Direct interaction of DNMT inhibitors to PrP<sup>C</sup> suppresses pathogenic process of prion

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Abstract  The conversion of the normal cellular prion protein (PrP<sup>C</sup>) to the misfolded pathogenic scrapie prion protein (PrP<sup>Sc</sup>) is the biochemical hallmark of prion replication. So far, various chemical compounds that inhibit this conformational conversion have been identified. Here, we report the novel anti-prion activity of SGI-1027 and its meta/meta analogue (M/M), previously known only as potent inhibitors of DNA methyltransferases (DNMTs). These compounds effectively decreased the level of PrP<sup>Sc</sup> in cultured cells with permanent prion infection, without affecting PrP<sup>C</sup> at the transcriptional or translational levels. Furthermore, SGI-1027 prevented effective prion infection of the cells. In a PrP aggregation assay, both SGI-1027 and M/M blocked the formation of misfolded PrP aggregates, implying that binding of these compounds hinders the PrP conversion process. A series of binding and docking analyses demonstrated that both SGI-1027 and M/M directly interacted with the C-terminal globular domain of PrP<sup>C</sup>, but only SGI-1027 bound to a specific region of PrP<sup>C</sup> with high affinity, which correlates with its potent anti-prion efficacy. Therefore, we report SGI-1027 and related compounds as a novel class of potential anti-prion agents that preferentially function through direct interaction with PrP<sup>C</sup>.

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1. Introduction

The accumulation of misfolded prion proteins (PrPs) associated with transmissible spongiform encephalopathies (TSEs), also known as prion diseases, results in neuronal cell death and formation of spongiform architecture in the central nervous system. Human prion diseases include Creutzfeldt-Jakob disease (CJD), Gerstmann-Sträussler-Scheinker disease (GSS), familial fatal insomnia (FFI), kuru and variant CJD (vCJD), whereas animal prion diseases include Scrapie in sheep, goats and moufflons, transmissible mink encephalopathy (TME), chronic wasting disease (CWD) in deer, and bovine spongiform encephalopathy (BSE) in cattle. The scrape is the earliest known prion disease found in European farms during the 18th century and designated as the first member of a new class of neurological disorders known as TSEs. Nowadays, neuroblastoma cell lines generated by infection with scrapie agent are commonly used as human prion disease model systems to understand pathological process and phenomenology in prion disorders, develop advanced diagnostic techniques, and evaluate drug effects. Prions composed of misfolded PrPs are infectious and replicated through a mechanism different from bacterial and viral pathogens. Biochemically, PrP misfolding is facilitated by the conformational change of a-helix-rich cellular PrP (PrPC) to b-sheet-rich scrapie PrP (PrPSc) followed by the formation of insoluble aggregates of misfolded PrPs. Thus, as a treatment strategy, stabilization of PrPC is critical to block the pathogenic PrP conversion process, despite that the detailed molecular mechanism for the conversion remains unclear.

Recently, several compounds have been reported to effectively remove PrPSc from prion-infected cells. Congo red, a compound to stain b-amyloid structure and quinacrine, a well-known anti-malarials drug, directly associates with PrPC and interferes with the conversion of PrPC to PrPSc, resulting in elimination of PrPSc. The Chicago sky blue 6B, identified from a fluorescence-based assay screening, has been shown to inhibit A b binding and reduce PrPSc levels. GN8 and its analogues identified from an in silico-based drug screen have been shown to interact with PrPC and stabilize the PrPSc conformation, resulting in efficient inhibition of prion replication. In addition, structurally modified compounds, GIP14 and GIP49 derived from GN8, have been shown the anti-prion activity in cell based test via direct interaction with PrPC. SGI-1027 and its meta analogue (M/M) were confirmed by mass spectrometry and by 1H and 13C NMR. The purity of synthesized SGI-1027 was determined using high-performance liquid chromatography. Commercially available SGI-1027 (Cat#:S7276, Selleckchem, Houston, TX, USA) was also purchased for comparison. The SGI-1027 analogue meta/methyl dimethyl sulfoxide (DMSO) solutions were added. Cells were incubated with compounds for five days and harvested for the PrPSc assay after examination of over 95% confluency.

