fig. 1A and B). Removal of the phenyl group (SN-007) in SN-001 impaired STING inhibition of IFnb induction in L929 transfected with HT-DNA. When the phenoxy methyl group was substituted by a phenyl acetate (SN-010) or phenol hydroxyl (SN-011), the compounds suppressed STING signaling more efficiently (Fig. 1A and B) with half maximal inhibitory concentration (IC_{50}) values of 81 nM and 76 nM, respectively, which were comparable to the IC_{50} of the cytosine-reactive STING covalent inhibitor H-151 (88 nM) (42). None of the series significantly affected basal IFnb gene expression (SI Appendix, Fig. S1J). SN-011 (1 μM) significantly suppressed the induction of Ifnb, Cxcl10, and Il6 mRNA in MEFs activated by various canonical STING stimulators (ISD, HT-DNA, HSV-1, c-di-GMP, and 2′3′-cGAMP) (Fig. 1C–E). The effect on STING was specific since IRF3 and NF-kB–responsive gene expression was not inhibited by SN-011 in Tmem173+MEFs challenged with LPS (Toll-like receptor 4, TLR4, agonist), CpG-DNA (TLR9 agonist), poly (I:C) (TLR3 agonist), or Sendai virus (SeV, Retinoic acid-inducible gene I, RIG-I, stimulator) (Fig. 1F and G). Thus, SN-011 is a specific inhibitor of STING-dependent signaling.

To further explore the inhibitory property of SN-011, we determined IC_{50} in different cell lines. SN-011 was active at nanomolar concentrations to inhibit 2′3′-cGAMP-induced Ifnb expression in MEFs, mouse bone marrow-derived macrophages (BMDMs) and human foreskin fibroblasts (HFFs) with IC_{50} values of 127.5, 107.1, and 502.8 nM, respectively (Fig. 1H–J). In comparison, the IC_{50} values of H-151 in BMDMs, MEFS, and HFFs were 138, 109.6, and 134.4 nM (Fig. 1H–J), indicating SN-011 and H-151 exhibit comparable inhibitory effects on mouse STING-dependent signaling in cell-based assays. Like SN-001, SN-011 was not cytotoxic in BMDMs and HFFs when added at 1.25 to 20 μM (SI Appendix, Fig. S1 K and L). These studies identify SN-011 as a lead compound with nanomolar activity for inhibiting STING in both human and mouse cells.

SN-011 binds to the CDN binding domain of STING. To confirm SN-011 functions by targeting the STING CDN binding domain, a biotinylated SN-011 derivative (SN-012) was synthesized by chemically attaching biotin to the hydroxyl group of SN-011. Biotinylation
had little effect on STING inhibition (Fig. 3A). A biotin pull-down confirmed that SN-012 bound to STING, but not other components of the STING pathway (Fig. 3B and C). Moreover, an excess of SN-011, but not SN-100, competed with SN-012 for binding to tagged STING or tagged soluble STING lacking the transmembrane domain (TM) region (amino acids 149 to 379) (Fig. 3D and E). Confocal microscopy revealed cytoplasmic perinuclear colocalization of STING and SN-012 (Fig. 3F). To
Fig. 2. SN-011 inhibits STING activation and signal transduction. (A) HFFs were pretreated with SN-011 or SN-100 (1 μM) and then stimulated with 2′,3′-cGAMP for 1 h. STING phosphorylation and oligomerization were analyzed by immunoblot probed for STING. (B) HFFs, pretreated with SN-011 or SN-100 (1 μM) or DMSO control, were infected with HSV-1 for 4 h before immunostaining for STING and GM130 (Golgi autoantigen) and confocal microscopy imaging. (C) HFFs, pretreated with SN-011, were stimulated with HT-DNA for 1 h or 2′,3′-cGAMP for 30 min before immunostaining for STING, calreticulin, and GM130 and subsequent confocal microscopy imaging analysis (Upper). Quantification of cells with STING puncta that colocalize with the Golgi (Lower). (D) HFFs were pretreated with SN-011 or SN-100 (1 μM) before infecting with HSV-1 for 3 h. Cell lysates were immunoprecipitated with STING antibody and immunoblotted with indicated antibodies. (E) HFFs, pretreated or not with SN-011 or SN-100 (1 μM) were stimulated with 2′,3′-cGAMP for 2 h and then analyzed for phosphorylated (p)-IRF3, TBK1, IκBα, and p65, and IRF3 dimerization by immunoblot. (F) HFFs, pretreated or not with SN-011 or SN-100 (1 μM), were stimulated with 2′,3′-cGAMP for 2 h. Cells were then immunostained with anti-IRF3 and imaged by confocal microscopy. (Left and Center) Representative images (Right) quantification of cells with nuclear IRF3. (G) HeLa, pretreated or not with SN-011 or SN-100 (1 μM), were stimulated with 2′,3′-cGAMP for 2 h and immunostained with anti-p65 and imaged by confocal microscopy. (Left and Center) Representative images (Right) quantification of cells with nuclear p65. Data in B, C, F, and G are mean ± SD from three independent experiments. The images are 63x magnification with a digital scan zoom of 3.0 that was used to enhance magnification. **P < 0.01. (Scale bars, 25 μm.)
confirm the STING binding site of SN-012, full-length STING and STING truncation mutants lacking the TM domain (amino acids 1 to 137), CBD (amino acids 138 to 340), or the C-terminal tail (CTT, amino acids 341 to 379) were expressed in HEK293T cells. A streptavidin pull-down of cell lysates was performed after adding SN-012. Loss of the TM domain or CTT did not affect STING binding to SN-012, but deletion of the CBD abolished the interaction (Fig. 3G), confirming that SN-012 binds to the STING CBD.

