Thiopurines inhibit coronavirus Spike protein processing and incorporation into progeny virions

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ABSTRACT

There is an outstanding need for broadly acting antiviral drugs to combat emerging viral diseases. Here, we report that thiopurines inhibit the replication of the betacoronaviruses HCoV-OC43 and SARS-CoV-2, and to a lesser extent, the alphacoronavirus HCoV-229E. 6-Thioguanine (6-TG) disrupted early stages of infection, limiting synthesis of full-length and subgenomic HCoV RNAs. Furthermore, consistent with our previous report on the effects of thiopurines on influenza A virus (IAV) glycoproteins, we observed that 6-TG inhibited accumulation of Spike glycoproteins from diverse HCoVs. Specifically, 6-TG treatment decreased the accumulation of Spike proteins and increased their electrophoretic mobility to match the properties of Spike following enzymatic removal of N-linked oligosaccharides with Peptide:N-glycosidase F (PNGaseF). SARS-CoV-2 virus-like particles (VLPs) harvested from 6-TG-treated cells were deficient in Spike. 6-TG treatment had a similar effect on lentiviruses pseudotyped with SARS-CoV-2 Spike; lentiviruses could be harvested from cell supernatants, but they were deficient in Spike and unable to infect human cells bearing ACE2 receptors. Together, these findings from complementary ectopic expression and infection models strongly indicate that defective Spike trafficking and processing is an outcome of 6-TG treatment. At low micromolar doses, the primary known mode of action of 6-TG is selective inhibition of the small GTPase Rac1. However, we show that selective chemical inhibitors of the small GTPases Rac1, CDC42 and Rho had no effect on Spike processing and accumulation, whereas the broad GTPase agonist ML099 was able to counter the effects of 6-TG, suggesting that an unknown GTPase could be the relevant 6-TG-target protein involved in regulating Spike processing and accumulation. Overall, these findings provide important clues about the mechanism of action of a candidate antiviral that can broadly target HCoVs and suggest that small GTPases may be promising targets for host-targeted antivirals.

57 **INTRODUCTION**

58 Coronaviruses (CoVs) are enveloped viruses with positive-sense, single-stranded RNA
59 ((+)ssRNA) genomes. Seven human CoVs (HCoVs) are divided into two genera, the
60 alphacoronaviruses (HCoV-NL63 and HCoV-229E) and betacoronaviruses (HCoV-OC43, HCoV-
61 HKU1, MERS-CoV, SARS-CoV and SARS-CoV-2). Following entry into host cells, the
62 (+)ssRNA CoV genome is immediately translated into polyproteins that are cleaved by viral
63 cysteine proteases into 16 non-structural proteins (NSPs). These NSPs include the transmembrane
64 nsp3-nsp4-nsp6 complex that generates a complex endoplasmic reticulum (ER)-derived
65 reticulovesicular network that includes replication organelles known as double-membrane vesicles
66 (DMVs) (1–8). In DMVs, the nsp3-nsp4-nsp6 complex provides a physical anchor for the viral
67 replicase-transcriptase complex (RTC) that replicates the large viral genome and synthesizes
68 subgenomic mRNAs (9, 10). These viral RNAs traverse a crown-shaped pore to exit the DMV (8).
69 In the cytoplasm, viral mRNAs are translated into structural proteins; Nucleocapsid (N) is
70 synthesized via free ribosomes in the cytoplasm, whereas mRNAs encoding envelope proteins are
71 translated and processed in the ER and accumulate in the ER-Golgi-intermediate compartment
72 (ERGIC). HCoV assembly takes place when full-length viral genomic RNA coated with N buds
73 into the ERGIC to acquire the viral envelope and associated envelope proteins (11–13). These
74 progeny viruses traverse the Golgi apparatus and *trans*-Golgi network (TGN), where envelope
75 proteins receive additional post-translational modifications, and exit the cell via lysosomal
76 exocytosis (14).

77 CoV envelope proteins are subject to extensive processing in the secretory pathway. The
78 viral envelope proteins Spike, Envelope (E) and Matrix (M) that are found in all HCoVs, as well
79 as Hemagglutinin-Esterase (H-E) found in only HCoV-OC43 and HCoV-HKU1, are synthesized
80 in the ER as transmembrane (TM) proteins (15). CoV Spike proteins are large type I TM proteins
81 that are heavily N-glycosylated, which promotes proper folding, trimerization and trafficking (16).
82 Subsequent proteolytic processing is required to activate these glycosylated Spike trimers,
83 generating the S1 attachment protein and liberating the mature amino-terminal fusion peptide of
84 the S2 fusion protein, both of which are essential components of infectious CoV virions that can
85 enter target cells (17, 18). Proteolytic activation of Spike can occur in the secretory pathway of
86 infected cells or unprocessed Spike can be incorporated into virions and Spike processing can
87 occur during attachment and entry into naïve cells in a process that involves multiple host serine

88 and cysteine proteases. M is the most abundant CoV envelope protein and it serves as a scaffold
89 for viral assembly. It is a multi-spanning membrane protein, with a small lumenal amino-terminus
90 that is N-glycosylated, and three transmembrane domains followed by a large, cytoplasmic
91 carboxy-terminal domain known as the endodomain that governs interactions with the other
92 structural proteins (Spike, E and N), as well as M-M interactions. E is a small type I transmembrane
93 protein that forms pentameric complexes and functions as a viroporin, increasing the lumenal pH
94 in the Golgi and protecting Spike from proteolysis (reviewed in (19)). The viroporin activity may
95 support de-acidification of lysosomes and subsequent lysosomal exocytosis. M and E proteins both
96 govern the intracellular trafficking and processing of Spike (20).

97 The striking remodeling of the ER to create replication organelles, as well as the reliance
98 on the ER for synthesis and processing of viral glycoproteins, has prompted investigations into the
99 effects of HCoV infection on ER stress and the unfolded protein response (UPR). Several
100 coronaviruses (CoVs) have been shown to activate the UPR, including infectious bronchitis virus
101 (IBV) (21, 22), mouse hepatitis virus (MHV) (23), transmissible gastroenteritis virus (TGEV) (24),
102 human coronavirus (HCoV)-OC43 (25) and SARS-CoV (26–28). However, proximal UPR sensor
103 activation does not always elicit downstream UPR transcription responses during CoV replication
104 (29), which suggests complex regulation of the UPR by certain CoVs. Ectopic expression of Spike
105 proteins from MHV (23), HCoV-HKU1 (27) and SARS-CoV (27, 30) have all been shown to be
106 sufficient for UPR activation in cell culture. Additional transmembrane CoV proteins have been
107 shown to be sufficient to induce the UPR, including SARS-CoV non-structural protein 6 (nsp6)
108 (31), ORF3a (32) and ORF8ab (33) proteins. Despite these discoveries, our understanding of the
109 regulation of the UPR in CoV infection remains incomplete, and little is known about UPR
110 regulation in SARS-CoV-2 infection.

111 The emergence of SARS-CoV and MERS-CoV from animal reservoirs, followed by the
112 current SARS-CoV-2 pandemic, has spurred efforts to discover and develop effective antivirals.
113 These efforts have benefitted from drug repurposing strategies to identify antivirals amongst drugs
114 that have already been approved for use in humans. We showed previously that thiopurines 6-
115 thioguanine (6-TG) and 6-thioguanosine (6-TGo) selectively inhibited influenza A virus (IAV)
116 replication by activating the UPR and interfering with the processing and accumulation of viral
117 glycoproteins (34). Thiopurines have been in clinical use for over 50 years to treat inflammatory
118 diseases and cancer and as immunomodulators. They include azathioprine, 6-mercaptopurine (6-

119 MP) and 6-TG. 6-TG is orally bioavailable and on the World Health Organization's List of
120 Essential Medicines. It is used to treat hematological malignancies, including acute lymphoblastic
121 leukemia (AML), acute lymphocytic leukemia (ALL) and chronic myeloid leukemia (CML), with
122 the primary mechanism of action involving conversion into thioguanine deoxynucleotides and
123 incorporation into cellular DNA, which preferentially kills rapidly dividing cancer cells (35, 36).
124 By contrast, the anti-inflammatory effect of sub-cytotoxic doses of 6-TG for treating inflammatory
125 bowel disease (IBD) is thought to be primarily due to inhibition of the small GTPase Rac1 (37,
126 38). This process requires 6-TG to be metabolized by the purine scavenging enzyme hypoxanthine
127 phosphoribosyltransferase 1 (HPRT1) to yield 6-thioguanosine 5'-monophosphate (6-TGMP),
128 which is then converted to 6-thioguanosine 5'-triphosphate (6-TGTP). 6-TGTP is the active form
129 of the molecule that has been shown to covalently modify a reactive cysteine in the p-loop of Rac1;
130 subsequent hydrolysis of the GTPase-bound 6-TGTP adduct yields a trapped, inactive Rac1-6-
131 TGDP product (37). These host-targeted properties of 6-TG, combined with our knowledge of how
132 6-TG inhibits IAV glycoprotein processing, motivated us to investigate whether 6-TG and related
133 thiopurines might similarly interfere with CoV glycoproteins. Moreover, we reasoned that this
134 kind of host-targeted antiviral activity might act synergistically with the previously reported direct-
135 acting antiviral activity of 6-TG as an inhibitor of MERS-CoV, SARS-CoV and SARS-CoV-2
136 papain-like cysteine proteases PL^{pro} *in vitro* (39–42). Using ectopic expression and cell culture
137 infection models, we discovered that 6-TG and 6-TGo inhibited replication of several CoVs
138 including SARS-CoV-2, which correlated with disruption of Spike processing, as well as Spike
139 accumulation and incorporation into progeny virions. Accumulation of viral subgenomic RNAs
140 and full-length genomes was also inhibited by these thiopurines. Finally, we were able to link the
141 antiviral mechanism of action to the primary known mode of action of 6-TG and related molecules
142 as selective inhibitors of small GTPases (37, 43, 44), which could be overcome by treating with a
143 pan-GTPase agonist. Our findings extend the understanding of the mechanism of action of these
144 candidate host-targeted antivirals and provide a means to study the impact of glycoprotein
145 maturation on coronavirus biology.

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148

149 **RESULTS**

150 **6-Thioguanine and 6-thioguanosine inhibit HCoV replication**. We tested the effects of three
151 thiopurines on SARS-CoV-2 replication in Calu-3 lung adenocarcinoma cells. Treatment with 6-
152 TG, the ribonucleoside 6-TGo, or the related thiopurine 6-MP, caused a striking 4-log decrease
153 in the release of infectious virions after 48 h of infection, with little effect on cell viability
154 [Selectivity Index (SI) 6-TG > 87.0, 6-TGo > 37.4, 6-MP >35.4] (**Figs. 1A, 1B, 1C**). The sub-
155 micromolar EC_{50} values that we observed for all three thiopurines in the Calu-3 infection model
156 were consistent with previously reported values from other groups (42, 45). 6-TG was well
157 tolerated in three other cell lines we used for HCoV infection models (HCT-8, Huh7.5, and
158 primary hTERT-immortalized fibroblasts) (Fig 1D). We tested the ability of 6-TG to inhibit the
159 betacoronavirus HCoV-OC43 and the alphacoronavirus HCoV-229E and found that low
160 micromolar doses of the ribonucleoside 6-TGo had similar inhibitory effects against HCoV-229E
161 and HCoV-OC43 in their respective infection models, whereas 6-MP had no effect **(Figs. 1E,**
162 **1F)**. Because UPR stimulators thapsigargin (Tg) and tunicamycin (TM) inhibit coronavirus
163 replication (46–49) and our previous work demonstrated that 6-TG can inhibit glycosylation of
164 influenza A virus (IAV) glycoproteins and stimulate ER stress (34), we included TM as a
165 positive control in these studies. In hTert-BJ cells, 6-TG inhibited HCoV-OC43 replication at
166 low micromolar doses, consistent with our observations in the HCT-8 cell infection model;
167 however, HCoV-229E replication in hTert-BJ cells was minimally affected across a range of
168 sub-cytotoxic concentrations (**Figs. 1G, 1H**). Together, these findings suggested that 6-TG was
169 more effective at inhibiting HCoV-OC43 and SARS-CoV-2 replication than HCoV-229E, and
170 that this differential susceptibility can be at least partly attributed to differences between these
171 viruses.

172

173 **6-Thioguanine impedes viral genome replication and subgenomic RNA synthesis.** Next, we
174 investigated which stages of virus replication were affected by 6-TG treatment. We performed
175 multi-round HCoV-OC43 infections of HEK293T cells at an MOI of 0.1. Infected cells were
176 treated with 10 μM 6-TG or DMSO immediately after infection, and cell lysates and
177 supernatants were harvested at regular intervals for the next 48 hours. 6-TG treatment caused a
178 ~40-fold reduction in infection during the first day of infection. Virion release from control cells

179 plateaued at 24 hours post-infection, whereas peak release of infectious virions from 6-TG-
180 treated cells occurred much later at 48 hours post-infection **(Fig. 2A)**. Similarly, measuring viral
181 particle release by RT-qPCR amplification of viral genomes revealed a ~20-fold reduction in
182 virus titer **(Fig. 2B)** throughout the first day of infection. Next, we investigated the ability of 6-
183 TG to disrupt viral RNA synthesis. Putative full-length RNA, as detected by primers targeting
184 *ORF1a*, was reduced by ~10-fold throughout most stages of infection. Similar decreases were
185 detected using primers targeting the coding region of *Spike* and *N* genes after 6 h post-infection,
186 with much larger 40-fold differences at 6 h post-infection **(Fig. 2C)**. These disruptions in viral
187 RNA accumulation correlated with changes in the localization of N, the viral nucleoprotein.
188 Immunostaining HCoV-OC43 infected cells with an anti-N antibody revealed a punctate staining
189 pattern at 6 hours post-infection **(Fig. 2D)**. By 24 h post-infection, N immunostaining was less
190 punctate and more peripheral as at later stages of infection. The N immunostaining was markedly
191 altered in 6-TG-treated infected cells, with brighter punctate staining patterns at 6 hours post-
192 infection and large puncta still visible at 24 h post-infection. The formation of replication
193 compartments was also delayed in 6-TG treated cells, as determined by immunostaining for
194 dsRNA **(Fig. 2E)**; specifically, we observed dsRNA signal at 6 hpi, which correlated with
195 decreased viral RNA detected by RT-qPCR **(Fig. 2C)**. Together, these findings indicate that 6-
196 TG reduces the synthesis of viral RNAs required to support efficient HCoV replication.