2. Materials and methods

2.1. Chemical synthesis

SGI-1027 was synthesized in a five-step synthetic route (Supporting Information Scheme S1). Reaction of 4-chloroquinoline and ethyl 4-aminobenzoate, followed by hydrolysis with KOH, yielded 4-(quinolin-4-ylamino) benzoic acid (1). N4-(4-Aminophenyl)-6-methylpyrimidine-2,4-diamine (2) was produced by the reaction of 2-amino-4-chloro-6-methylpyrimidine and 4-nitroaniline, followed by reduction with stannous chloride dihydrate (SnCl2·2H2O). Condensation of 1 and 2 generated the final product SGI-1027. The intermediates and final product were confirmed by mass spectrometry and by 1H and 13C NMR. The purity of synthesized SGI-1027 was determined using high-performance liquid chromatography. Commercially available SGI-1027 (Cat#:S7276, Selleckchem, Houston, TX, USA) was also purchased for comparison. The SGI-1027 analogue meta/methyl dimethyl sulfoxide (DMSO) solutions were added. Cells were incubated with compounds for five days and harvested for the PrPSc assay after examination of over 95% confluency.

2.2. Cell culture and chemical treatment

N2a, ScN2a, and SMB cell lines were cultured in Dulbecco’s modified Eagle’s medium (DMEM) supplemented with 10% fetal bovine serum, 1% penicillin/streptomycin, and 1% GlutaMax (Invitrogen, Carlsbad, CA, USA) and split every five days. The cells were initially seeded at 2% confluency in 10 cm culture dishes. After cells adhered to the dish surface, different concentrations of SGI-1027 and M/M dimethyl sulfoxide (DMSO) solutions were added. Cells were incubated with compounds for five days and harvested for the PrPSc assay after examination of over 95% confluency.

2.3. Cell-based PrPSc assay

After a five-day incubation with the compounds, cells were lysed in 1 mL cell lysis buffer (20 mmol/L Tris, pH 8.0; 150 mmol/L NaCl; 0.5% Nonidet P-40; 0.5% sodium deoxycholate), and solubilized lysate was separated from cell debris. Protein in the cell lysate was quantified using a bicinchoninic acid protein assay kit (Pierce, Rockford, IL, USA). Thirty µg of protein without treatment of protease K (PK) was loaded into Western blotting to analyze total PrP protein and bIII-tubulin, and 2 mg of cell lysate was incubated with 20 µg/mL PK (Invitrogen) for 1 h at 37 °C to examine PK-resistant PrPSc. The protein pellet was collected by centrifugation for 1 h at 16,000 g at 4 °C. For Western blot analysis, monoclonal anti-PrP antibodies 5C6 (gifted from G. Telling, Colorado State University, USA) and anti-bIII-tubulin antibody (sc-69879, Santa Cruz, CA, USA) were used. Membranes were developed with ECL Prime Detection Reagents (GE Healthcare, Amersham, UK) in the G:Box Chemi XR5 system (Syngene, Cambridge, UK).
densitometry of PrP<sup>Sc</sup> bands was analyzed using GeneTools software (Syngene, Cambridge, UK).

2.4. Cell-based prion infectivity assay

A modified cell blot assay was used to evaluate SGI-1027 effect against pathogenic prions infection<sup>2</sup>. N2a cells were seeded in 96-well plates, cultured for 12 h, and exposed to scrapie prion (RLM strain)-infected mouse brain homogenate for 96 h together with increasing concentration of SGI-1027. The 90%–100% confluent cells were split at a 1:10 ratio and cultured for an additional five days with SGI-1027. Then, 20,000 cells were transferred to 96-well nitrocellulose filter-bottomed plates and incubated for an additional 12 h for adhering to the membrane. The membrane was washed with phosphate buffered saline (PBS) and soaked with lysis buffer (50 mmol/L Tris-Cl, pH 8.0; 150 mmol/L NaCl; 0.5% sodium deoxycholate; 0.5% Triton X-100). The dried membranes were then treated with PK solution (5 g/mL PK in lysis buffer) for 90 min at 37 °C, washed with PBS, and incubated with 2 mmol/L phenylmethylsulfonyl fluoride (PMSF) for 2 min at room temperature to stop PK digestion. After washing with PBS, the membrane was incubated with denaturing buffer (3 mol/L guanidinium thiocyanate, 10 mmol/L Tris-Cl, pH 8.0) for 10 min and then rinsed three times with water. The membrane was further blocked with 5% skim milk TBS-T for 1 h and incubated with the anti-PrP antibody 5C6 for 1 h. After washing with TBS-T, horseradish peroxidase-conjugated anti-mouse secondary antibody was used to detect signal. The membrane was developed with the ECL system, and densitometry was analyzed using GeneTools software (Syngene, Cambridge, UK).

