

# Methods

## SEARCH-MaP of the 2,924 nt segment of SARS-CoV-2 genomic RNA

A DNA template of the 2,924 nt segment of the SARS-CoV-2 genome, plus an upstream T7 promoter, was amplified from our previously constructed pmirGLO plasmid with 250 nM primers TAATACGACTCACTATAGAATAATGAGCTTAGTCCTGTTGCACTACG and TAAATTGCGGACATACTTATCGGCAATTTTGTTACC (Thermo Fisher Scientific) using 2X CloneAmp HiFi PCR Premix (Takara Bio) in a 50 µl volume with initial denaturation at 98°C for 60 s; 35 cycles of 98°C for 10 s, 65°C for 10 s, and 72°C for 15 s; and final extension at 72°C for 60 s. The 50 µl PCR product was mixed with 10 µl of 6X Purple Loading Dye (New England Biolabs) alongside 10 µl of 0.1X 1 kb DNA Ladder (New England Biolabs) and electrophoresed through a 1% agarose gel – 50 ml of 1X tris-acetate-EDTA buffer (Boston BioProducts), 0.5 g of SeaKem Agarose (Lonza), and 5 µl of 10,000X SYBR Safe (Invitrogen) – in 1X tris-acetate-EDTA buffer (Boston BioProducts) at 60 V for 60 min. The band at roughly 3 kb was excised and the DNA purified using a Zymoclean Gel DNA Recovery Kit (Zymo Research) according to the manufacturer's protocol; samples were eluted in 10 µl of nuclease-free water (Fisher Bioreagents) and measured with a NanoDrop (Thermo Fisher Scientific). To increase the DNA yield, the gel-extracted DNA was amplified by a second round of PCR followed by gel extraction, using the same protocol as above. To remove contaminants after the second gel extraction, the DNA was further purified using a DNA Clean & Concentrator-5 kit (Zymo Research) according to the manufacturer's protocol; it was eluted in 10 µl of nuclease-free water (Fisher Bioreagents) and measured with a NanoDrop (Thermo Fisher Scientific).

RNA was transcribed using a MEGAscript T7 Transcription Kit (Invitrogen) according to the manufacturer's protocol. Specifically, 150 ng of DNA template from the previous step was diluted to 8 µl in nuclease-free water (Fisher Bioreagents),

mixed with 2  $\mu$ l of each of the four 10X NTP solutions followed by 2  $\mu$ l of the 10X reaction buffer and 2  $\mu$ l of the 10X enzyme mix, and then incubated at 37°C for 3 hr. The DNA template was then degraded by adding 1  $\mu$ l of TURBO DNase (Invitrogen) and incubating at 37°C for 15 min. The RNA transcript was purified using an RNA Clean & Concentrator-5 kit (Zymo Research) according to the manufacturer's protocol; samples were eluted in 20  $\mu$ l of nuclease-free water (Fisher Bioreagents) and measured with a NanoDrop (Thermo Fisher Scientific). DID YOU CONFIRM THE RNA HAS NO OFF-TARGET BANDS?

Antisense oligonucleotides (ASOs) were ordered from Integrated DNA Technologies in a 96-well PCR plate, each ASO already resuspended to 10  $\mu$ M in 1X IDTE buffer (10 mM Tris, 0.1 mM EDTA). Each ASO pool (of up to 5 ASOs) was made by mixing 2.5  $\mu$ l (25 pmol) of each constituent ASO (Supplementary Table ??); the total volume of each pool was adjusted to 12.5  $\mu$ l by adding TE Buffer: 10 mM Tris (Invitrogen) with 0.1 mM EDTA (Invitrogen). Each 12.5  $\mu$ l ASO pool was then mixed with 1  $\mu$ l (425 ng, 453 fmol) of RNA (55X molar excess of each ASO) in a PCR tube. The tubes were heated to 95°C for 60 seconds to denature the RNA, then placed on ice for several minutes. The RNA was transferred to 1.5 ml tubes; to each, 35  $\mu$ l of 1.4X refolding buffer comprising 400 mM sodium cacodylate pH 7.2 (Electron Microscopy Sciences) and 6 mM magnesium chloride (Invitrogen) was added, followed by incubation at 37°C for 25 min to allow the RNA to refold and bind the ASOs. No-ASO control 1 was handled in the same manner but with 12.5  $\mu$ l of TE Buffer in lieu of an ASO pool. For no-ASO control 2, 12.5  $\mu$ l of TE Buffer was added after placing on ice and before adding refolding buffer, to confirm that the timing of adding TE buffer would not alter the RNA structure.