**Mutation at the STING–SN-011 Interface Decreases the Inhibitory Effect of SN-011.** In silico docking was used to determine the interaction between human STING CTD (PDB ID code 4EFS) and SN-011. The docking structure suggested that two molecules of SN-011 were in the STING CDN binding pockets (Fig. 4E). Each SN-011 aligned along the STING dimer interface with the biphenyl group at the base (Fig. 4F). In the docking structure, SN-011 was anchored to the STING dimer interface by a combination of hydrogen bonds and a stacking interaction (Fig. 4F). Notably, the biphenyl base...
group of SN-011 stacked against the aromatic ring of Tyr167 and was further stabilized by Glu-260. The phenolic hydroxyl and sulfonamide groups of SN-011 formed several hydrogen bonds with Leu212, Ser243, and Tyr245. Consistently, substitution of the hydroxyl group, which interacted with Ser243 via hydrogen bonding, with hydrogen (SN-007) or a methyl group (SN-008), significantly decreased inhibitory activity (Fig. 1 A and B). As the fluorobenzene group in SN-011 did not interact with soluble human STING in the structure, we synthesized an analog of SN-011, named SN-013, without the fluorobenzene group. SN-013 inhibited 2′,3′-cGAMP-induced Ifnb gene expression with IC<sub>50</sub> values of 101.5 nM, and 539.6 nM in MEF and HFF cells, respectively, which were comparable to those of SN-011 (Fig. 4 B and C).

To confirm that the key STING residues identified by structural analysis mediate SN-011 binding, surface plasmon resonance (SPR) was used to measure the binding affinity and kinetics between SN-011 and soluble human STING. Soluble human STING bound SN-011 with an affinity (K<sub>d</sub>) of 4.03 nM (Fig. 4D), which is lower than that of the natural 2′,3′-cGAMP ligand (K<sub>d</sub> = 9.23 nM) (Fig. 4E). Notably, the binding kinetics of SN-011 (fast association and dissociation) and 2′,3′-cGAMP (slow association and dissociation) were markedly different. In contrast to WT STING, the S243A mutant had lower binding affinities to SN-011 (K<sub>d</sub> = 176 nM) (Fig. 4F) and the control compound SN-100 did not bind (Fig. 4G).

Next, we examined the effect of the mutants on STING signaling and SN-011 inhibition. Overexpression of S243A mutant induced less IFNB than WT STING both basally and in the presence of 2′,3′-cGAMP and SN-011 was less active at inhibiting what IFNB was produced (Fig. 4H and I). Taken together, these data confirm that the identified residues in the STING dimer interface mediate binding of SN-011 and its inhibitory activity.