197 In our recent study, the antiviral mechanism of action of 6-TG and 6-TGo against IAVs
198 involved activation of the UPR and interference with the processing and accumulation of viral
199 glycoproteins. In these experiments, IAV infection of vehicle-treated A549 cells revealed very
200 little detectable UPR late in infection at 24 h post-infection, whereas 6-TG stimulated all three
201 arms of the UPR, with transactivation of XBP1s target gene *ERdj4*, ATF6-N target genes *BiP* and
202 *HERPUD1* and ATF4 target gene *CHOP* (34). Thus, thiopurines markedly altered the ER
203 proteostasis landscape to the detriment of IAV replication. By contrast, many HCoVs have been
204 shown to activate the UPR, including infectious bronchitis virus (IBV) (21, 22), mouse hepatitis
205 virus (MHV) (23), transmissible gastroenteritis virus (TGEV) (24), human coronavirus (HCoV)-
206 OC43 (25) and SARS-CoV (26–28). Here, HCoV-OC43 infection caused induction of *Xbp1*
207 transcript, potent accumulation of spliced *Xbp1*, and transactivation of XBP1s target genes *ERdj4*
208 and *Edem1*, providing strong evidence for activation of the IRE1 arms of the UPR **(Figs. S1A,**
209 **S1B)**. Regulation of the PERK/ATF4 arm of the UPR may be more complex, as HCoV-OC43

210 infection caused accumulation of *ATF3* mRNA but no change in *CHOP*, even though they are both
211 encoded by ATF4 target genes. Similarly, we observed increased expression of ATF6-N target
212 genes *HERPUD1* and *Xbp1* but no increases in BiP mRNA or protein **(Figs. S1A, S1B)**. Thus,
213 HCoV-OC43 interactions with the UPR appear to be complex and marked by strong stimulation
214 of IRE1, which is consistent with observations from others (25). In marked contrast to our IAV
215 studies, 6-TG treatment generally delayed or suppressed the downstream UPR transcriptional
216 response **(Fig. S1A)**, which could be attributed to 6-TG-mediated delays in viral replication and
217 the accumulation of viral RNAs and proteins **(Fig. 2)**. Finally, it should be noted that UPR
218 transcripts accumulated to high levels in vehicle-treated cells despite the fact that HCoV-OC43,
219 like all HCoVs, has mechanisms to potently shut off host antiviral gene expression (25). Using
220 ribopuromycinylation assays, we demonstrated that HCoV-OC43 greatly reduced translation of
221 host mRNAs at the expense of viral mRNAs encoding a few abundant viral proteins **(Fig. S1C,**
222 **lane 4)**. 6-TG treatment had no effect on global rates of translation initiation in HCoV-OC43
223 infected cells, with the only changes evident being the apparent loss of some abundant viral
224 proteins **(Fig. S1C, lane 6)**. Together, these observations suggested that 6-TG inhibition of HCoV-
225 OC43 infection limits the strong activation of IRE1 and accumulation of XBP1s target genes, and
226 that even though 6-TG interferes with synthesis of viral full-length genomic RNAs and
227 subgenomic RNAs, host shutoff is unperturbed.

228

229 **6-Thioguanine inhibits Spike processing and accumulation.** We previously reported that 6-TG
230 and 6-TGo inhibited the processing and accumulation of IAV glycoproteins hemagglutinin (HA)
231 and neuraminidase (NA) (34). Here, we observed a similar defect in SARS-CoV-2 infected cells;
232 lysates harvested from SARS-CoV-2-infected Calu-3 cells at 48 h post-infection showed a sharp
233 decrease in all four structural proteins following 6-TG treatment **(Fig. 3A)**, consistent with a sub-
234 micromolar EC50 discussed above **(Fig. 1B)**. Treatment of SARS-CoV-2-infected Huh-7.5 cells
235 with 10 μM 6-TG also reduced the accumulation of viral structural proteins, which was especially
236 evident for Spike **(Fig. 3B)**. These findings led us to further investigate the effects of 6-TG on
237 SARS-CoV-2 structural protein expression. Transfection of HEK293T cells with each SARS-
238 CoV-2 structural protein independently revealed that 6-TG had no effect on E or N accumulation,
239 whereas Spike processing was noticeably inhibited (**Fig. 3C**). We also observed that 6-TG

240 treatment caused a loss of a slow-migrating species of M **(Fig. 3C)**, which likely represented the
241 glycosylated form of the protein that has been previously reported for other HCoVs (50). Thus, it
242 appears that amongst the SARS-CoV-2 structural proteins, only the glycosylated Spike and M
243 proteins are altered when they are expressed independently in HEK293T cells.

244 To further explore the effects of 6-TG on Spike, we ectopically expressed Spike, then
245 treated the cells with a range of sub-cytotoxic 6-TG concentrations before harvesting lysates and
246 processing for immunoblotting **(Figs. 3D, 3E)**. Spike appeared as two bands when immunoblots
247 are probed with an anti-S1 receptor binding domain (RBD) antibody, a high-molecular weight
248 (MW) precursor S0 band (~203 kDa) and a lower molecular weight band representing the protease-
249 cleaved S1 attachment protein (~96 kDa). Increasing concentrations of 6-TG once again led to the
250 accumulation of a prominent single band at an unexpected MW (~137 kDa) **(Fig. 3D)**. Because 6-
251 TG treatment caused Spike to migrate faster during SDS-PAGE than expected, we hypothesized
252 that the lower MW species could arise from a glycosylation defect. We treated lysates from Spike-
253 expressing HEK293T cells with Peptide-*N*-Glycosidase F (PNGase F), an amidase that cleaves the
254 bond between N-acetylglucosamine (GlcNAc) and asparagine, effectively removing all N-linked
255 glycans from the polypeptide chain (unless the core GlcNAc is modified by α-1,3-fucose) (51).
256 PNGase F treatment caused Spike from the DMSO-treated cells to migrate similarly to Spike from
257 6-TG-treated cells **(Fig. 3F)**. We confirmed the identity of the high MW Spike band as the
258 uncleaved S0 precursor protein by generating and testing a mutant Spike protein in which the basic
259 residues in the furin cleavage site joining S1 and S2 were substituted by alanines, yielding a
260 protease cleavage-resistant Spike protein. Cells transfected with this S0 construct and treated with
261 6-TG prior to lysis revealed that the S0 construct was also sensitive to PNGaseF treatment; the 6-
262 TG/PNGaseF-treated S0 migrated similarly to 6-TG/PNGaseF-treated WT Spike by SDS-PAGE.
263 Several studies have mapped O-linked glycans on SARS-CoV-2 Spike (52–54); these
264 modifications appear to follow the "O-follow-N rule" whereby N-glycosylation is followed by O-
265 glycosylation on nearby residues (52). Thus, the apparent differences in molecular weight between
266 vehicle/PNGaseF-treated Spike and 6-TG/PNGaseF-treated Spike could stem from residual O-
267 linked glycans on Spike that are absent in the 6-TG-treated proteins. These findings were
268 corroborated using carboxy-terminal FLAG-tagged Spike proteins from SARS-CoV-2 and MERS-
269 CoV that also displayed a fast-migrating, under-glycosylated S0 species and loss of the S2 subunit

270 following 6-TG treatment **(Fig. 3G)**. Taken together, these results suggest that 6-TG inhibits
271 normal glycosylation and processing of Spike.

272 A failure of Spike to migrate from the ER to the Golgi could inhibit glycan maturation and
273 cleavage by furin. In our previous work, we observed that 6-TG treatment did not reduce levels of
274 Class I HLA proteins at the cell surface (34), which we interpreted as evidence that 6-TG did not
275 globally affect processing and secretion of host cell glycoproteins. Here, we tested the role of 6-
276 TG on the secretory pathway by using a *Gaussia* luciferase assay, which is secreted from cells by
277 way of a native secretion signal (55). As a control we used the Arf1-inhibitor Brefeldin A (BFA)
278 which potently inhibits protein trafficking from the ER to the Golgi (56, 57). BFA is toxic to cells
279 at micromolar doses, but we could still detect secretory pathway inhibition at 250 nM for 20 h
280 without overt cytotoxicity **(Figs. S2A, S2B)**. A short-term, 6 h treatment with 6-TG (10 μM) had
281 little effect on *Gaussia* luciferase secretion, whereas treatment with BFA (10 μM) greatly
282 decreased secretion. We tested a longer 20 h treatment of 6-TG where we co-transfected Firefly
283 luciferase (Luc2) with *Gaussia* luciferase to help control for the inhibitory effects of 6-TG on
284 HEK293T cell proliferation. This extended 6-TG treatment caused a slight loss of detectable
285 *Gaussia* luciferase activity in the cell supernatant, but once again low-dose treatment of BFA
286 greatly inhibited secretion and increased intracellular retention of *Gaussia* luciferase (Fig. S3C)
287 These experiments strongly corroborated our prior observations that 6-TG treatment does not
288 globally disrupt the secretory pathway. Because of our previous observations of 6-TG-mediated
289 defects in Spike glycosylation, processing and trafficking, we decided to test whether low-dose,
290 long-term treatment with BFA would be sufficient to recapitulate the effects of 6-TG treatment on
291 Spike. However, unlike 6-TG, the secretion inhibitor BFA did not cause any changes in Spike
292 accumulation or processing, as indicated by identical electrophoretic mobility of Spike on
293 immunoblots compared to vehicle control **(Fig. S2D).**

294 To directly monitor Spike protein secretion, we used flow cytometry and surface staining
295 of unpermeablized HEK293T cells transfected with Spike. We co-transfected cells with an EGFP
296 plasmid and gated on EGFP+ cells to measure changes in Spike accumulation. 6-TG reduced
297 surface expression of Spike by ~50% resulting in fewer Spike-positive cells and reduced mean
298 fluorescence intensity. In these experiments, we also tested a Spike protein in which the 19 C-
299 terminal residues were removed (Spike-Δ19); this widely used strategy removes an ER-retrieval
300 signal and enhances incorporation into lentivirus particles (58–60). We found a similar ~50%

301 reduction in trafficking and surface expression of Spike-Δ19 **(Fig. S2E)**. Together, these
302 experiments indicate that 6TG inhibits normal trafficking of Spike to the cell surface but does not
303 broadly inhibit secretion.

304

305 **6-Thioguanine causes a coronavirus assembly defect.** It has been shown that co-transfection of
306 all four SARS-CoV-2 structural proteins allows secretion of virus-like particles (VLPs) (20),
307 which is concordant with earlier studies of other CoV structural proteins (61). However, we
308 observed that when Spike, E, M and N expression vectors were co-transfected into cells, 6-TG
309 treatment not only altered the accumulation and processing of Spike, but also dramatically reduced
310 accumulation of E and M proteins (**Fig. 4A**). Cell supernatants were collected, filtered and pelleted
311 in a sucrose cushion to isolate VLPs, which were then characterized by immunoblotting. We
312 observed a dramatic reduction in VLP production from 6-TG-treated HEK293T cells, and these
313 residual VLPs completely lacked Spike (**Fig. 4B**). These findings indicate that 6-TG not only
314 prevents Spike processing and accumulation, but also its incorporation into VLPs. We then co-
315 transfected cells again with Spike, E, M, and N but omitted structural proteins individually to better
316 understand mechanisms of defective assembly. Our main conclusions are: 1) 6-TG treatment of
317 cells expressing all structural proteins causes a strong Spike-dependent decrease in E expression,
318 2) M resists the Spike glycosylation defect caused by 6-TG, and 3) N enhances expression of E
319 **(Fig 4C)**. To determine if Spike from 6-TG treated cells was still functional, we employed a
320 lentivirus pseudotyping method using Spike-Δ19, which is widely used to measure the neutralizing
321 antibodies to SARS-CoV-2 (58, 62, 63). We performed immunoblots on pseudotyped viruses
322 (PVs) recovered from three independent preparations that we purified by ultracentrifugation
323 through a 20% sucrose cushion. Unlike our previous immunoblots of ectopically expressed Spike
324 from transfected cells, we observed that most of the Spike proteins incorporated into the PVs were
325 fully cleaved into the prominent S1 band **(Fig. 4D)**. However, 6-TG treatment led to a dramatic
326 loss of Spike S0 and S1 species from the purified PVs, compared to little effect on HIV p24 levels
327 in PV cores. We quantified PV yield from these cells by amplifying lentiviral genomes via RT-
328 qPCR from filtered, unconcentrated cell supernatants. 6-TG treatment did not significantly reduce
329 the quantity of capsid-protected genomes released from cells compared to vehicle control **(Fig.
330 4E)**. To determine the effects of 6-TG on PV infectivity, we used purified PVs to infect HEK293A
331 cells that stably express the ACE2 receptor and measured luciferase production in the recipient

332 cells as a measure of successful lentiviral infection. Consistent with deficient Spike incorporation
333 into PVs, we observed that 6-TG treatment reduced PV infectivity by over 50-fold compared to
334 PVs derived from vehicle-treated cells **(Fig. 4F)**. By contrast, PVs derived from vehicle control-
335 and 6-TG-treated cells were equally competent to infect ACE2-deficient HEK293A cells at low
336 levels. This suggests that 6-TG treatment not only inhibits Spike glycosylation and processing, but
337 it also inhibits Spike trafficking and incorporation into lentiviral particles. We next investigated
338 whether these 6-TG-mediated assembly defects altered the morphology of HCoV particles. We
339 concentrated supernatant from HCoV-OC43 infected 293A cells by ultracentrifugation and imaged
340 virions by transmission electron microscopy using negative staining. We observed fewer viral
341 particles in the 6-TG treated samples, and while these particles were of similar size, we noted fewer
342 particles with clearly discernible Spikes **(Fig. 4G)**. Taken together, the strong effects of 6-TG on
343 Spike in transient transfections, heterologous lentivirus infections, and authentic HCoV infections,
344 provide evidence for an additional antiviral mode of action for 6-TG beyond PLpro inhibition or
345 defects in viral RNA synthesis.

346

347 **6-Thioguanine must be processed by HPRT1 to inhibit Spike processing and coronavirus**
348 **replication.**

349 We observed comparable antiviral activities of 6-TG and its ribose-conjugated analogue 6-TGo
350 throughout these studies. Metabolism of 6-TG is initiated by the purine scavenging enzyme
351 hypoxanthine phosphoribosyltransferase 1 (HPRT1) to yield 6-thioguanosine 5'-monophosphate
352 (6-TGMP) **(Fig. 5A)**. 6-TGMP can then be converted to 6-thioguanosine 5'-triphosphate (6-
353 TGTP), the active form of the molecule that has been shown to form a covalent bond with a
354 reactive cysteine in the p-loop of Rac1; subsequent hydrolysis of Rac1-6-TGTP to a diphosphate
355 form renders the GTPase inactive (37). Considering this information, we next sought to determine
356 whether conversion of 6-TG to a ribonucleoside was required for its antiviral activity. First, we
357 synthesized N9-methyl 6-thioguanine (6-TGMe), which prevents conjugation to a ribose sugar due
358 to the methyl group at N9 of the urine ring **(Fig. 5A)**. 6-TGMe displayed low cytotoxicity and no
359 antiviral activity against HCoV-OC43 across a broad range of concentrations **(Fig. 5B)**. Likewise,
360 6-TGMe had no effect on SARS-CoV-2 Spike processing across a range of concentrations between
361 5 μM and 20 μM **(Fig. 5C)**. To corroborate this finding, we used RNA interference to silence

362 expression of *HPRT1* in 293T cells prior to infection with HCoV-OC43 and treatment with 6-TG
363 or vehicle control. RT-qPCR confirmed effective silencing of *HPRT1*(**Fig. 5D**), which had no
364 effect on HCoV-OC43 infection in vehicle control-treated cells **(Fig. 5E)**. By contrast, *HPRT1*
365 silencing significantly restored viral replication in the presence of 6-TG, although replication did
366 not return to the levels in control cells. Together, these findings indicate that 6-TG is a pro-drug
367 that must be metabolized by HPRT1 to convert it to an active form.