For chemical probing, 1.5  $\mu$ l of neat DMS (Sigma-Aldrich) was added to each tube for a total volume of 50  $\mu$ l including 320 mM DMS, 280 mM sodium cacodylate, 4.2 mM magnesium chloride, and 9.1 nM RNA. DMS was initially mixed by swirling the pipette tip and then kept suspended by shaking at 500 rpm in a ThermoMixer C (Eppendorf) throughout the treatment at 37°C for 5 min. Reactions were quenched by adding 30  $\mu$ l neat beta-mercaptoethanol (Sigma-Aldrich) and

mixing thoroughly by pipetting. Each sample of DMS-modified RNA was purified using an RNA Clean & Concentrator-5 kit (Zymo Research) according to the manufacturer's protocol; samples were eluted in 10  $\mu$ l of nuclease-free water (Fisher Bioreagents) and measured with a NanoDrop (Thermo Fisher Scientific).

ASOs were removed from each sample using TURBO DNase (Invitrogen) according to the manufacturer's protocol. Briefly, 4  $\mu$ l of each DMS-modified RNA was mixed with 4  $\mu$ l of nuclease-free water (Fisher Bioreagents), 1  $\mu$ l of 10X TURBO DNase Buffer, and 1  $\mu$ l of TURBO DNase in a PCR tube; and then incubated at 37°C for 30 min. To stop each reaction, 2  $\mu$ l of DNase Inactivation Reagent was mixed in and incubated at room temperature for 10 min, and mixed throughout by flicking several times. The DNase Inactivation Reagent was precipitated by spinning the tubes on a benchtop PCR tube centrifuge for 10 min, then transferring 4  $\mu$ l of each supernatant to a new tube.

For reverse transcription, each 4  $\mu$ l sample of DNased, DMS-modified RNA was mixed with 6  $\mu$ l of nuclease-free water (Fisher Bioreagents), 4  $\mu$ l of 5X First Strand Buffer (Invitrogen), 1  $\mu$ l of 10 mM dNTPs (Promega), 1  $\mu$ l of 100 mM dithiothreitol (Invitrogen), 1  $\mu$ l of RNaseOUT (Invitrogen), 1  $\mu$ l of TGIRT-III (InGex), 1  $\mu$ l of 10  $\mu$ M FSE reverse primer CTTTCGTCCTTTTCTTGGAAGCGACA (Integrated DNA Technologies), and 1  $\mu$ l of 10  $\mu$ M section-specific reverse primer (Integrated DNA Technologies, Supplementary Table ??), for a total volume of 20  $\mu$ l. RNA was reverse transcribed at 57°C for 90 min, followed by inactivation at 85°C for 15 min. To remove the RNA template from the cDNA, 1  $\mu$ l of Hybridase Thermostable RNase H (Lucigen) was added to each tube and incubated at 37°C for 20 min.