**SN-011 Abrogates SAVI-Associated Mutant STING Signal Activation.**

To evaluate the therapeutic potential of SN-011, we tested its in vitro ability to inhibit the autoactivation of human STING carrying GOF mutations N154S, V155M, G166E, C206Y, R281Q, and R284G linked to SAVI, an autoinflammatory disease caused by GOF mutations in TRME173, the gene encoding STING (29, 30, 48, 49). WT and SAVI-linked mutated human STING were expressed in HEK293T cells. Cells expressing the GOF human STING mutants exhibited high levels of IFNB, CXCL10, and TNFα mRNA, which were inhibited by incubation with SN-011 (SI Appendix, Fig. S3 A). SN-011 incubation also markedly decreased the recruitment of TBK1 and IRF3 to the STING signalosome, assessed by STING pull-down (SI Appendix, Fig. S3B), and also reduced TBK1 and IRF3 phosphorylation induced by STING SAVI mutants (SI Appendix, Fig. S3C). These GOF mutants spontaneously oligomerize more than WT STING when expressed in HEK293T cells (13, 14), SN-011 disrupted oligomerization by WT as well as mutant STING (SI Appendix, Fig. S3D). Notably, SN-011 significantly inhibited the spontaneous accumulation of STING GOF mutants with the Golgi apparatus, suggesting that SN-011 locks STING GOF mutants into a conformation that is incompatible with ER-to-Golgi translocation (SI Appendix, Fig. S4A and B). Together, these data suggest that SN-011 could be used to inhibit STING activation caused by either WT STING or mutant STING in SAVI patients.

**SN-011 Suppresses Systemic Inflammation in Trexl<sup>+</sup>-Mice.**

Accumulation of cytosolic self-DNA causes severe and fatal STING-dependent IFN-mediated autoimmune disease especially in the heart and other muscles in Trexl<sup>+</sup>-mice (26, 50, 51). To begin to evaluate whether SN-011 could be used therapeutically to inhibit STING signaling, BMDMs, harvested from WT and Trexl<sup>+</sup>-mice, were treated for 12 h with 500 nM SN-011 or DMSO and then analyzed by RNA-sequencing (RNA-seq) (Fig. 5A). SN-011 treatment significantly reduced the IFN signature of Trexl<sup>+</sup>-BMDMs, which was confirmed by measuring expression of Ifnb and representative IFN-stimulated genes (ISGs) by quantitative PCR (Cxcl10, Isg15, and Iil6) (Fig. 5B). To test the ability of SN-011 to protect Trexl<sup>+</sup>-mice, SN-011 (5 mg/kg) or medium was injected intraperitoneally three times per week for a month into 4-wk-old WT and Trexl<sup>+</sup>-mice. During the course of treatment, 3 of 10 untreated Trexl<sup>+</sup>-mice died, while none of the 10 mice that received SN-011 died (P = 0.018) (Fig. 5C). At the end of the month, surviving mice were killed and heart, stomach, tongue, and muscle were analyzed by hematoxylin and eosin (H&E) staining, which showed severe multiorgan inflammation in untreated Trexl<sup>+</sup>-mice, which was reduced by SN-011 treatment (Fig. 5D). Moreover, Ifnb and representative ISG mRNA levels assessed by quantitative PCR of RNA isolated from whole tissues at the time of killing were also significantly reduced (SI Appendix, Fig. S5A). Moreover, serum antinuclear antibody was markedly reduced by SN-011 treatment (Fig. 5E). SN-011 also significantly reduced the number of activated CD69<sup>+</sup> CD8 T cells and memory CD4<sup>+</sup>CD62L<sup>+</sup>lowCD4<sup>+</sup>CD62L<sup>+</sup>lowCD4<sup>+</sup>CD62L<sup>+</sup>low T cells to near normal levels in the spleens of treated Trexl<sup>+</sup>-mice (SI Appendix, Fig. S5 B and C). SN-011 had no significant effect on the number of splenic activated CD4<sup>+</sup> T cells. Thus, SN-011 strongly reduced inflammation and protected Trexl<sup>+</sup>-mice from death.