368

369 **6-Thioguanine inhibits Spike maturation by inhibiting an unidentified cellular GTPase.** 6-
370 TG inhibits several different GTPases including Rac1, RhoA, and Cdc42 (37, 43, 44). This mode
371 of action was previously shown to inhibit rotavirus replication at sub-micromolar concentrations
372 (64). Here, we sought to determine if any of the known targets of 6-TG were responsible for defects
373 in Spike maturation. We tested known inhibitors of Rac1 (Rac1 Inhibitor V), RhoA (Rhosin), and
374 Cdc42 (CASIN) for cytotoxic effects in HEK293T cells after 24 h incubation using an alamarBlue
375 assay to identify optimal sub-cytotoxic doses for further testing (**Figs. 6A, 6B)**. We also tested a
376 GTPase agonist ML099 that can potently activate Rac1, RhoA, and Cdc42, among other GTPases
377 (65). None of the three GTPase inhibitors had any effect on Spike processing or accumulation
378 **(Fig. 6C)**. Because many additional GTPases have redox-sensitive cysteine residues that could
379 interact with 6-TG, we reasoned that 6-TG could affect viral glycoproteins through an as-yet-
380 unidentified GTPase. In support of this notion, we observed that the broadly acting small GTPase
381 agonist ML099 maintained normal Spike processing in the presence of 6-TG **(Fig. 6D)**. Pre-
382 treating the cells with ML099 before addition of 6-TG further enhanced this effect **(Fig. 6E)**. We
383 attempted to rescue HCoV-OC43 titer in both HCT-8 and HEK293A infection models but instead
384 found that ML099 was itself acting as an antiviral agent **(Fig. 6F)**. While this was worth testing,
385 this result was unsurprising as viral infection likely requires specific or unperturbed GTPase
386 function, including frequent cycling between GTP- and GDP-bound forms. Overall, these data
387 suggest that 6-TG inhibits Spike maturation by inhibiting an unidentified cellular GTPase.

388

389
390

391 **DISCUSSION**

392 The reliance of viruses on the host cell biosynthetic and secretory apparatus, combined with the
393 existence of varied and potent host antiviral mechanisms, makes host targeted antivirals (HTAs)
394 useful additions to our armamentarium of direct-acting antivirals (DAAs). By targeting these host
395 cell processes, HTAs may not be so easily subverted by the rapid viral evolution that frequently
396 undermines DAAs. We recently reported that the thiopurines 6-TG and 6-TGo inhibit influenza A
397 virus (IAV) by selectively disrupting the normal processing and accumulation of HA and NA
398 glycoproteins (34). We hypothesized that other enveloped viruses that rapidly produce a burst of
399 viral glycoproteins would also be susceptible to these thiopurines. Here, we reported that the
400 thioguanine 6-TG disrupted the normal processing and accumulation of CoV Spike glycoproteins
401 and inhibited the release of infectious progeny. This drug-induced Spike processing defect
402 disrupted incorporation of SARS-CoV-2 Spike into VLPs or pseudotyped lentiviruses, which
403 subsequently prevented infection of susceptible, ACE2-expressing cells (Fig. 7). We also
404 significantly advanced our understanding of the molecular mechanism of action of these
405 thiopurines, which had previously been shown to inhibit the small GTPase Rac1 by forming a
406 covalent bond with a redox-sensitive cysteine, preventing further guanine nucleotide exchange.
407 We showed that selective chemical inhibitors of the related small GTPases Rac1, CDC42 and Rho
408 had no effect on Spike processing and accumulation, but a broad GTPase agonist was able to
409 counter the effects of 6-TG, suggesting that there are additional, unknown GTPase targets of 6-TG
410 that are required for normal Spike processing and accumulation. Together, these findings suggest
411 that functioning small GTPases are essential for virus replication and that further development of
412 GTPase inhibitors as host-directed antivirals is warranted.

413 We were intrigued by how 6-TG and 6-TGo strongly inhibited processing and
414 accumulation of IAV and CoV glycoproteins, whereas other viral proteins were relatively
415 unperturbed. However, we also observed that these thiopurines had little effect on global host
416 protein synthesis and secretion. Together, these observations suggested that viral glycoproteins
417 may have properties that make them uniquely sensitive to these drugs. Certainly, viral
418 glycoproteins must adhere to temporal or physical constraints that most host glycoproteins do not.
419 All glycoproteins are synthesized, folded and post-translationally modified in the ER. However,
420 viral glycoproteins can impose an acute burden on the ER when they are rapidly synthesized in
421 large numbers in a relatively brief time frame. This burden may differ in severity depending on

422 the extent of shutoff of host gene expression, as viruses with efficient host shutoff mechanisms
423 would deplete host glycoproteins and facilitate viral utilization of cellular biosynthetic and
424 secretory apparatus. Viral envelope proteins are often more heavily glycosylated than their host
425 counterparts, which can shield them from antibody recognition. Because N-glycosylation is a
426 dynamic process involving glycan trimming and maturation monitored by lectin chaperones like
427 calnexin and calreticulin, viral infection may impose specific burdens on these components of the
428 ER quality control machinery. This may result in delayed trafficking of glycoproteins through the
429 secretory pathway, leading to their degradation. Finally, it should be noted that viral glycoproteins
430 are often assembled into large homo- and hetero-oligomeric complexes that must traffic to sites of
431 assembly. Together, these aspects of viral glycoproteins likely place additional burdens on the ER
432 and associated machinery that governs glycoprotein folding, modification and trafficking.

433 Because cellular GTPases play important roles in viral glycoprotein biogenesis and
434 trafficking, they may be good targets for host-directed antivirals. Viral assembly occurs at distinct
435 sites like the plasma membrane (influenza A viruses) or the ERGIC (coronaviruses). Small
436 molecules that disrupt efficient viral glycoprotein processing, oligomerization and trafficking
437 could have the effect of 'misplacing' these important viral components and inhibiting essential
438 steps in viral assembly and egress. We speculate that 6-TG and 6-TGo inhibit GTPases involved
439 in key steps of viral glycoprotein synthesis, processing and trafficking, diverting them from their
440 roles in viral assembly and consigning them to degradation via cellular catabolic processes. While
441 these drugs are well-tolerated in humans, we believe that more can be gained by identifying and
442 characterizing their mode of action against the GTPases that have thus far been elusive.

443

444 **MATERIALS AND METHODS**

445 **Cell lines.** Human embryonic kidney 293T and 293A cells, human hepatoma Huh-7.5 (66) and
446 African green monkey kidney Vero cells were all maintained in Dulbecco's modified Eagle's
447 medium (DMEM; ThermoFisher Scientific) supplemented with 10% fetal bovine serum (FBS,
448 ThermoFisher Scientific), 100 U/mL penicillin, 100 µg/mL streptomycin, and 2 mM L-
449 glutamine (Pen/Strep/Gln; ThermoFisher Scientific, 15140122 and 25030081). HCT-8 cells were
450 cultured as above with additional 1X MEM Non-Essential Amino Acids (NEAA, Gibco)
451 supplemented. Baby hamster kidney (BHK-21) were maintained as above yet supplemented with

452 5% FBS. African green monkey kidney Vero'76 and human lung adenocarcinoma Calu-3 cells
453 were maintained in DMEM (Sigma-Aldrich, D5796; St. Louis, MO, USA) supplemented with
454 10% fetal bovine serum (ThermoFisher Scientific, 16000-044) and 1X Penicillin-Streptomycin
455 (Gibco, 15140148). hTert-immortalized human foreskin fibroblast (BJ) cells (a kind gift from
456 William Hahn, Dana-Farber Cancer Institute, Boston, USA) cells were maintained in a 4:1 blend
457 of knockout DMEM and medium 199 (ThermoFisher Scientific) with 15% FBS and
458 Pen/Strep/Gln. All cells were maintained at 37°C in 5% CO_2 atmosphere. To generate 293A-
459 ACE2 cells, 293A cells were stably transduced with a lentivirus vector encoding ACE2 (pLJM1-
460 ACE2-BSD) or an empty vector control (pLJM1-B*) (67), then selected and maintained in 10
461 µg/mL Blasticidin S HCl (ThermoFisher, A11139030).
462
463 **Chemical Inhibitors.** 6-thioguanine (6-TG, A4882), 2-amino-6-mercaptopurine riboside hydrate
464 (6-TGo, 858412), 6-mercaptopurine (6-MP, 38171), brefeldin A (BFA; B7651), CASIN
465 (SML1253), ML-099 (SML1258), Rac1 inhibitor V (5308200001), rhosin (555460),
466 thapsigargin (Tg) and tunicamycin (TM) were all purchased from Sigma-Aldrich. N9-methyl 6-
467 thioguanine (6-TGMe) was synthesized in house as described in Supporting Information. All
468 drugs were solubilized in dimethyl sulfoxide (DMSO) and stored at -80˚C. Stock concentrations
469 were diluted to the indicated concentrations in cell culture media.
470
471 **Human coronavirus infections and quantitation.** Stocks of severe acute respiratory syndrome
472 coronavirus 2 (SARS-CoV-2) were propagated in Vero'76 cells (for strain SARS-CoV-
473 2/Canada/ON/VIDO-01/2020, used in Fig. 1A) or Vero E6 cells (SARS-CoV-2/SB3-TYAGNC,
474 used in Figs. 3A, 3B). To generated virus stocks, cells were infected at a low MOI for 1h in
475 serum-free DMEM then incubated at 37°C in DMEM supplemented with 2% FBS and 1X
476 Pen/Strep. Once CPE reached 75% at 2-3 d post-infection, the viral supernatant was harvested,
477 centrifuged at 5000 x *g* for 5 min, and then the cleared viral supernatant was aliquoted and stored
478 at -80°C. Stocks were titered by plaque assay on Vero E6 cells (68) or TCID50 on Vero'76 cells
479 calculated using the Spearman-Kärber method.
480 Stocks of human coronavirus OC43 (hCoV-OC43; ATCC, VR-1558) were propagated in
481 Vero cells. Cells were infected at a MOI of 0.05 for 1 h at 33°C in serum-free DMEM. After 1 h,
482 the infected cells were maintained in DMEM supplemented with 1% FBS and Pen/Strep/Gln for

483 five days at 33°C. Upon harvest, the culture supernatant was centrifuged at 1000 x *g* for 5 min at
484 4°C, aliquoted, and stored at -80°C. Stocks of human coronavirus 229E (hCoV-229E; ATCC,
485 VR-740) were prepared similarly to hCoV-OC43 yet using Huh-7.5 cells and DMEM
486 supplemented with 2.5% FBS and Pen/Strep/Gln. Viral titers were enumerated by median tissue
487 culture infectious dose ($TCID_{50}$) assays. Following the serial dilution of the samples, the
488 appropriate cell line was infected for 1 h at 37°C prior to the replacement of the inoculum for the
489 indicated overlay medium and incubated at 37°C: BHK-21 cells (hCoV-OC43,
490 DMEM/1%FBS/Pen/Strep/Gln, 5 days), Huh-7.5 cells (hCoV-229E,
491 DMEM/2.5%FBS/Pen/Strep/Gln, 4 days), or Vero'76 cells (SARS-CoV-2,
492 DMEM/2%FBS/Pen/Strep/Gln, 5 days). Viral titers were calculated using the Spearman-Kärber
493 method.
494 To test the effect of the indicated compounds on hCoV replication, 293A, 293T, BJ,
495 Calu-3, HCT-8, or Huh-7.5 cells were infected with hCoV diluted in serum-free DMEM at the
496 indicated MOI and temperature for 1 h. After 1 h, the inoculum was removed, replaced with
497 DMEM/Pen/Strep/Gln containing 1% FBS and NEAA (HCT-8), 2% FBS (Calu-3), 2.5% FBS
498 (Huh-7.5, 293A or 293T), or 5% FBS (BJ) supplemented with DMSO or drug at the indicated
499 concentration, and maintained for an additional 23 h at the indicated temperature. Infected BJ
500 cells were incubated at 33°C during virus replication; all other cells were incubated at 37°C. For
501 infections of 293A, BJ, HCT-8, or Huh-7.5, the infected cells were scraped into the culture
502 medium and stored at -80°C. For SARS-CoV-2-infected Calu-3 cells or HCoV-OC43 infected
503 293T cells virus was collected from culture supernatants at 48 h post-infection and stored at -
504 80°C. Titers of hCoV-OC43, hCoV-229E, and SARS-CoV-2 were determined using $TCID_{50}$
505 assays as indicated above.
506
507 **Cytotoxicity assays.** Cells seeded into 96-well tissue culture plates were treated with drugs
508 diluted at indicated concentrations and incubated with the cells for 20 h. At 20 h post-treatment,
509 10% alamarBlue Cell Viability Reagent (ThermoFisher Scientific, DAL1025) diluted in
510 DMEM/Pen/Strep/Gln containing 1% FBS and NEAA (HCT-8), 2.5% FBS (Huh-7.5 or 293T),
511 or 5% FBS (BJ) was added and further incubated for 4 h. Plates were read on FLUOstar Omega
512 96 well plate reader at an excitation of 544 nm, and an emission of 580-590 nm. Drug treatments
513 were then normalized to DMSO. For viability experiments using Calu-3 cells, cells grown in 96-