The cDNA products were amplified using the Advantage HF 2 PCR Kit (Takara Bio) according to the manufacturer's protocol. Specifically, 1  $\mu$ l of unpurified cDNA was mixed with 8.25  $\mu$ l of nuclease-free water (Fisher Bioreagents), 1.25  $\mu$ l of 10X Advantage 2 PCR Buffer, 1.25  $\mu$ l of 10X Advantage-HF 2 dNTP Mix, 0.25  $\mu$ l of 50X Advantage-HF 2 Polymerase Mix, 0.25  $\mu$ l of 10 mM forward primer (Integrated DNA Technologies, Supplementary Table ??), and 0.25  $\mu$ l of 10 mM reverse primer (Integrated DNA Technologies, Supplementary Table ??), for a total volume of 12.5

μl. After an initial denaturation at 94°C for 60 s, 25 cycles of 94°C for 30 s, 60°C for 30 s, and 68°C for 60 s were run, followed by a final extension at 68°C for 60 s. For each cDNA, the PCR products were pooled (5 μl each) and then purified using a DNA Clean & Concentrator-5 kit (Zymo Research) according to the manufacturer's protocol; samples were eluted in 20 μl of nuclease-free water (Fisher Bioreagents) and measured with a NanoDrop (Thermo Fisher Scientific).

A 200 ng aliquot of each pool of PCR products was diluted in 10 mM Tris-HCl, pH 8 (Invitrogen) to a total of 50 μl. Aliquots were prepared for sequencing using the NEBNext Ultra II DNA Library Prep Kit for Illumina (New England Biolabs) according to the manufacturer's protocol with the following modifications. During two-step size selection after adapter ligation, 27.5 μl and 12.5 μl of NEBNext Sample Purification Beads were used in the first and second steps, respectively, to select inserts of 280-290 bp. Indexing PCR was run at half scale (25 μl total volume) for 3 cycles. Each PCR product was mixed with 2.5 μl of 10X E-Gel Sample Loading Buffer (Invitrogen) and electrophoresed through a 2% E-Gel SizeSelect II Agarose Gel (Invitrogen) according to the manufacturer's instructions. Samples were extracted in 50 μl nuclease-free water (Fisher Bioreagents). DNA concentrations were measured using a Qubit 3.0 Fluorometer (Thermo Fisher Scientific) according to the manufacturer's protocol. Samples were pooled and sequenced using an iSeq 100 Sequencing System (Illumina) with 2 x 150 bp paired-end reads according to the manufacturer's protocol.

## **Screening coronavirus long-range interactions computationally**

All coronaviruses with reference genomes in the NCBI Reference Sequence Database ? were searched for using the following query:

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refseq[filter] AND ("Alphacoronavirus"[Organism] OR  
                    "Betacoronavirus"[Organism] OR  
                    "Gammacoronavirus"[Organism] OR
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"Deltacoronavirus"[Organism])

The complete record of every reference genome was downloaded both in FASTA format (for the reference sequence) and in Feature Table format (for feature locations). The location of the frameshift stimulating element (FSE) in each genome was estimated from the feature table, and the nearest instance of TTAAAC was used as the slippery site, using a custom Python script. The 2,000 nt segment beginning 100 nt upstream of and ending 1,893 nt downstream of the slippery site was used for predicting long-range interactions involving the FSE. Genomes with ambiguous nucleotides (e.g. N) in this segment were discarded. For each coronavirus genome, up to 100 secondary structure models of the 2,000 nt segment were generated using Fold version 6.3 from RNAstructure ? with -M 100 and otherwise default parameters. Then, for each position, the fraction of models for the coronavirus in which the base at the position paired with any other base between positions 101 (the first base of the slippery sequence) and 250 was calculated using a custom Python script. The coronaviruses were clustered by their fraction vectors using the unweighted pair group method with arithmetic mean (UPGMA) and a euclidean distance metric, implemented in Seaborn version 0.11 ? and SciPy version 1.7 ?. The resulting hierarchically-clustered heatmap was examined manually to select coronaviruses based on the prominence of potential long-range interactions with the FSE (relatively large fractions far from positions 101-250).