**SN-011 Exhibits Low Cytotoxicity and High Specificity in Comparison with H-151.**

To compare potential cytotoxicity of SN-011 and H-151, cell viability and cell death were examined after adding different concentrations of each compound (1 to 10 μM) for 12 to 36 h to MEFs, Tnem173<sup>−/−</sup> MEFs, and 3T3 cells (SI Appendix, Fig. S6 A–F). SN-011 had no significant effect on cell viability, whereas H-151 significantly impaired cell viability and caused cell death (SI Appendix, Fig. S6 A–F). Moreover, H-151 was less specific for STING signaling since it more potently than SN-011 suppressed Ifnb and inflammatory cytokine (Ifna and Ifnb) mRNA induction triggered by STING-independent stimuli, LPS, poly (I:C) and hp-RNA, in L929, HFFs, and Tnem173<sup>−/−</sup> MEFs (SI Appendix, Fig. S6 G–I). These data indicate that SN-011 is a more specific inhibitor of STING-dependent signaling than H-151 in vitro.

Next, we compared the inhibitory effects of SN-011 and H-151 on self-DNA–triggered inflammatory responses in Trexl<sup>+</sup>-BMDMs by RNA-seq analysis. Both SN-011 and H-151 suppressed differentially expressed (DE) ISG genes to a comparable extent independently of the false-discovery rate (FDR) cutoff used for the analysis (0.05, 0.01, 0.001) (SI Appendix, Fig. S7A). The number, overlap and magnitude of significantly down-regulated and up-regulated DE ISG genes after SN-011 or H-151 treatment were not significantly different (SI Appendix, Fig. S7 B–D). To further assess and compare the efficacy of the two compounds in vivo, 10 mg/kg SN-011 or H-151 was injected intraperitoneally into 6-wk-old Trexl<sup>+</sup>-mice daily for 2 wk. Ifnb and ISGs expression in the affected tissues of Trexl<sup>+</sup>-mice were comparably suppressed by SN-011 and H-151 (SI Appendix, Fig. S7E). H&E staining also showed comparable amelioration of heart inflammation by both compounds (SI Appendix, Fig. S7 F and G). Taken together, these data show that SN-011 and H-151 comparably inhibit STING-mediated inflammation in both cell-based and Trexl<sup>+</sup> mouse models.

**Discussion**

In this study, we performed a large-scale virtual screen against the STING CDN-binding pocket to identify STING antagonists. Structural optimization identified SN-011 as a potent STING inhibitor that impedes STING oligomerization, trafficking and activation in response to cytosolic DNA and markedly decreases STING-driven expression of type I IFNs and proinflammatory cytokines. SN-011 binds to the CDN-binding pocket with higher affinity than the endogenous cGAS product 2′,3′-cGAMP and locks the STING dimer in an open, inactive conformation. SN-011 inhibits STING-dependent signaling, with IC<sub>50</sub> values of ~100 nM and ~500 nM for mouse and human cells, respectively. SN-011
Fig. 4. Mutations of the STING-SN-011 interface reduce inhibition by SN-011. (A) Intermolecular contacts of SN-011 bound to hSTING-CTD (amino acids 149 to 379) in virtual docking structure (Left). SN-011 and contacted STING amino acids are shown as a stick model. Hydrogen-bonds with distance are labeled in green (Right). (B and C) MEFs (B) and HFFs (C) were pretreated with the indicated concentrations of SN-013 before 2'3'-cGAMP stimulation for 3 h. Induction of Ifnb mRNA was measured by quantitative PCR. The dose-dependent inhibitory curve was fit to calculate the IC50s. (D) Biacore analysis of hSTING-CTD and SN-011 binding (Left). The binding affinity ($K_d$) was determined by fitting the binding data to a steady-state 1:1 binding model (Right). RU, response units. (E) Biacore analysis of hSTING-CTD and 2'3'-cGAMP binding. The binding affinity ($K_d$) was determined by fitting the binding data to a kinetics 1:1 binding model. (F) Biacore analysis of hSTING-CTD (S243A) and SN-011 binding (Left). $K_d$ was determined by fitting the binding data to a steady-state 1:1 binding model (Right). (G) Biacore analysis of hSTING-CTD and SN-100 binding. (H) HEK293T cells, transfected with Flag-hSTING or its mutants, were treated 12 h later with DMSO or SN-011 (10 μM) for 12 h. mRNA was measured by quantitative PCR assay (Left). The inhibition ratio of SN-011 relative to DMSO control was calculated based on Ifnb mRNA levels (Right). **P < 0.01. Gene expression was normalized to Gapdh.
inhibits induction of interferons and inflammatory cytokines in multiple in vitro mouse and human models of STING activation, including stimulation with 2′3′-cGAMP, HSV-1 infection, Trex1 deficiency, or overexpression of cGAS-STING proteins. Importantly SN-011 also inhibits the spontaneous activation of GOF STING mutants that cause SAVI. In Trex1−/− mice, SN-011 was
well tolerated, strongly inhibited hallmarks of inflammation and autoimmunity, and prevented death. Collectively, these studies suggest that SN-011 is an attractive lead compound for developing drugs to inhibit STING-dependent signaling.