2.5. MTT assay

To measure the cytotoxicity of SGI-1027 and M/M, ScN2a cells were seeded in a 24-well culture plate and incubated with SGI-1027 and M/M for 5 days. On the final day, 0.5 mg/mL MTT was added to the culture medium, and cells were further incubated for 2 h. After adding 0.05 mol/L HCl-isopropanol, the MTT formazan product was measured at 570 nm with background subtraction at 650 nm using an Infinite M200Pro Multimode Reader (Tecan, Männedorf, Switzerland)<sup>13</sup>.

2.6. RT-PCR

RNA was isolated using TRIzol (Invitrogen) from ScN2a cells incubated with 1 µmol/L SGI-1027 and 4 µmol/L M/M for five days. cDNA was synthesized from 1 µg RNA by SuperScript II (Invitrogen). RT-PCR was performed using 1 µL of synthesized cDNA with primers for mouse Prnp gene (5'<GGCGCAAG-GAGGGGTACCCAT-3' and 5'-GGCCAAG-GGTGGTCC-GCCAAG-3') and Gapdh, a housekeeping gene as the internal control (5'-GTTGTCCTGGGACTCTTA-3' and 5'-GGTGGTCC-AAGGTTCTTA-3').

2.7. Expression and purification of recombinant human PrP (rhPrP)

rhPrP was prepared from E. coli. First, the cDNA fragment encoding the C-terminal core of human PrP (90–230) was cloned into pET100/D-TOPO plasmids (Invitrogen). Next, the expression vector was transformed into E. coli BL21 Star (DE3, Invitrogen), and the transformed bacterial cells were grown at 37 °C until OD<sub>600</sub>=0.5. After adding 1 mmol/L isopropyl β-D-thiogalactopyranoside to induce rhPrP expression, bacterial cells were further cultured for an additional 5 h. rhPrP expression was monitored using SDS-polyacrylamide gel electrophoresis. rhPrP was purified as following; bacterial cells were lysed using the CelLytic B lysis reagent (Sigma–Aldrich, St. Louis, MO, USA). Inclusion bodies were then solubilized from the cell lysate using CelLytic IB (Sigma–Aldrich). Ni-NTA agarose affinity chromatography was used to collect the His-tagged rhPrP<sup>2</sup>.

2.8. Circular dichroism (CD) spectrometry of rhPrP

rhPrP was diluted ~0.2 mg/mL in 20 mmol/L sodium acetate (pH5.5) and CD spectra were measured using a Chirascan circular dichroism spectrometer (Applied Photophysics, Surrey, UK). The spectra were collected from 190 to 260 nm with 1 nm bandwidth and 1 mm path length at 25 °C.

2.9. Synthesis of biotinylated peptides

Biotin-conjugated PrP peptides were chemically synthesized (Biosistem, Ansan, Korea). During solid-phase peptide synthesis, the α amino groups were protected with Fmoc and Boc. After synthesis of the crude peptide, the peptide-resin was incubated with cleavage solution for 3 h. The molecular weight of the peptides released from the resin was verified by mass spectrometry and the confirmed peptides were separated using HPLC.

2.10. Surface plasmon resonance (SPR) analysis

SPR analysis was conducted with the ProteOn XPR36 protein interaction array system (Bio-Rad, Hercules, CA, USA). Purified rhPrP and biotinylated peptides were placed on a ProteOn GLH Sensor Chip (Bio-Rad, Hercules, CA, USA) via amine coupling and on a ProteOn NLC Sensor Chip (Bio-Rad, Hercules, CA, USA) via binding to avidin, respectively, at a density of ~3000 resonance units. SGI-1027 and M/M were diluted with PBS (pH 7.0) and injected into a flow cell at a flow rate of 100 µL/min. Five different concentrations of each compound were injected, and the dissociation phase was monitored. Data were analyzed using ProteOn Manager Software 2.0 with standard Langmuir models to fit kinetic data. The flow cell was washed with 10 mmol/L NaOH or 0.01% Triton X-100 for 30 s before the injection of each new sample. The equilibrium response (Req) value or maximum response value in the sensorgram was divided by the molecular weight to determine the binding response between PrP and the compounds. A high affinity interaction was represented as low K<sub>d</sub> or rapid recognition and binding (high K<sub>a</sub>). Formation of a stable complex was calculated using the equation K<sub>d</sub> = K<sub>d</sub>/K<sub>a</sub>.