## **SEARCH-MaP of the 1,799 nt segment of SARS-CoV-2 genomic RNA**

A DNA template of the 1,799 nt segment of the SARS-CoV-2 genome, plus an upstream T7 promoter, was amplified from the SARS Coronavirus 2 1,799 bp construct (Twist Bioscience) with 250 nM primers TAATACGACTCACTATAGGTACTGGTCAGGCAATAACAGTTACAC and GACCCCATTTATTAAATGGAAAACCAGCTG (Integrated DNA Technologies) using 2X CloneAmp HiFi PCR Premix (Takara Bio) in a 20 µl volume with initial denaturation at 98°C for 30 s; 30 cycles of 98°C for 10

s, 65°C for 10 s, and 72°C for 10 s; and final extension at 72°C for 60 s. The PCR product was purified using a DNA Clean & Concentrator-5 kit (Zymo Research) according to the manufacturer's protocol; it was eluted in 18 µl of 10 mM Tris-HCl pH 8 (Invitrogen) and measured with a NanoDrop One (Thermo Fisher Scientific). RNA was transcribed using a HiScribe T7 High Yield RNA Synthesis Kit (New England Biolabs) according to the manufacturer's protocol. Specifically, 100 ng of DNA template from the previous step was diluted to 8 µl in nuclease-free water (Fisher Bioreagents), mixed with 2 µl of each of the four 10X (100 mM) NTP solutions followed by 2 µl of the 10X reaction buffer and 2 µl of the 10X T7 RNA polymerase mix, and then incubated at 37°C for 11 hr. The DNA template was then degraded by adding 1 µl of TURBO DNase (Invitrogen) and incubating at 37°C for 30 min. The RNA transcript was purified using an RNA Clean & Concentrator-25 kit (Zymo Research) according to the manufacturer's protocol; samples were eluted in 50 µl of nuclease-free water (Fisher Bioreagents) and measured with a NanoDrop One (Thermo Fisher Scientific).

For each antisense oligonucleotide (ASO) treatment, 1 pmol (580 ng) of RNA was diluted to 8 µl in nuclease-free water (Fisher Bioreagents) and mixed with 100 pmol (1 µl at 100 µM) each of zero, one, or two ASOs (Integrated DNA Technologies, Supplementary Table ??); the total volume was adjusted to 10 µl by adding nuclease-free water (Fisher Bioreagents). In a PCR tube, the RNA was heated to 95°C for 60 s to denature it, then placed on ice for 5-10 min. Meanwhile, 1.15X refolding buffer was assembled from 75 µl of 400 mM sodium cacodylate pH 7.2 (Electron Microscopy Sciences), 0.6 µl of 1 M magnesium chloride (Invitrogen), and 11.5 µl nuclease-free water (Fisher Bioreagents). If no ASO would be added during refolding, then an additional 1 µl of nuclease-free water (Fisher Bioreagents) was added. The refolding buffer was pre-warmed to 37°C in a 1.5 ml tube. The denatured, chilled RNA was pipetted into the pre-warmed refolding buffer and incubated at 37°C for 15-20 min to refold the RNA. If an ASO would be added during refolding, then 1 µl (100 pmol) of ASO was added. The RNA was incubated for another 15 min to allow any newly added ASOs to bind.

For chemical probing, 1.9  $\mu$ l of neat DMS (Sigma-Aldrich) was added for a total volume of 100  $\mu$ l including 200 mM DMS, 300 mM sodium cacodylate, 6 mM magnesium chloride, and 10 nM RNA. DMS was initially mixed by swirling the pipette tip and then kept suspended by shaking at 500 rpm in a ThermoMixer C (Eppendorf) throughout the treatment at 37°C for 5 min. The reaction was quenched by adding 20  $\mu$ l neat beta-mercaptoethanol (Sigma-Aldrich) and mixing thoroughly by pipetting. DMS-modified RNA was purified using an RNA Clean & Concentrator-5 kit (Zymo Research) according to the manufacturer's protocol; RNA was eluted in 15  $\mu$ l of nuclease-free water (Fisher Bioreagents) and measured with a NanoDrop One (Thermo Fisher Scientific).