514 well plates were treated with drugs diluted at indicated concentrations and incubated with the
515 cells for 48 h. At 48 h post-treatment, a one-fifth volume of CellTiter 96 AQueous One Solution
516 Cell Proliferation Assay (G3580, Promega) was added to DMEM/Pen/Strep containing 2% FBS
517 and incubated for 2 h. Plates were read at an absorbance of 490 nm with an xMark™ Microplate
518 Absorbance Spectrophotometer (Bio-Rad). Values were imported into GraphPad PRISM (v.9)
519 and CC_{50} values were calculated by fitting a non-linear curve to the data. Selectivity index (SI)
520 was calculated by dividing the IC_{50} (calculated above) by the CC_{50}.
521
522 **Real-time quantitative PCR.** Total RNA from cells was extracted using the RNeasy Plus Mini
523 Kit (QIAGEN, 74134) following the manufacturer's protocol. Synthesis of cDNA was
524 performed using the Maxima H Minus First Strand cDNA Synthesis Kit (ThermoFisher
525 Scientific, K1652) using random primers. Quantitative PCRs were performed using 200 nM
526 primers, 1:250 (final) diluted cDNA, and 1X GoTaq qPCR Master Mix (Promega, A6002).
527 Amplifications were performed using a CFX Connect Real-Time PCR Detection System (Bio-
528 Rad) and Bio-Rad CFX Manager 3.1 software. To measure supernatant virions, supernatant was
529 mixed 1:1 with virus lysis buffer [20 mM Tris HCl pH7.4, 300 mM NaCl, 2.5% NP-40, and 40
530 U/mL RNAaseOUT (ThermoFisher)] for 5 min, then diluted 1:5 with nuclease-free water before
531 2 µL was used as template in a 10 µL Go-Taq 1-Step RT-qPCR (Promega, A6020) reaction (69).
532 Primer sequences are listed in Table 1.
533
534 **Immunofluorescence microscopy.** 293T were seeded on #1.5 coverslips (Zeiss, 411025-0003-
535 000) coated with poly-L-lysine (Sigma, P2658). The following day the cells were infected with
536 HCoV-OC43, to harvest the cells were washed once with 1x Dulbecco's PBS (ThermoFisher)
537 and fixed with 4% paraformaldehyde (Electron Microscopy Services) PBS for 15 min at room
538 temperature. Coverslips were blocked and permeablized in staining buffer [1% human serum
539 (Sigma,4552) heat-inactivated at 56°C for 1h, 0.1% Triton X-100 PBS] for 1 h at room
540 temperature, then stained with 1:500 dilution anti-OC43 N (MAB9012, Millipore Sigma)
541 overnight at 4°C. The following day the coverslips were washed three times with PBS, then
542 stained with goat anti-mouse Alexa 488 (ThermoFisher, R37120) in staining buffer for 1 h at
543 room temperature in the dark. Coverslips were then counterstain for 5 min with Hoescht 33342
544 (ThermoFisher, 62249), washed three times with PBS, then mounted on coverglass using

545 ProLong Gold anti-fade reagent (ThermoFisher, P36930). Z-stacks were imaged on a Zeiss
546 LSM880 and processed into maximum intensity projections using Zen Black (Zeiss).
547
548 **Western Blotting.** Cell monolayers were washed once with ice-cold PBS and lysed in 2x
549 Laemmli buffer (4% [wt/vol] sodium dodecyl sulfate (SDS), 20% [vol/vol] glycerol, 120 mM
550 Tris-HCl [pH 6.8]). DNA was sheared by repeated pipetting with a 21-gauge needle before
551 adding 100 mM dithiothreitol (DTT) and boiling at 95˚C for 5 min. Samples were stored at -20˚C
552 until analysis. Total protein concentration was determined by DC protein assay (Bio-Rad) and
553 equal quantities were loaded in each SDS-PAGE gel. For ribopuromycylation assays, a modified
554 version of the protocol by Schmidt, *et al.* (63) was used where the indicated samples were treated
555 with 10 µg/ml puromycin (ThermoFisher, A1113803) for 10 min, followed by a PBS wash, and
556 lysate preparation for immunoblotting as indicated above. Lysates from the ribopuromycylation
557 assays were loaded into gels prepared using the TGX Stain-Free FastCast Acrylamide Kit (Bio-
558 Rad, 1610183) (Fig. S1A). Lysates for quantitative Spike western blotting were loaded onto
559 TGX Stain-Free 4-20% gradient gels (Bio-Rad, 4568094) (Fig. 3D). Peptide-*N*-Glycosidase F
560 (PNGase F; NEB, P0704) treatment of lysates was performed as described in the manufacturer's
561 directions. All proteins after SDS-PAGE were transferred to polyvinylidene difluoride (PVDF)
562 membranes (Bio-Rad) with the Trans-Blot Turbo transfer apparatus (Bio-Rad). Membranes were
563 blocked with 5% bovine serum albumin in tris-buffered saline/0.1% [vol/vol] tween-20 (TBS-T)
564 before probing overnight at 4˚C with antibodies raised to the following targets: mouse anti-
565 puromycin (Millipore-Sigma, MABE343), mouse anti-OC43 N (CoV antibody, OC43 strain,
566 clone 541-8F, Millipore-Sigma, MAB9012), rabbit anti-BiP (Cell signaling Technologies (CST),
567 mouse anti-XBP1s (CST, #12782), mouse anti-CHOP (CST, #2895), rabbit anti-α-Tubulin (CST,
568 #2125), rabbit anti-SARS-CoV-2 S1 RBD (Elabscience, E-AB-V1006), anti-SARS-CoV-2 E
569 (abbexa, abx226552), anti-SARS-CoV-2 M (Novus Biologicals, NBP3-05698), rabbit anti-
570 SARS-CoV-2 N (Novus Biologicals, NBP3-05730), mouse anti-FLAG (CST, #2368), mouse
571 anti-HIV-p24 (Abcam, ab9071) anti-Strep tag (IBA, 2-1507-001), anti-HRPT1 (Santa Cruz
572 Biotechnologies, sc-376938)and anti-β-actin (CST, #4967). Membranes were washed with TBS-
573 T and incubated with HRP-linked secondary antibodies prior to detection with Clarity ECL
574 chemiluminescence reagent (Bio-Rad). All blots were imaged on a Bio-Rad ChemiDoc-Touch
575 system. Molecular weights were determined using the Broad Range, Color Prestained Protein

576 Standard (NEB, P7719) or Precision Plus Protein All Blue Prestained Protein Standards (BioRad,
577 1610373). Molecular weights in kDa are indicated on the left of blot images. For quantitation of
578 western blots, the total antibody signal intensity was divided by the Stain-Free total protein
579 signal. Images were analyzed using Image Lab 6.1 (Bio-Rad). Images were cropped and
580 annotated using Affinity Designer (Serif).
581
582 **Plasmid generation and transfections.** All plasmids were purified using the QIAprep Spin
583 Miniprep or QIAfilter Plasmid Midi Kits (QIAGEN) and all restriction enzymes were purchased
584 from New England Biolabs (NEB). The pcDNA3-SARS-CoV-2-Spike plasmid contains a
585 codon-optimized ORF for Spike from GenBank NC_045512 that was synthesized by GenScript
586 (a kind gift from David Kelvin) then cloned between the KpnI and BamHI sites of pcDNA3.1(+).
587 A 19 residue C-terminal truncation of Spike (SΔ19) and Spike with a C-terminal FLAG tag was
588 generated by PCR. A Spike mutant lacking the Furin cleavage site between S1 and S2 (P681S,
589 R682G, R683G, R685del), and two-proline stabilizing mutants, K986P and V987P (S-2P) (70–
590 72) was generated by PCR mutagenesis using KOD Xtreme Hot Start DNA Polymerase (Sigma,
591 71975-M). pcDNA3-Membrane (M) and pcDNA3-Envelope (E) were cloned from pLVX-
592 EF1alpha-SARS-CoV-2-M-2xStrep-IRES-Puro and pLVX-EF1alpha-SARS-CoV-2-E-2xStrep-
593 IRES-Puro (kind gifts from Neven Krogan, available from Addgene #141386 and #141385)
594 using PCR to remove the 2xStrep epitope tag. pCMV3-MERS-FLAG was purchased from
595 SinoBiologicals (VG40069-CF). pLJM1-Luc2 used in generating Spike-pseudotyped
596 lentiviruses was generated by cloning Luc2 from pGL4.26 (Promega) into pLJM1-B* (67).
597 pLJM1-ACE2-BSD was cloned by from cDNA of generated from Caco-2 cells. Primer
598 sequences are listed in Table 2. 293T cells were transfected using polyethylenimine (PEI),
599 Linear, MW 25000 (Polysciences Inc., 23966) dissolved in water (pH 7.4). Both plasmids and
600 PEI were diluted in OptiMEM (Gibco), then combined for 15 min before adding to cell
601 monolayers in serum-free DMEM. PEI was used at 3:1 ratio to plasmid DNA. After 4 h, serum-
602 free media was replaced with DMEM containing 10% FBS with indicated treatments unless
603 otherwise indicated. For pre-treatments with ML099. the drug was applied at the time of
604 transfection, then refreshed when the media was changed 4 h after transfection. Generally, cells
605 were lysed for immunoblotting analysis at 24 h post-transfection (hpt). For flow-cytometry and

606 immunofluorescence experiments, cells were instead transfected with FugeneHD (Promega,
607 E2311) according to the manufacturer's instructions.
608

609 **siRNA knockdown experiments.** All siRNAs were obtained from Invitrogen. 293T cells (1-1.5
610 x 10^5 cells/mL) in 10% DMEM were reverse transfected with Lipofectamine RNAiMAX
611 (Invitrogen, 13778075) and 10 nM of Silencer Select negative siRNA #2 (4390846), HPRT1
612 siRNA #1 (s6889), or HPRT1 siRNA #2 (s6888) diluted in OptiMEM (Gibco, 31985070). RNA
613 was harvested from cells 48 hpt knockdown validation by RT-qPCR. For determining the effect
614 of HPRT1 knockdown on viral titre after 6-TG treatment, the reverse transfected cells were
615 infected at 24 hpt at an MOI of 0.1 then treated with DMSO or 10 µM 6-TG as described above.
616 After a 24 h infection, the cell supernatant for titration, and the infected monoloayers were lysed
617 with 2X Laemmli Buffer and processed for western blotting.

618

619 **Production of SARS-CoV-2 virus-like particles.** To generate SARS-CoV-2 virus-like
620 particles, 293T cells were seeded in a 10 cm dish and co-transfected with 2 µg of each pcDNA-
621 Spike, pcDNA-M, pcDNA-E, and pLVX-EF1alpha-SARS-CoV-2-N-2xStrep-IRES-Puro (a kind
622 gift from Neven Krogan, available from Addgene #141391) with PEI, then treated with 6-TG or
623 DMSO as described above. After two days, supernatant was harvested, filtered, concentrated,
624 and analyzed by western blot as described above for SARS-CoV-2 Spike-pseudotyped lentivirus.

625

626 **SARS-CoV-2 Spike-pseudotyped lentiviruses.** To generate Spike-pseudotyped lentivirus
627 particles, 293T cells were seeded in a 10 cm dish and co-transfected with 3 µg pLJM1-Luc2, 2
628 µg pSPAX2 (a kind gift from Didier Trono; Addgene #12260), and 2 µg of pcDNA3- SΔ19 with
629 PEI, then treated with 6-TG or DMSO as described above. After two days, supernatant was
630 harvested, filtered through a 0.45 µm filter, aliquoted and stored at -80°C until use. Genomes
631 were quantified using a qPCR Lentivirus Titer Kit (Applied Biological Materials, LC900) as per
632 the manufacturer's instructions. Infectious pseudotyped particles were measured by infecting
633 293A cells stably expressing ACE2 or an EV control. Cell lysates were harvested 24 h after
634 infection in Reporter Lysis Buffer (Promega, E397A), lysed by freeze thawing at -80°C, and
635 luciferase activity was measured using Luciferase Assay reagent (Promega) on a FLUOstar

636 Omega microplate reader (BMG Labtech). For concentration and western blot analysis, filter
637 supernatant was underlaid with 20% sucrose PBS using a pipetting needle and centrifuged at 39
638 000 rpm for 2 h using an SW-41 rotor (Beckman Coulter). The supernatant and sucrose solution
639 were carefully removed, and the pellet was resuspended in PBS, mixed in equal proportions with
640 2x Laemmli Buffer with 100 mM DTT and boiled at 95°C for 5 min before analysis by western
641 blot.

642

643 **Transmission electron microscopy (TEM).** Samples were prepared and visualized as described
644 in (73). Briefly, HCoV-OC43 containing supernatant was concentrated by ultracentrifugation as
645 described above, then applied to Formvar/carbon coated grids and left to settle to 10 min. The
646 grid was then rinsed with distilled water then stain with 2% w/v uranyl acetate for 30 s. Residual
647 stain was wicked off with filter paper then left to air dry completely. Grids were imaged on a
648 JEM 1230 TEM (JEOL) running at 80 kV using an OCRA-HR camera (Hamamatsu). Sample
649 preparation, fixation, and TEM imaging were performed twice with representative images from
650 one independent experiment shown.

651

652 **Quantitation of SARS-CoV-2 Spike surface expression.** 293T cells were co-transfected with
653 pEGFP-N1 and plasmids expressing SARS-CoV-2 Spike (FL) or SARS-CoV-2 Spike-Δ19 for
654 24 h using FugeneHD (Promega). The cells were treated with DMSO or 10 µM 6-TG at 4 h post-
655 transfection. At 24 h post-transfection, the cells were lift with 10 mM EDTA PBS and pelleted at
656 300 x *g* for 5 min. Cells were washed once with wash buffer (2 mM EDTA, 2% FBS, PBS), then
657 stained with 0.1 µg/sample Alexa Fluor 647-conjugated mouse-anti SARS-CoV-2 Spike S1
658 (R&D Systems, FAB105403R-100UG) at 4°C for 30 min in the dark. Cells were then washed
659 then fixed with 2% paraformaldehyde (Electron Microscopy Sciences, 15710) PBS 4°C for 30
660 min in the dark, then washed and stored at 4°C in the dark until analysis using a FACSCelesta
661 cell analyzer (BD Biosciences) configured with 405 nm, 488 nm, and 640 nm lasers using the
662 same acquisition voltages for all replicates with at least 50000 single cells acquired per sample.
663 The data were analyzed using FCS Express v. 6.06.0040 (De Novo Software) where transfected
664 single cells were selected by EGFP fluorescence and analyzed for Spike surface expression via
665 Alexa Fluor 647 fluorescence.

666

667 ***Gaussia* luciferase secretion assays.** For short-term treatments, 293T were transfected with
668 pCMV-*Gaussia* Luc Vector (ThermoFisher Scientific, 16147) as described above. After 18 h,
669 medium was removed and replaced with fresh medium containing 6-TG, BFA, or DMSO. After
670 6 h medium was removed, debris was cleared by centrifuging samples at 5,000 × *g* for 5 min,
671 then samples were stored at -80°C until measuring *Gaussia* luciferase activity using the *Gaussia*
672 Luciferase Flash Assay Kit (ThermoFisher Scientific, 16158) as per the manufacturer's
673 directions on a FLUOstar Omega microplate reader (BMG Labtech). For long-term treatments,
674 293T cells were co-transfected with pCMV-*Gaussia* Luc and pLJM1-Luc2 and treated 6 h post
675 transfection. After 24 h, supernatant harvested as described above. The cell monolayer was lysed
676 in Reporter Lysis Buffer (Promega) as described above. To measure both Luciferase and *Gaussia*
677 luciferase activity in samples, we used the Dual-Luciferase Reporter Assay System (Promega,
678 E1910), which although designed for firefly and *Renilla* luciferase, can be readily adapted for
679 firefly and *Gaussia* luciferase as both *Gaussia* and *Renilla* luciferase both use coelenterazine as a
680 substrate.

681

682 **Statistical analysis.** Statistical analysis and graphing was performed using GraphPad PRISM
683 (v.8 or v.9). Statistically significant differences were determined using Dunnett's multiple
684 comparison test for one-way ANOVA and Šídák's multiple comparison test for two-way
685 ANOVA.