2.11. PrP amyloid formation assay (PAFA)

Ten µg rhPrP was reacted in 0.2 mL reaction buffer (PBS [pH 7.0], 0.2 mol/L guanidine hydrochloride and 10 µmol/L thioflavin T [Sigma–Aldrich]). Various concentrations of SGI-1027 and M/M were mixed with the PAFA mixture and incubated at 37 °C for 48 h with continuously shaking at 300 revolutions per min. The formation of rhPrP aggregates was detected by reading the fluorescence of amyloid-bound ThT in a 96-Well Black UniPlateTM Microplate (GE Healthcare, Piscataway, NJ, USA) using an Infinite M200Pro Multimode reader (Tecan, Männedorf, Switzerland).
2.12. Molecular docking analysis

Two compounds were docked to 4KML chain A using SwissDock in the accurate mode with default parameters and ranked based on Cluster and Fullfitness. Protein-ligand interactions were analyzed using LIGPLOT. Structures were visualized by UCSF Chimera and PyMol (PyMOL Molecular Graphics System, Version 1.8 Schrödinger, LLC).

2.13. Statistical analysis

A t-test method was used for the data analysis. All represented values in multiple trials are the mean ± SD and a P-value less than 0.05 was considered for significance.

3. Results and discussion

SGI-1027, synthesized in-house from a quinoline-based compound in five steps (Scheme S1), effectively eliminated PrPSc in ScN2a cells, a neuroblastoma cell line infected with prions. The PrPSc level gradually decreased as the concentration of SGI-1027 increased till completely eliminated at 0.5 μmol/L (Fig. 1A). The densitometry analysis identified the half-maximal concentration of PrPSc inhibition (IC50) by SGI-1027 at 50 nmol/L (Fig. 1B), indicating its high potency compared with other previously tested anti-prion compounds. In SMB, a prion-infected cell line of mesenchymal origin, SGI-1027 effectively eliminated PrPSc, showing similar IC50 value as seen in ScN2a cells (Supporting Information Fig. S1), which further indicated the anti-prion effect of SGI-1027 was not limited to a certain cell type. In contrast, M/M, an SGI-1027 analogue, with four-fold stronger DNMT inhibition potency than SGI-1027, eliminated PrPSc less effectively with the IC50 value at 4 μmol/L. M/M only partially removed PrPSc at 1 μmol/L in ScN2a cells, while SGI-1027 completely eliminated PrPSc at same concentration (Fig. 1C). Thus, the efficacy of SGI-1027 to eliminate PrPSc was about 80 times greater than that of M/M (Supporting Information Fig. S2). These results suggest that the molecular basis of the anti-prion activity of SGI-1027 and M/M is more likely independent of their DNMT potency.

The molecular basis of prion infection can be explained by the biochemical event associated with the initial conformational change of PrPSc in the cell membrane via dimerization to the pathogenic PrPSc, and thus inhibiting this process could possibly reduce prion infection. SGI-1027, shown to inhibit PrPSc propagation in prion-infected cells, may also prevent prion infection in normal cells. To test our hypothesis, we analyzed the effects of SGI-1027 in a cell-based prion infection assay. We observed that PrPSc propagation was interrupted in N2a cells inoculated with a scrapie (RML strain) prions at 1 μmol/L SGI-1027 concentration (Fig. 1D). In contrast, N2a cells inoculated with a scrapie and low concentration SGI-1027 or without SGI-1027 treatment were susceptible to prion infection. These results suggest that SGI-1027 can effectively prevent prion infection in normal N2a cells.