In comparison, other recently identified STING antagonists are either inactive (C-176, C-178) or have low bioactivity against human STING (NO2-Fas, Astin C, compound 18) (42–45). Compound 18 binds deep in the cleft of the human STING dimer, but with an IC50 of ~11 μM, about 20-fold higher than SN-011, even after optimization by analyzing SARs (44). The most promising reported STING antagonist, H-151, is a covalent inhibitor that binds to a reactive Cys91 in the transmembrane domain of STING to inhibit activation-induced palmitoylation (42). SN-011 and H-151 equivalently inhibit STING in mouse cell lines, with an IC50 value of ~100 nM. Elevated ISG expression in Trex1−/− BMDMs were similarly ameliorated by in vitro exposure to SN-011 or H-151. When SN-011 and H-151 were administered at the same dose (10 mg/kg), both compounds comparably suppressed inflammation in the affected tissues (heart, stomach, tongue, and muscle) in Trex1−/− mice. Future preclinical experiments to compare pharmacokinetics and dynamics, efficacy, and safety of both drugs administered back-to-back at different doses in mouse AGS and SAVI models will be needed to further explore the relative advantages of each compound. Like other Cys-reactive drugs, which are notoriously nonspecific and covalently bind to unpaired Cys in many proteins, H-151 likely has more off-target activities than SN-011 (32, 53). H-151 significantly impaired cell viability and induced cell death while SN-011 was not cytotoxic. In addition, H-151 showed potent inhibitory effects on TLR- or RIG-I-mediated signaling in cell-based assays compared to SN-011. All of these data indicate that SN-011 shows better specificity and safety than H-151. The ability to modify these lead compounds to optimize STING inhibition and their pharmacological properties will ultimately determine which compounds can lead to effective new treatments of STING-mediated diseases.

Insights into the structural basis for SN-011 activity was provided by docking analysis. In the docking structure, SN-011 bound to the STING dimer interface in the CDN-binding pocket to lock STING in an inactive open conformation. One molecule of SN-011 bound to each STING monomer with an extended binding site along the pocket. SPR confirmed the stoichiometry of STING monomer to SN-011 as 1:1 with a binding dissociation constant of 4.03 nM. By comparison, compound 18 lies in the bottom of the cleft of the STING dimer (PDB ID code 6MXE) in a 1:2 binding stoichiometry with an affinity of ~50 μM for the binding of the first molecule and an affinity of ~2 nM for the binding of the second molecule (44). This spatial and affinity difference may explain the different inhibitory activities between SN-011 and compound 18. Moreover, the interaction between STING and SN-011 over an extended binding site is mediated by residues Tyr167, Leu212, Ser243, Tyr245, and Glu260 in STING, all of which are evolutionarily conserved between species. Tyr167 and Glu260 are essential for CDN binding and Ser243 and Tyr245 are in the lid region, which involves lid for-
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