686

687 **Graphics.** Molecular models were created with NCBI PubChem
688 (http://pubchem.ncbi.nlm.nih.gov/) The model presented in Fig. 7 was adapted from
689 "Coronavirus Replication Cycle", by BioRender.com (2022). Retrieved from
690 https://app.biorender.com/biorender-templates.

691

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705

706 **CONFLICT OF INTEREST**

707 E.S.P. is a consultant for Aegis Life Inc. All other authors declare no conflicts of interest.

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710 **Table 1**. Primer sequences for RT-qPCR analysis

Target	Sequence (5′-3′)	
OC43 Orf1a	F – ATATGGCCAAGGCTGGTGAC	R – ATGTAACACGCCTTCCAGCA
OC43 S	F – TCTTCCGAACCAGCATTGCT	R – TAATGGGTTGCAGCTGTCGT
OC43 N	F – GGACCCAAGTAGCGATGAGG	R – GTGCGCGAAGTAGATCTGGA
18S	F – TTCGAACGTCTGCCCTATCAA	R – GATGTGGTAGCCGTTTCTCAGG
HPRT1	F – CGAGATGTGATGAAGGAGATG	R – GCAGGTCAGCAAAGAATTTATAG
Xbp1	F – TAGCAGCTCAGACTGCCAGA	R – CCAAGCGCTGTCTTAACTCC
ERdj4	F – CGCCAAATCAAGAAGGCCT	R – CAGCATCCGGGCTCTTATTTT
EDEM1	F – TTGACAAAGATTCCACCGTCC	R – TGTGAGCAGAAAGGAGGCTT
ATF3	F – AGGCGACGAGAAAGAAATAAG	R – TTCACACTTTCCAGCTTCTC
CHOP	F – ATGAACGGCTCAAGCAGGAA	R – GGGAAAGGTGGGTAGTGTGG
HERPUD1	F – AACGGCATGTTTTGCATCTG	R – GGGGAAGAAAGGTTCCGAAG
BiP	F – GCCTGTATTTCTAGACCTGCC	R – TTCATCTTGCCAGCCAGTTG

714 **Table 2.** Primers used for cloning and PCR mutagenesis

Gene	Sequence (5′-3′)
Spike	F - AATTGGTACCATGTTCGTCTTTCTGGTTCTGTTGCC
	R - AATTGGATCCTCAAGTGTAGTGCAGTTTCACGC
Spike-S0	F - CTCCGTGGCAAGCCAGTCGATCATCGCCTAC
	R - GCGCCTCCACTCGAGTTCGTCTGGGTCTGGTA
Spike-Flag	F - AATTGGTACCATGTTCGTCTTTCTGGTTCTGTTGCC
	R - AATTGGATCCTTACTTATCGTCGTCATCCTTGTAAT CAGAGCCTCCACCCCCAGTGTAGTGCAGTTTCACGC
Spike-Δ19	F - AATTGGTACCATGTTCGTCTTTCTGGTTCTGTTGCC
	R - AATTGGATCCTTAACAACAACTACCGCAACTGC
Spike-2P	F - CCGGAGGCCGAGGTGCAGATCGAC
	R - TGGGTCCAGTCTTGACAGGATGTCGTTC
E	F - AATTGCTAGCACCATGTACAGCTTCG
	R - AATTGAATTCTTAAACGAGGAGATCCGGCAC
M	F - AATTGCTAGCACCATGGCCGACTCAAATGG
	R - AATTGAATTCTTACTGGACGAGTAAAGC
ACE2	F - AATTACCGGTATGTCAAGCTCTTCCTGGC
	R - AATTGTCGACCTAAAAGGAGGTCTGAACATCATCAG

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718 **FIGURE LEGENDS**

719 **Figure 1. Thiopurines 6-thioguanine and 6-thioguanosine inhibit coronavirus replication.**
720 **(A)** Structures of thiopurines used this study in comparison to guanine. **(B)** Calu-3 cells were
721 infected with SARS-CoV-2 at an MOI of 0.1 then treated with 6-thioguanine (6-TG), 6-
722 thioguanosine (6-TGo), or 6-mercaptopurine (6-MP). Supernatant was harvested after 48 h, and
723 stored at -80∞C until titering on Vero'76 cells. Mock-infected cells were similarly treated with 6-
724 TG, 6-TGo, 6-MP, or DMSO vehicle control for 48 h before testing cell viability with CellTiter
725 96 AQueous One (n=3 ± SEM). Dotted line indicated Limit of Detection. **(C)** Summary table of
726 Cellular Cytotoxicity (CC_{50}), Effective concentration (EC_{50}), and Selectivity Index (SI)
727 calculated for (A-C). **(D)** Alamar Blue cell viability assay of hTert-BJ, HCT-8, and Huh-7.5 cells
728 treated with 6-TG (n=3±SEM).**(E)** TCID assays for HCoV-OC43 infected HCT-8 cells and **(F)**
729 HCoV-229E infected Huh-7.5. Cells were infected with an MOI of 0.1 then treated with 6-TG,
730 6-TGo, 6-MP, or DMSO (n=3 ± SEM, statistical significance was determined by one-way
731 ANOVA). **(F)** hTERT-BJ cells were infected with HCoV-OC43 or HCoV-229E at an MOI of
732 0.1 and treated with 6-TG, Tm, or DMSO. Supernatant was harvested after 23 h and stored at -
733 80∞C before titering on BHK-21 or Huh7.5 (n=3-4 ± SEM, statistical significance was
734 determined by one-way ANOVA). **(G)** hTERT-BJ cells were infected with HCoV-OC43 or **(H)**
735 HCoV-229E at an MOI of 0.1 and treated with 6-TG, Tm, or DMSO. Supernatant was harvested
736 after 23 h and stored at -80∞C before titering on BHK-21 or Huh7.5 (n=3-4 ± SEM, statistical
737 significance was determined by one-way ANOVA). LoD = Limit of Detection for virus titer. (*,
738 $p<0.05$; **, $p<0.01$; ns, non-significant)

739 **Figure 2. 6-TG reduces CoV protein and mRNA accumulation. (A-C)** 293T cells were
740 infected with HCoV-OC43 at an MOI of 0.1 then treated with 10 µM 6-TG or DMSO vehicle

741 control. Supernatant and total RNA from the cells were harvested at the times indicated and
742 stored at -80∞C until **(A)** titering on BHK-21 or **(B)** quantification of viral genomes by RT-
743 qPCR. Cell monolayers were harvested for **(C)** RT-qPCR analysis of viral RNA accumulation
744 (n=3 statistical significance was determined by paired ratio t test; *, $p<0.05$; **, $p<0.01$; ns, non-
745 significant) **(D)** 293T cells were grown on coverslips then infected with HCoV-OC43 and treated
746 with 6-TG as in (A), then fixed and immunostained for N or **(E)** dsRNA. Nuclei are
747 counterstained with Hoechst. Scale bar = 20 µm.

748 **Figure 3. 6-TG inhibits Spike glycosylation and cleavage. (A)** Calu-3 cells were infected with
749 SARS-CoV-2 at an MOI of 7, then treated with 6-TG or DMSO. Lysates were harvested 48 h
750 after infection and were probed by western blotting as indicated. Concentrations in legend are in
751 µM. **(B)** Huh-7.5 cells were infected with SARS-CoV-2 at an MOI of 5, then treated with 6-TG
752 or DMSO. Lysates were harvested 48 h after infection and were probed by western blotting as
753 indicated. Concentrations in legend are in µM. **(C)** 293T cells were transfected with SARS-CoV-
754 2 S, M, Envelope (E), Nucleoprotein (N) with a C-terminal 2xStrep tag, or EV then treated with
755 10 µM 6-TG or DMSO vehicle control. Lysates were harvested 24 h after transfection and
756 probed by western blotting as indicated. **(D)** 293T cells were transfected with SARS-CoV-2
757 Spike or EV then treated with 6-TG or DMSO vehicle control. Lysates were harvested 24 h after
758 transfection and were probed by western blotting as indicated. Concentrations in legend are in
759 µM. **(E)** Alamar Blue cell viability assay of 6-TG treated 293T cells (n=3±SEM). **(F)** 293T cells
760 were transfected with SARS-CoV-2 Spike (S), a Spike mutant lacking the Furin cleavage site
761 between S1 and S2 (S0), or EV then treated with 10 µM 6-TG or DMSO vehicle control. Lysates
762 were harvested 24 h after transfection, treated with PNGase F to remove N-linked glycans, and

763 probed by western blotting as indicated. **(G)** as in (C) except 293T cells were transfected with
764 C-terminal FLAG-tagged Spike (S-FL) or HCoV-MERS Spike (MERS).

765 **Figure 4. 6-TG stimulates an assembly defect and inhibits Spike virion incorporation. (A)**
766 293T cells were transfected with equal quantities of SARS-CoV-2 S, M, E, and N plasmids or
767 empty vector (EV) then treated with 10 μM 6-TG or DMSO vehicle control. Lysates were
768 harvested 48 h after transfection and probed by western blotting as indicated. **(B)** Virus-like
769 particles from supernatants of cells transfected in (B) were concentrated by ultracentrifugation
770 through a 20% sucrose cushion, resuspended in PBS, then harvested with an equal volume of 2x
771 Laemmli buffer. Samples from two independent lentivirus preparations were probed by western
772 blotting as indicated. **(C)** 293T cells were transfected with S, E, M, and N in a 1:2:2:1 ratio,
773 substituting one of the structural proteins for EV as indicated, treated with 6-TG or DMSO then
774 processed as in (A). **(D)** SARS-CoV-2 Spike pseudotyped, luciferase-expressing lentivirus
775 particles were concentrated by ultracentrifugation through a 20% sucrose cushion, resuspended
776 in PBS, then harvested with an equal volume of 2x Laemmli buffer. Samples from three
777 independent lentivirus preparations were probed by western blotting as indicated. **(E)** Genomes
778 from three independent lentivirus preparations were quantified by RT-qPCR (n=3, statistical
779 significance was determined by paired t-test; ns, non-significant). **(F)** 293A cells stably
780 expressing ACE2 or empty vector control were transduced with lentivirus from three
781 independent preparations. After 24 h, lysates were harvested and measured for luciferase activity
782 (n=3, statistical significance was determined by two-way ANOVA; *, $p<0.05$; ns, non-
783 significant). **(G)** 293A cells were infected HCoV-OC43 at an MOI of 0.1 =, then treated with 6-
784 TG or DMSO. Supernatants were concentrated as in (C), before virions were fixed and imaged
785 by TEM with negative staining. Five virions from both 6-TG- and DMSO-treated samples are

786 shown at 150,000 X magnification. Scale bar = 100 nm. Arrowhead indicates examples of Spike
787 protein extending from virion.

788 **Figure 5. 6-TG inhibits Spike maturation through GTPase inhibition. (A)** 6-TG is
789 conjugated to phosphoribosyl diphosphate (PRPP) by HPRT1 to form 6-TG monophosphate. 6-
790 TG methylated at the N9 nitrogen was designed to be resistant to processing by HPRT1. **(B)**
791 293T cells were infected with HCoV-OC43 at an MOI of 0.1 then treated with 6-TG or 6-TG-
792 Me. Supernatant was harvested at 24 hpi and stored at -80∞C until titering on BHK cells. (n=3
793 statistical significance was determined by paired ratio t test; *, $p<0.05$; **, $p<0.01$; ns, non-
794 significant). **(C)** 293T cells were transfected with SARS-CoV-2 Spike or an empty vector control
795 then treated with 6-TG, 6-TG-Me, or DMSO vehicle control. Lysates were harvested 24 h after
796 transfection and probed by western blotting as indicated. **(D)** 293T cells were reversed
797 transfected with siRNA and total RNA was harvested after 48 h. HPRT1mRNA abundance was
798 measured by RT-qPCR (n=3, ±SEM statistical significance was determined by one way
799 ANOVA; ***, $p<0.001$). **(E)** As in D but cells were infected with HCoV-OC43 at an MOI of 0.1
800 24 h after siRNA treatment and supernatant was harvested and titered as in **(B)** (n=4 ±SEM
801 statistical significance was determined by paired ratio t test; **, $p<0.01$; ***, $p<0.001$; ns, non-
802 significant).

803 **Figure 6. 6-TG inhibits Spike maturation through GTPase inhibition. (A)** alamarBlue cell
804 viability assay of 293T cells treated Rac1 Inhibitor V (Rac1iV), Rhosin, CASIN, or ML099
805 (n=3±SEM). **(B)** Summary table of Cellular Cytotoxicity (CC_{50}) and inhibitor target of
806 compounds tested in (A). **(C)** 293T cells were transfected with SARS-CoV-2 Spike or an empty
807 vector control (EV) then treated with 6-TG, GTPase inhibitors, or DMSO vehicle control.
808 Concentrations in legend are in μM. Lysates were harvested 24 h after transfection and were

809 probed by western blotting as indicated. **(D)** 293T cells were transfected with plasmids encoding
810 Spike or EV then co-treated with 6-TG, 100 μM ML099 GTPase agonist, or DMSO. Lysates
811 were harvested 24 h after transfection and were probed by western blotting as indicated.
812 Concentrations in legend are in μM **(E)** as in (D) except some samples were pre-treated (Pre) for
813 4 h with ML099. **(F)** HCT-8 and 293A were infected with an MOI of ~0.1 then treated with 10
814 μM 6-TG or DMSO vehicle control. After 24 h, the supernatants was harvested and stored at -
815 80∞C until titering on BHK-21 (n=3 ± SEM, statistical significance was determined by one-way
816 ANOVA; *, p<0.05; **, p<0.01; ns, non-significant). LoD = Limit of Detection for virus titer.

817 **Figure 7. 6-TG inhibits multiple essential steps in virus replication and assembly.** 6-TG
818 inhibits nsp3, delaying formation of replication compartments and reducing accumulation of
819 viral RNA. 6-TG also inhibits normal glycosylation of Spike, which fails to be properly
820 packaged in egressing virions. As a result, the total number of virions released from infected
821 cells is reduced and those that are released have fewer Spikes on their surface.

822 **Figure S1. Activation of the unfolded protein response (UPR) during OC43 infection. (A)**
823 293T cells were infected with HCoV-OC43 at an MOI of 0.1 then treated with 10 μM 6-TG or
824 DMSO vehicle control. Total RNA from the cells were harvested at the times indicated and
825 stored at -80∞C until RT-qPCR analysis of UPR target genes. **(B)** 293A cells were infected as in
826 (A), then treated with 10 μg 6-TG, 1μg thapsigargin (Tg), or DMSO. Cells were treated with 10
827 μg/mL of puromycin for 10 min prior to harvest 24 h after infection. Lysates were probed by
828 western blot as indicated. **(C)** Total puromycin intensity from (E) was quantified relative to total
829 protein load and are graphed normalized to the mock-infected, DMSO-treated cells (n=3 ± SEM,
830 statistical significance was determined by paired t-test compared to mock-infected, DMSO-
831 treated cells; *, p<0.05; **, p<0.01; ***, p<0.001; ns, non-significant).