Though the anti-cancer therapeutic effects of SGI-1027 and M/M are reported via manifesting apoptotic induction in cancer cells, in our cytotoxicity studies, most of the ScN2a cells incubated with up to 1 μmol/L SGI-1027 were viable (Supporting Information Fig. S3A and B), and 80% of cells death started from 2 μmol/L concentration. Considering that SGI-1027 completely eliminated PrPSc at nmol/L concentrations, its anti-prion activity was not associated with induced cell death or proliferative defects. M/M was even less cytotoxic than SGI-1027. Over 90% of cells were viable up to 4 μmol/L, and significant cell death observed at

Figure 1  Anti-prion activity of the DNMT inhibitor SGI-1027. (A) Western blots to measure elimination of PrPSc by SGI-1027 from ScN2a cells. (B) Densitometry analysis of PrPSc bands. The average PrPSc levels and error bars represent the means and standard deviations obtained from the analysis performed with three independent western blots. (C) Comparison of the PrPSc elimination effect of 1 μmol/L of SGI-1027 and M/M. DMSO was used as a vehicle and the PrPSc level of vehicle-treated sample represents the control. (D) Efficacy of SGI-1027 in preventing prion infection. N2a cells cultured without prion inoculum were used as a control for infection (No). For efficacy measurement, N2a cells inoculated with prions but not incubated with SGI-1027 were used as a positive control and ScN2a cells without SGI-1027 incubation were used as a negative control. The efficacy of SGI-1027 in preventing prion infection was measured as the ratio of PrP with and without protease digestion (+PK/−PK) by densitometric quantification of the cell blot. Error bars are mean ± SD of three independent trials.
8 μmol/L (Fig. S3A and B). Thus, our previously observed PrPSc elimination at 4 μmol/L was not due to the induced ScN2a cell death, either. Clearly, the anti-prion activity of SGI-1027 and M/M was irrelevant to the influences of cell division or apoptosis.

Previous study has shown that SGI-1027 and M/M alter the expression of various genes by inhibiting DNMTs25,29. Thus, we investigated the expression of Prnp, the gene encoding PrPC, and found that the transcript was unaltered at 1 μmol/L SGI-1027 or 4 μmol/L M/M in ScN2a cells (Supporting Information Fig. S4). In addition, PrP remained as the same level in cells incubated with or without SGI-1027 or M/M (Fig. 1A and C). Thus, both mRNA and protein levels of PrPC were unaffected by SGI-1027 and M/M, suggesting that PrPSc elimination from prion-infected cells is irrelevant to their epigenetic control of DNMT family proteins.

The quinoline ring structure on the previously reported anti-prion compounds is crucial for those compounds to interact directly with PrP to reduce PrPSc level39-41. Both SGI-1027 and M/M include a quinoline ring in their structures, and thus their inhibitory effect might be due to direct interaction with PrP. To test their binding with PrP, we first bacterially expressed and purified recombinant human PrP spanning amino acid residues 90-230 (rhPrP) (Supporting InformationFig. S5A), and then used circular dichroism (CD) spectrometry to confirm that the purified rhPrP retained its conformation, with dominant α-helical and low β-sheet content, resembling the native conformation of PrP C (Fig. S5B). Next, we used surface plasmon resonance (SPR) binding assay with quinacrine, known to bind to the C-terminal domain of PrPSc23, as a positive control. Quinacrine showed rapid association and dissociation with rhPrP, but increasing concentration (2-10 μmol/L) escalated SPR responses without saturation (Fig. 2A), indicating the non-specific interaction with PrPSc42. We further conducted the SPR analysis on both SGI-1027 and M/M. The sensorgram curve of both compounds showed rapid association to reach equilibrium (Req) and rapid dissociation to return to baseline without delayed flow (Fig. 2A). Moreover, the binding efficiency of both SGI-1027 and M/M were five to six times higher than that of quinacrine. At the same concentration, 2 μmol/L, the binding response values of SGI-1027 and M/M were 70 and 90, respectively, whereas that of quinacrine was 20 (Fig. 2B). More importantly, SGI-1027 showed a saturated binding response with an equilibrium of association and dissociation at 2.5 μmol/L, while M/M showed a proportional increase of binding response to compound concentration without saturation, similar to that of quinacrine (Fig. 2A). Therefore, though both compounds interacted with rhPrP, their interaction modes were not identical despite their high interaction affinity. The SPR results suggested that SGI-1027 specifically interacted with a certain region of PrPC in a binding manner different from the physical adherence of M/M and quinacrine in nonspecific manner42. The interaction of both laboratory-synthesized and commercially purchased SGI-1027 to rhPrP were identical in SPR binding assay (Fig. 2A). Analysis of kinetic data showed that the equilibrium dissociation rate constants (K_D) of SGI-1027 were 1.61 μmol/L for laboratory-synthesized and 2.01 μmol/L for commercially purchased, respectively (Fig. 2B). The binding efficiency of SGI-1027 to rhPrP was 45 times stronger than M/M. In fact, SGI-1027 gave the lowest K_D value among all tested anti-prion compounds showing specific interaction with PrPSc, about 2.4 times better than the previously reported GN8, with a K_D value of 3.9 μmol/L41,43. Although Congo red was reported with a K_D value comparable to SGI-1027, it showed non-specific interaction with PrPSc without binding saturation42, similar as seen in quinacrine and M/M (Fig. 2A). We attribute the better efficiency of SGI-1027 at eliminating PrPSc from ScN2a cells to its direct and specific interaction with PrPSc (Fig. S2).