Before reverse transcription, 1  $\mu$ l of DMS-modified RNA was mixed with 7  $\mu$ l nuclease-free water (Fisher Bioreagents), 1  $\mu$ l of 10 mM dNTPs (Promega), and 1  $\mu$ l of 10  $\mu$ M FSE reverse primer CTTCGTCCTTTTCTTGGAAGCGACA (Integrated DNA Technologies) in a PCR tube. The tube was heated at 65°C for 5 min to denature the RNA and anneal the primer, then placed on ice for 5 min. Meanwhile, 2X reverse transcription mix was assembled from 5  $\mu$ l of nuclease-free water (Fisher Bioreagents), 4  $\mu$ l of 5X Induro RT Reaction Buffer (New England Biolabs), and 1  $\mu$ l of Induro Reverse Transcriptase (New England Biolabs). The 10  $\mu$ l of denatured nucleic acids was mixed with 10  $\mu$ l of 2X reverse transcription mix. RNA was reverse transcribed at 57°C for 30 min, followed by inactivation at 95°C for 1 min.

The FSE section was amplified by mixing 1  $\mu$ l of unpurified cDNA with 7  $\mu$ l of nuclease-free water (Fisher Bioreagents), 10  $\mu$ l of Q5 High-Fidelity 2X Master Mix (New England Biolabs), 1  $\mu$ l of FSE forward primer CCCTGTGGGTTTTTCACTTAAAAAC (Integrated DNA Technologies), and 1  $\mu$ l of FSE reverse primer CTTCGTCCTTTTCTTGGAAGCGACA (Integrated DNA Technologies); initially denaturing at 98°C for 30 s; 30 cycles of 98°C for 10 s, 65°C for 20 s, and 72°C for 20 s; and finally extending at 72°C for 120 s. Amplification was confirmed by electrophoresing 1  $\mu$ l of the PCR product through an E-Gel EX Agarose Gel, 2% (Invitrogen) and checking for a 283 bp band. The PCR product was purified using a DNA Clean & Concentrator-5 kit (Zymo Research) according to the manufacturer's

protocol; it was eluted in 20  $\mu$ l of 10 mM Tris-HCl pH 8 (Invitrogen) and measured with a NanoDrop One (Thermo Fisher Scientific).

A 50-100 ng aliquot of the purified FSE amplicon was diluted in 10 mM Tris-HCl pH 8 (Invitrogen) to a total of 25  $\mu$ l. A sequencing library was generated using the NEBNext Ultra II DNA Library Prep Kit for Illumina (New England Biolabs) according to the manufacturer's protocol with the following modifications. To conserve reagents, all steps were performed at half volume, including reactions, bead cleanups, and washes. During two-step size selection after adapter ligation, 14  $\mu$ l and 7  $\mu$ l of SPRIselect Beads (Beckman Coulter) were used in the first and second steps, respectively, to select inserts of 283 bp. Also to conserve reagents, indexing PCR was run with each primer at 400 nM (instead of 1000 nM specified in the protocol), for 4 cycles. After indexing, PCR products were pooled in pairs; each pool (50  $\mu$ l) was mixed with 5  $\mu$ l of 10X E-Gel Sample Loading Buffer (Invitrogen), and 25  $\mu$ l was electrophoresed through a 2% E-Gel SizeSelect II Agarose Gel (Invitrogen) according to the manufacturer's instructions. Samples were extracted in 50  $\mu$ l nuclease-free water (Fisher Bioreagents). DNA concentrations were measured using a Qubit 4 Fluorometer (Thermo Fisher Scientific) according to the manufacturer's protocol. Samples were pooled and sequenced using a NextSeq 1000 Sequencing System (Illumina) with 2 x 150 bp paired-end reads according to the manufacturer's protocol.

## **DMS-MaPseq of live transmissible gastroenteritis virus**