832 **Figure S2. 6-TG reduces surface expression of Spike but does not globally limit secretion.**
833 **(A)** alamarBlue cell viability assay of 293T cells treated with brefeldin A (BFA) (n=4±SEM).
834 **(B)** 293T cells were transfected with *Gaussia* luciferase for 18 h then treated with 6-TG, BFA or
835 DMSO vehicle control for 6 h . Supernatants were recovered from the cells and measured for
836 luciferase activity. **(C)** 293T cells were transfected with both luciferase and *Gaussia* luciferase
837 then treated with 6-TG, BFA, or DMSO. After 24 h, supernatants were removed and analyzed as
838 in (B). Cell lysate was harvested in Reporter Lysis Buffer and stored at -80∞C until both
839 luciferase and *Gaussia* luciferase activity was measured. (For B and C, n=3 ± SEM, statistical
840 significance was determined by paired t-test compared to DMSO-treated cells; *, $p<0.05$; **,
841 $p<0.01$; ***, $p<0.001$; ns, non-significant). **(D)** 293T cells were transfected with SARS-CoV-2
842 Spike or EV then treated with 6-TG, BFA, or DMSO. Lysates were harvested 24 h after
843 transfection in 2x Laemmli buffer and were probed by western blotting as indicated. **(E)** 293T
844 cells were co-transfected with EGFP and either Spike (S), Spike with 19 residue C-terminal
845 truncation (SΔ19), or EV and then treated with 10 μM 6-TG or DMSO. After 24 h, cells were
846 harvested, surface-stained for Spike then fixed prior to analysis by flow cytometry. EGFP+ cells
847 were gated for analysis of number of Spike+ cells and Median Fluorescent Intensity (MFI)
848 (n=4±SEM statistical significance was determined by paired t-test between 6-TG and DMSO
849 treated cells; *, $p<0.05$).

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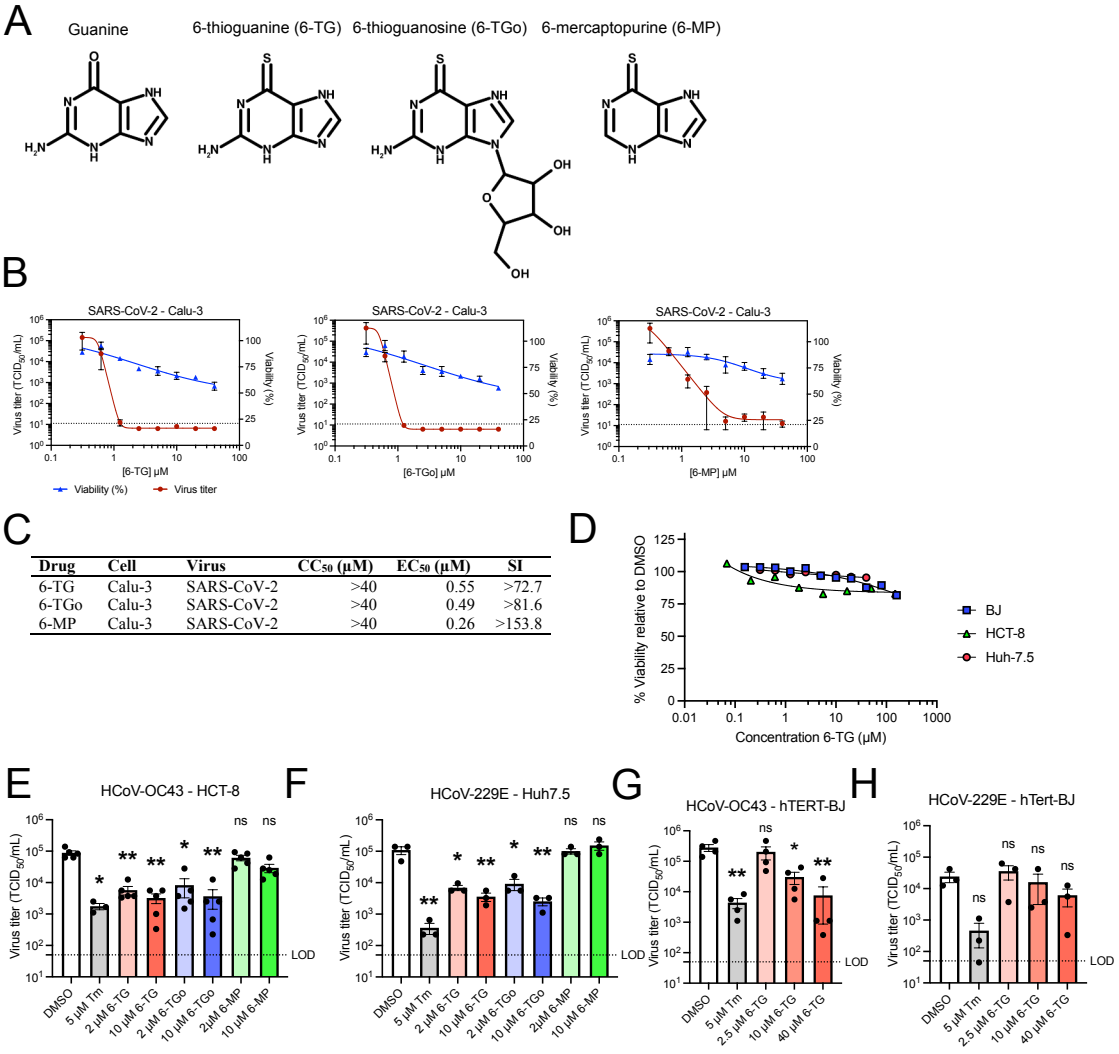

Drug	Cell	Virus	CC_{50} (µM)	EC_{50} (µM)	SI
6-TG	Calu-3	SARS-CoV-2	>40	0.55	>72.7
6-TGo	Calu-3	SARS-CoV-2	>40	0.49	>81.6
6-MP	Calu-3	SARS-CoV-2	>40	0.26	>153.8

Figure 1. Thiopurines 6-thioguanine and 6-thioguanosine inhibit coronavirus replication. (A) Structures of thiopurines used this study in comparison to Guanine. **(B)** Calu-3 cells were infected with SARS-CoV-2 at an MOI of 0.1 then treated with 6-thioguanine (6-TG), 6-thioguanosine (6-TGo), or 6-mercaptopurine (6-MP). Supernatant was harvested after 48 h, and stored at -80°C until titering on Vero'76 cells. Mock-infected cells were similarly treated with 6-TG, 6-TGo, 6-MP, or DMSO vehicle control for 48 h before testing cell viability with CellTiter 96 AQueous One (n=3 ± SEM). Dotted line indicated Limit of Detection. **(C)** Summary table of Cellular Cytotoxicity (CC_{50}), Effective concentration (EC_{50}), and Selectivity Index (SI) calculated for (A-C). **(D)** Alamar Blue cell viability assay of hTert-BJ, HCT-8, and Huh-7.5 cells treated with 6-TG (n=3±SEM).**(E)** TCID assays for HCoV-OC43 infected HCT-8 cells and **(F)** HCoV-229E infected Huh-7.5. Cells were infected with an MOI of 0.1 then treated with 6-TG, 6-TGo, 6-MP, or DMSO (n=3 ± SEM, statistical significance was determined by one-way ANOVA). **(F)** hTERT-BJ cells were infected with HCoV-OC43 or HCoV-229E at an MOI of 0.1 and treated with 6-TG, Tm, or DMSO. Supernatant was harvested after 23 h and stored at -80°C before titering on BHK-21 or Huh7.5 (n=3-4 ± SEM, statistical significance was determined by one-way ANOVA). **(G)** hTERT-BJ cells were infected with HCoV-OC43 or **(H)** HCoV-229E at an MOI of 0.1 and treated with 6-TG, Tm, or DMSO. Supernatant was harvested after 23 h and stored at -80°C before titering on BHK-21 or Huh7.5 (n=3-4 ± SEM, statistical significance was determined by one-way ANOVA). LoD = Limit of Detection for virus titer. (*, $p<0.05$; **, $p<0.01$; ns, non-significant)

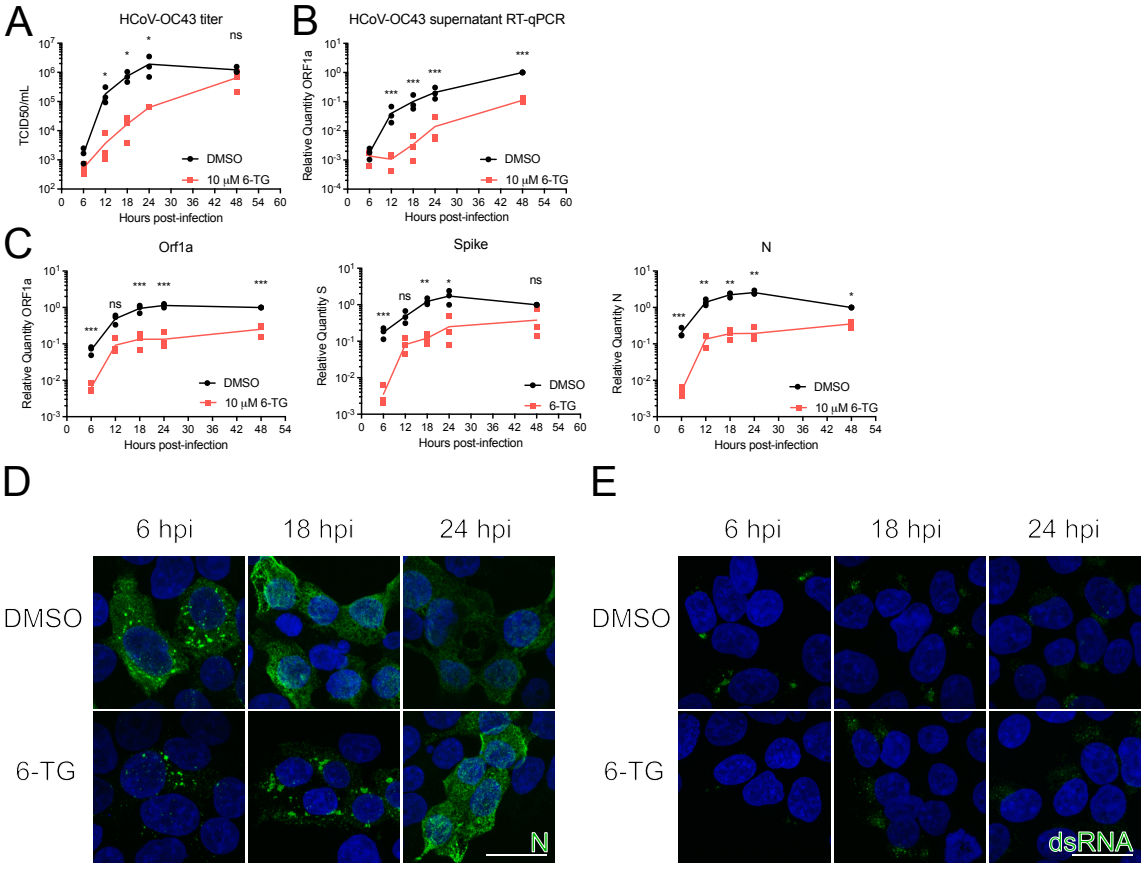

Figure 2. 6-TG reduces CoV protein and mRNA accumulation. (A-C) 293T cells were infected with HCoV-OC43 at an MOI of 0.1 then treated with 10 µM 6-TG or DMSO vehicle control. Supernatant and total RNA from the cells were harvested at the times indicated and stored at -80°C until **(A)** titering on BHK-21 or **(B)** quantification of viral genomes by RT-qPCR. Cell monolayers were harvested for **(C)** RT-qPCR analysis of viral RNA accumulation (n=3 statistical significance was determined by paired ratio t test; *, $p<0.05$; **, $p<0.01$; ns, non-significant) **(D)** 293T cells were grown on coverslips then infected with HCoV-OC43 and treated with 6-TG as in (A), then fixed and immunostained for N or **(E)** dsRNA. Nuclei are counterstained with Hoechst. Scale bar = 20 µm.