Figure 2 SPR analysis of direct interaction between the DNMT inhibitors and rhPrP. (A) The sensorgram curves derived from the interactions of immobilized rhPrP with commercially purchased (C) and laboratory-synthesized (L) SGI-1027 and its analogue M/M. Interaction of rhPrP with quinacrine was used as a positive control. (B) Analysis of kinetic data for the equilibrium dissociation rate constants (K_D) of tested compounds. Analysis was performed under various concentrations of each compound: 0, 1.25, 2.5, 5, 10, and 20 μmol/L. All SPR data analysis and correction was performed through the use of intuitive software wizards in ProteOn Manager Software.
NMR and computational simulation studies suggest that N159 at the A-S2 loop and E196 at the B-E-C loop are necessary for PrP conversion. In the SwissDock simulation analysis of unbiased blind docking, we determined the top-scored predicted binding sites for SGI-1027 and M/M to localize the binding region on PrPC. The results indicated SGI-1027 interacted with three regions on PrP<sup>E</sup>: residues 118–122, 125–131, and 161–163 (Fig. 3A). A previously reported nanobody known to interact with residues 123–125 in the β0-β1 loop, 164–170 in the β2-α2 loop, and 174–185 in the α2-helix of PrP<sup>E</sup> stabilizes the PrP<sup>E</sup> structure, and thus these two compounds, SGI-1027 and M/M, might bind and function similarly as the nanobody in their anti-prion activity.

In the LIGPLOT analysis, the 2-amino-6-methylpyridine ring of SGI-1027 formed three hydrogen bonds, interacting with residues H155, N159, and Y162, which occur in a relatively hydrophilic region of PrP<sup>C</sup>. The same ring of M/M formed a single hydrogen bond only with N159 (Fig. 3B). Specifically, the quinoline ring of both compounds preferred to interact with a more hydrophobic domain of PrP<sup>C</sup> containing multiple residues: L130, H155, Y157, P158, E160, Y162, and H187 (Fig. 3A). The segment of PrP<sup>C</sup> spanning residues 90–175 is transformed into a four-stranded β-sheet core organized in a β-helical configuration, and the further downstream C-terminal segment of PrP<sup>C</sup>, including two helical regions, α2 and α3, is maintained in PrP<sup>Sc</sup>. Thus, the hydrogen bonds formed with both compounds probably contribute to PrP<sup>C</sup> stabilization, preventing the region spanning residues 90–175 from undergoing conformational changes to multiple β-sheets as seen in PrP<sup>Sc</sup>. Also, the conserved palindromic motif AGAAAGAGA (residues 113–120 of PrP<sup>E</sup>) has been reported to play a role in the conversion of PrP<sup>E</sup> to PrP<sup>Sc</sup>. Therefore, the palindromic sequence in PrP<sup>C</sup> occupied by SGI-1027 and M/M could no longer function properly to be converted to PrP<sup>Sc</sup>, which resulted the inhibition of pathogenic prion formation. Similar values of computationally calculated free energy change (ΔG) of SGI-1027 and M/M (−7.51 and −7.59 kJ/mol, respectively) were obtained (Fig. 3C). Further analysis from the binding complex structures suggests that the greater binding affinity of SGI-1027 than M/M is congruent with the increased number of hydrogen bonds between SGI-1027 and PrP<sup>C</sup> and consistent with its greater anti-prion activity than M/M in our previous cell-based assay studies (Fig. 3B).