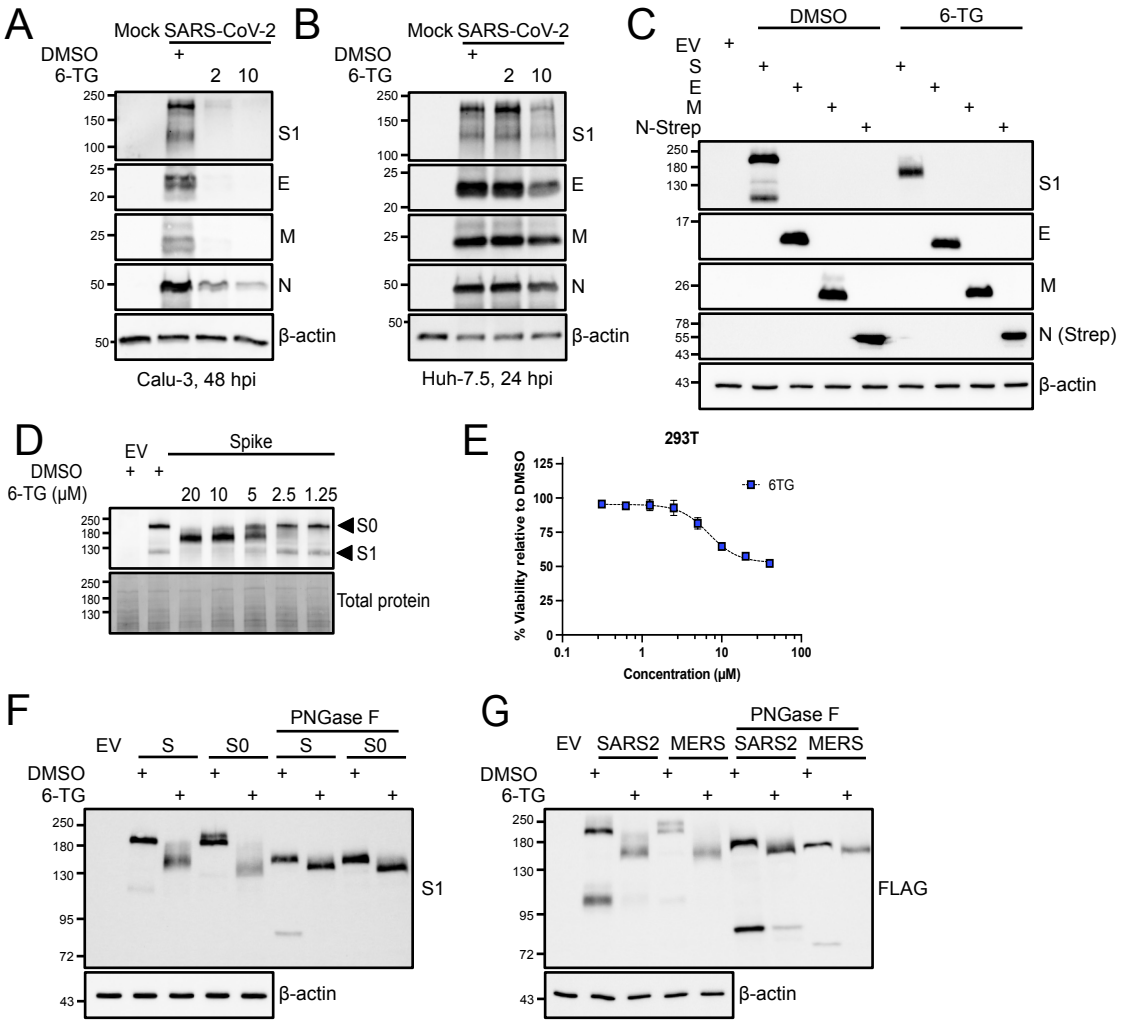

Figure 3. 6-TG inhibits Spike glycosylation and cleavage. **(A)** Calu-3 cells were infected with SARS-CoV-2 at an MOI of 7, then treated with 6-TG or DMSO. Lysates were harvested 48 h after infection and were probed by western blotting as indicated. Concentrations in legend are in μM. **(B)** Huh-7.5 cells were infected with SARS-CoV-2 at an MOI of 5, then treated with 6-TG or DMSO. Lysates were harvested 48 h after infection and were probed by western blotting as indicated. Concentrations in legend are in μM. **(C)** 293T cells were transfected with SARS-CoV-2 S, M, Envelope (E), Nucleoprotein (N) with a C-terminal 2xStrep tag, or EV then treated with 10 μM 6-TG or DMSO vehicle control. Lysates were harvested 24 h after transfection and probed by western blotting as indicated. **(D)** 293T cells were transfected with SARS-CoV-2 Spike or EV then treated with 6-TG or DMSO vehicle control. Lysates were harvested 24 h after transfection and were probed by western blotting as indicated. Concentrations in legend are in μM. **(E)** Alamar Blue cell viability assay of 6-TG treated 293T cells (n=3±SEM). **(F)** 293T cells were transfected with SARS-CoV-2 Spike (S), a Spike mutant lacking the Furin cleavage site between S1 and S2 (S0), or EV then treated with 10 μM 6-TG or DMSO vehicle control. Lysates were harvested 24 h after transfection, treated with PNGase F to remove N-linked glycans, and probed by western blotting as indicated. **(G)** as in (C) except 293T cells were transfected with C-terminal FLAG-tagged Spike (S-FL) or HCoV-MERS Spike (MERS).

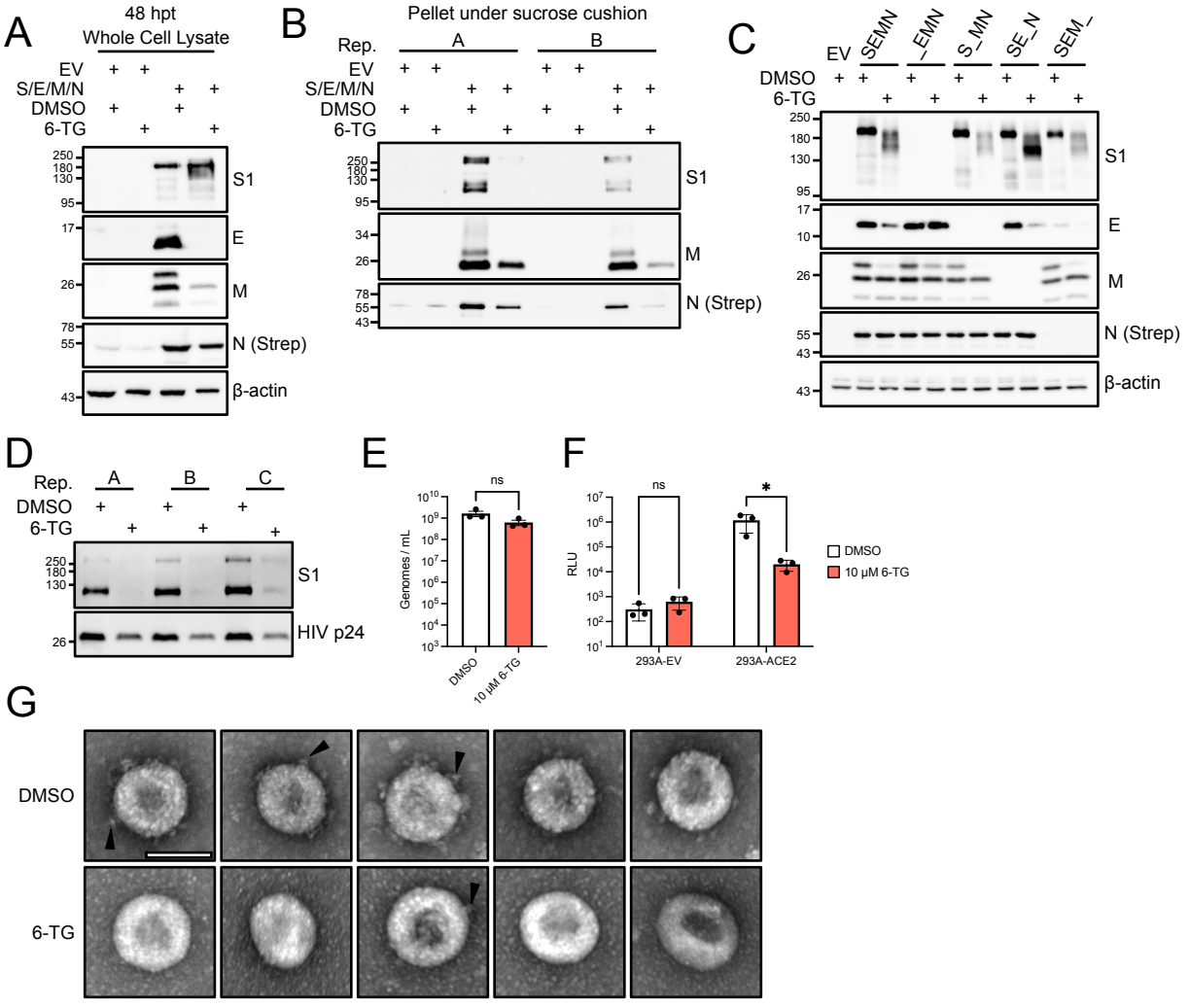

Figure 4. 6-TG stimulates an assembly defect and inhibits Spike virion incorporation. (A) 293T cells were transfected with equal quantities of SARS-CoV-2 S, M, E, and N plasmids or empty vector (EV) then treated with 10 µM 6-TG or DMSO vehicle control. Lysates were harvested 48 h after transfection and probed by western blotting as indicated. **(B)** Virus-like particles from supernatants of cells transfected in (B) were concentrated by ultracentrifugation through a 20% sucrose cushion, resuspended in PBS, then harvested with an equal volume of 2x Laemmli buffer. Samples from two independent lentivirus preparations were probed by western blotting as indicated. **(C)** 293T cells were transfected with S, E, M, and N in a 1:2:2:1 ratio, substituting one of the structural proteins for EV as indicated, treated with 6-TG or DMSO then processed as in (A). **(D)** SARS-CoV-2 Spike pseudotyped, luciferase-expressing lentivirus particles were concentrated by ultracentrifugation through a 20% sucrose cushion, resuspended in PBS, then harvested with an equal volume of 2x Laemmli buffer. Samples from three independent lentivirus preparations were probed by western blotting as indicated. **(E)** Genomes from three independent lentivirus preparations were quantified by RT-qPCR (n=3, statistical significance was determined by paired t-test; ns, non-significant). **(F)** 293A cells stably expressing ACE2 or empty vector control were transduced with lentivirus from three independent preparations. After 24 h, lysates were harvested and measured for luciferase activity (n=3, statistical significance was determined by two-way ANOVA; *, $p<0.05$; ns, non-significant). **(G)** 293A cells were infected HCoV-OC43 at an MOI of 0.1 =, then treated with 6-TG or DMSO. Supernatants were concentrated as in (C), before virions were fixed and imaged by TEM with negative staining. Five virions from both 6-TG- and DMSO-treated samples are shown at 150,000 X magnification. Scale bar = 100 nm. Arrowhead indicates examples of Spike protein extending from virion.

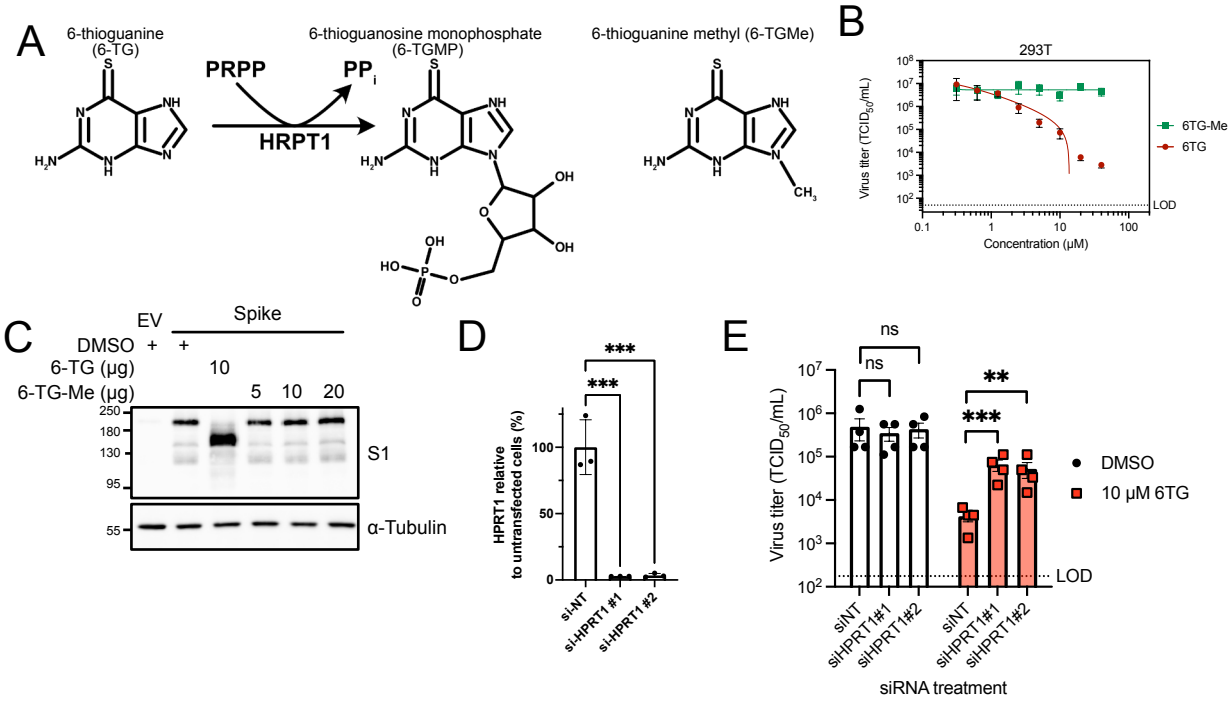

Figure 5. 6-TG inhibits Spike maturation through GTPase inhibition. (A) 6-TG is conjugated to phosphoribosyl diphosphate (PRPP) by HPRT1 to form 6-TG monophosphate. 6-TG methylated at the N9 nitrogen was designed to be resistant to processing by HPRT1. **(B)** 293T cells were infected with HCoV-OC43 at an MOI of 0.1 then treated with 6-TG or 6-TG-Me. Supernatant was harvested at 24 hpi and stored at -80°C until titering on BHK cells. (n=3 statistical significance was determined by paired ratio t test; *, $p<0.05$; **, $p<0.01$; ns, non-significant). **(C)** 293T cells were transfected with SARS-CoV-2 Spike or an empty vector control then treated with 6-TG, 6-TG-Me, or DMSO vehicle control. Lysates were harvested 24 h after transfection and probed by western blotting as indicated. **(D)** 293T cells were reversed transfected with siRNA and total RNA was harvested after 48 h. HPRT1mRNA abundance was measured by RT-qPCR (n=3, ±SEM statistical significance was determined by one way ANOVA; ***, $p<0.001$). **(E)** As in D but cells were infected with HCoV-OC43 at an MOI of 0.1 24 h after siRNA treatment and supernatant was harvested and titered as in **(B)** (n=4 ±SEM statistical significance was determined by paired ratio t test; **, $p<0.01$; ***, $p<0.001$; ns, non-significant).

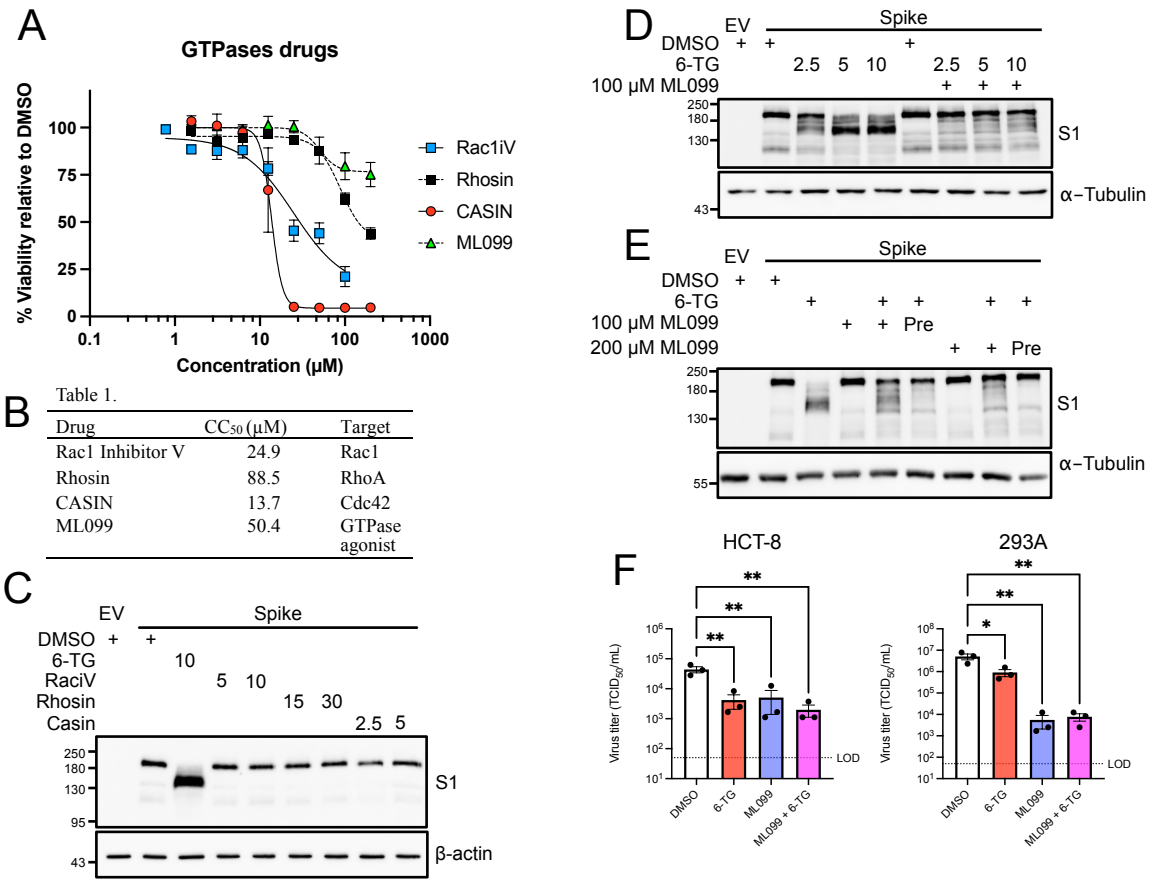

Figure 6. 6-TG inhibits Spike maturation through GTPase inhibition. (A) alamarBlue cell viability assay of 293T cells treated Rac1 Inhibitor V (Rac1iV), Rhosin, CASIN, or ML099 (n=3±SEM). **(B)** Summary table of Cellular Cytotoxicity (CC_{50}) and inhibitor target of compounds tested in (A). **(C)** 293T cells were transfected with SARS-CoV-2 Spike or an empty vector control (EV) then treated with 6-TG, GTPase inhibitors, or DMSO vehicle control. Concentrations in legend are in μM. Lysates were harvested 24 h after transfection and were probed by western blotting as indicated. **(D)** 293T cells were transfected with plasmids encoding Spike or EV then co-treated with 6-TG, 100 μM ML099 GTPase agonist, or DMSO. Lysates were harvested 24 h after transfection and were probed by western blotting as indicated. Concentrations in legend are in μM **(E)** as in (D) except some samples were pre-treated (Pre) for 4 h with ML099. **(F)** HCT-8 and 293A were infected with an MOI of ~0.1 then treated with 10 μM 6-TG or DMSO vehicle control. After 24 h, the supernatants was harvested and stored at -80°C until titering on BHK-21 (n=3 ± SEM, statistical significance was determined by one-way ANOVA; *, $p<0.05$; **, $p<0.01$; ns, non-significant). LoD = Limit of Detection for virus titer.

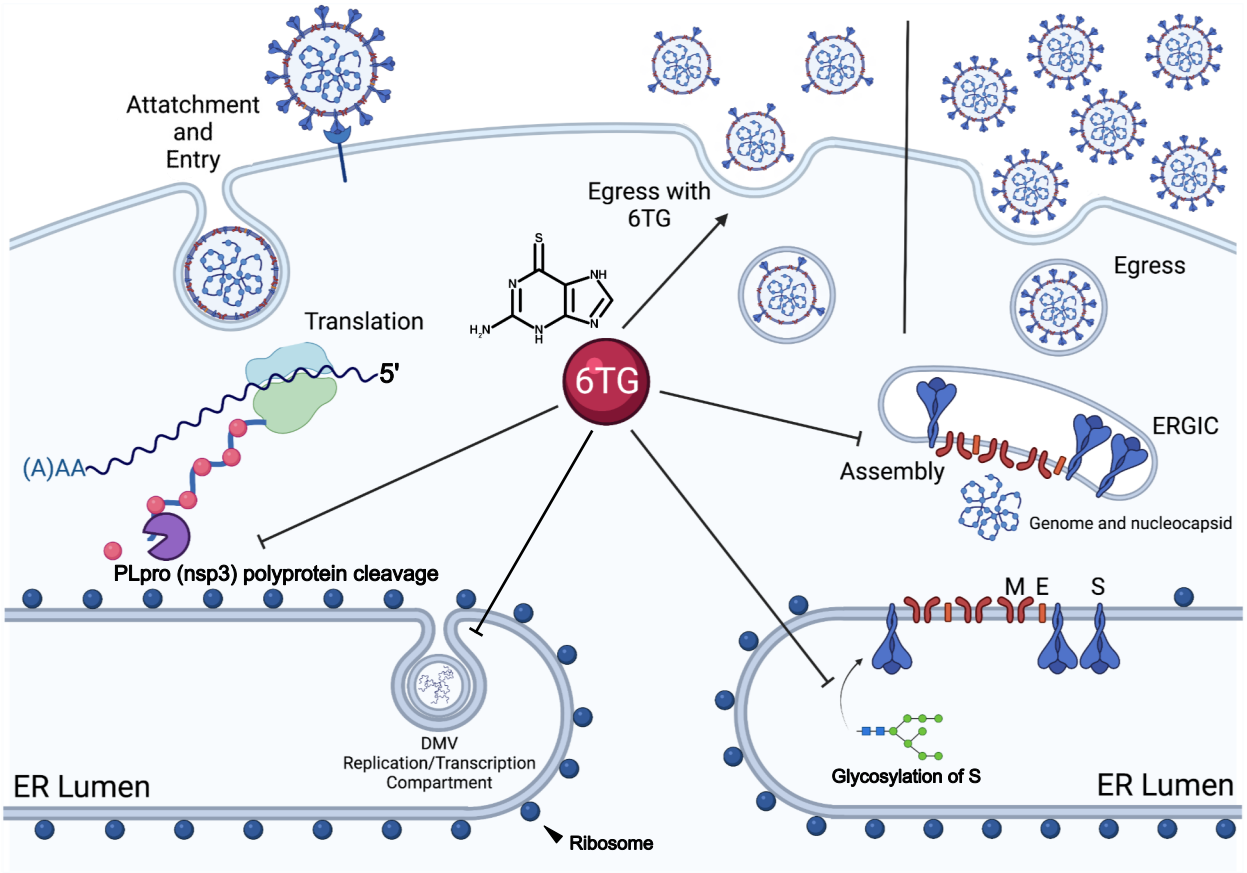

Figure 7. 6-TG inhibits multiple essential steps in virus replication and assembly. 6-TG inhibits nsp3, delaying formation of replication compartments and reducing accumulation of viral RNA. 6-TG also inhibits normal glycosylation of Spike, which fails to be properly packaged in egressing virions. As a result, the total number of virions released from infected cells is reduced and those that are released have fewer Spikes on their surface.

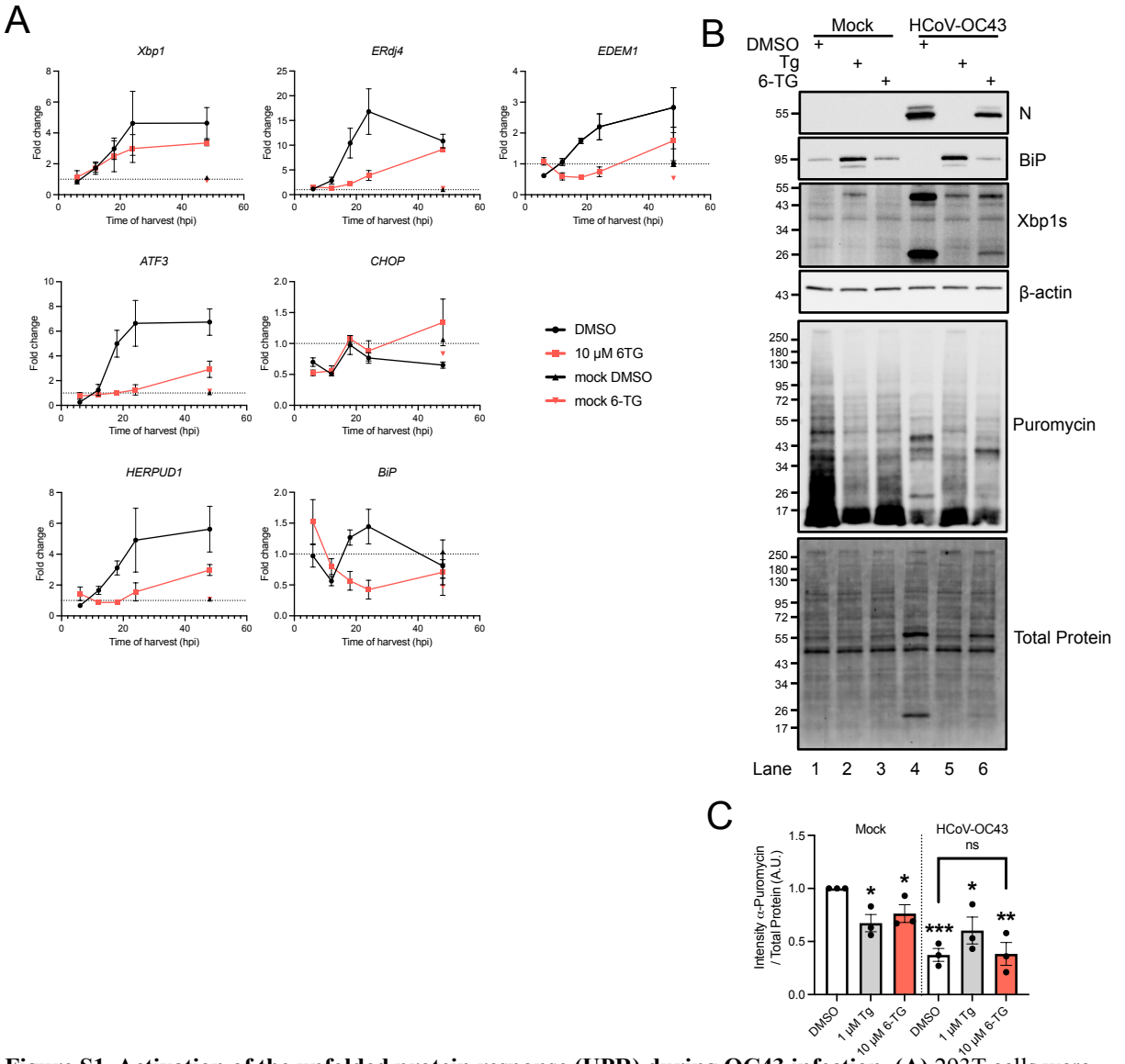

Figure S1. Activation of the unfolded protein response (UPR) during OC43 infection. (A) 293T cells were infected with HCoV-OC43 at an MOI of 0.1 then treated with 10 μM 6-TG or DMSO vehicle control. Total RNA from the cells were harvested at the times indicated and stored at -80°C until RT-qPCR analysis of UPR target genes. **(B)** 293A cells were infected as in (A), then treated with 10 μg 6-TG, 1μg thapsigargin (Tg), or DMSO. Cells were treated with 10 μg/mL of puromycin for 10 min prior to harvest 24 h after infection. Lysates were probed by western blot as indicated. **(C)** Total puromycin intensity from (E) was quantified relative to total protein load and are graphed normalized to the mock-infected, DMSO-treated cells (n=3 ± SEM, statistical significance was determined by paired t-test compared to mock-infected, DMSO-treated cells; *, $p<0.05$; **, $p<0.01$; ***, $p<0.001$; ns, non-significant).

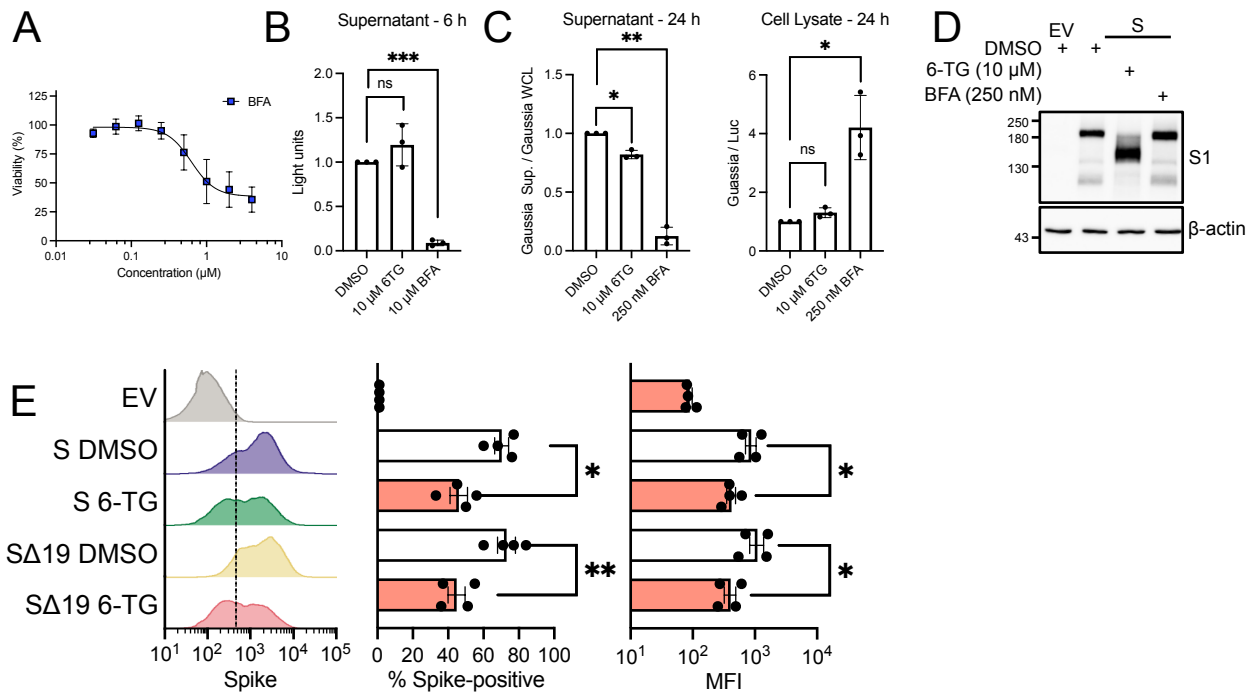

Figure S2. 6-TG reduces surface expression of Spike but does not globally limit secretion. (A) alamarBlue cell viability assay of 293T cells treated with brefeldin A (BFA) (n=4±SEM). **(B)** 293T cells were transfected with *Gaussia* luciferase for 18 h then treated with 6-TG, BFA or DMSO vehicle control for 6 h . Supernatants were recovered from the cells and measured for luciferase activity. **(C)** 293T cells were transfected with both luciferase and *Gaussia* luciferase then treated with 6-TG, BFA, or DMSO. After 24 h, supernatants were removed and analyzed as in (B). Cell lysate was harvested in Reporter Lysis Buffer and stored at -80°C until both luciferase and *Gaussia* luciferase activity was measured. (For B and C, n=3 ± SEM, statistical significance was determined by paired t-test compared to DMSO-treated cells; *, $p<0.05$; **, $p<0.01$; ***, $p<0.001$; ns, non-significant). **(D)** 293T cells were transfected with SARS-CoV-2 Spike or EV then treated with 6-TG, BFA, or DMSO. Lysates were harvested 24 h after transfection in 2x Laemmli buffer and were probed by western blotting as indicated. **(E)** 293T cells were co-transfected with EGFP and either Spike (S), Spike with 19 residue C-terminal truncation (SΔ19), or EV and then treated with 10 μM 6-TG or DMSO. After 24 h, cells were harvested, surface-stained for Spike then fixed prior to analysis by flow cytometry. EGFP+ cells were gated for analysis of number of Spike+ cells and Median Fluorescent Intensity (MFI) (n=4±SEM statistical significance was determined by paired t-test between 6-TG and DMSO treated cells; *, $p<0.05$).