To confirm the simulated docking results for SGI-1027 and M/M, we chemically synthesized biotin-tagged PrP peptides that partially overlapped on both ends and used them to screen the binding sites of compounds in PrP<sup>C</sup> (Supporting Information Table S1). In the SPR binding assay, only two peptides, spanning residues 112–146 and 138–172, specifically interacted with SGI-1027 (Table 1). The residue L130 that participated in hydrophobic interaction with SGI-1027 in docking study is present in the peptide spanning residues 112–146. Moreover, the peptide spanning residues 138–172 contains H155, N159, and Y162 for the formation of three hydrogen bonds, as well as H155, Y157, P158, E160, and Y162 for the hydrophobic interaction with SGI-

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**Table 1** Interactions of PrP peptides with laboratory-made (L-) and purchased (C-) SGI-1027 and M/M.

| Peptide  | Quinacrine | L-SGI1027 | C-SGI1027 | M/M |
|----------|------------|-----------|-----------|-----|
| 23–61    | X          | X         | X         | X   |
| 57–91    | O          | X         | X         | O   |
| 89–120   | X          | X         | X         | X   |
| 112–146  | O          | O         | O         | O   |
| 128–159  | X          | X         | X         | X   |
| 138–172  | O          | O         | O         | O   |
| 157–193  | O          | X         | X         | O   |
| 169–203  | X          | X         | X         | O   |
| 193–231  | O          | X         | X         | O   |

O, binding; X, no binding.

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Figure 3  Computational analysis of the binding domain of PrP<sup>C</sup> with SGI-1027 and M/M. (A) Surface representation of PrP<sup>C</sup> to show the compound binding pocket on structured region of human PrP<sup>C</sup>. Red, acidic or negatively charged region; blue, basic or positively charged region; white, neutral region. (B) Predicted binding mode of PrP<sup>C</sup> (pink, ribbon) with SGI-1027 (cyan, stick) and M/M (green, stick). Detailed analysis of the interaction shows residues of PrP<sup>C</sup> for compounds with a stick representation. Hydrogen bond: yellow dash. (C) Binding parameters predicted by SwissDock for PrP<sup>C</sup> interaction with SGI-1027 and M/M.
delayed accumulation and shift to PrPSc extension from amyloid less steep elongation phase to reach plateau, representing the curves in the presence of SGI-1027, showed long lag phase and purple, cyan, and dark blue). The biphasic pattern of the ThT- previously reported nanobody 44, we measured the effects of SPR results (Fig. 2).

peptides spanning residues 23
Unlike SGI-1027, M/M interacted with most peptides, except two residues 61 and 89 (Table 1), which also corresponded to its non-specific interaction with PrPSc in our in vitro interaction with the critical region of PrPC, and thus prevent it from undergoing further conformational change into 6. Cobb NJ, Surewicz WK. Prion diseases and their biochemical mechanisms. Biochemist

interaction between SGI-1027 and PrPSc at the specific sites stabilized PrPSc, retarding the subsequent oligomeric or amyloid formation and extension49, delaying the further aggregation50, and thus prevented its conversion to PrPSc. At the same concentration, SGI-1027 inhibited the formation of PrP aggregates more strongly than M/M, showing effective suppression of PrP aggregates, based on its delayed lag phase and lower ThT fluorescence value (Supporting Information Fig. S8). These results closely correlate with the higher binding affinity of SGI-1027 to PrPSc via three hydrogen bonds (Figs. 2B and 3B) and its greater anti-prion activity in ScN2a cells (Fig. 1).

In summary, we report the potent anti-prion activity of SGI-1027. Through cell-based analysis on PrPSc level, in vitro PrP aggregation assay, in vitro binding analysis, and in silico docking simulation of SGI-1027 and its analogue M/M, we demonstrate that the anti-prion activity of SGI-1027 is due to its direct, specific, and high-affinity interaction with the critical region of PrPSc, and thus prevent it from undergoing further conformational conversion into β-sheets in PrPSc. The potency of SGI-1027 is outstanding among all tested anti-prion compounds showing specific interaction to PrPSc so far. Structural modification of SGI-1027 to further increase its anti-prion activity and reduce its cytotoxicity will be a promising future in the development of potential therapeutic compounds for prion disease.

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Appendix A. Supporting information

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