CD169-mediated restrictive SARS-CoV-2 infection of macrophages induces pro-inflammatory responses

Running title: Innate immune sensing of SARS-CoV-2 in macrophages

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Abstract

Exacerbated and persistent innate immune response marked by pro-inflammatory cytokine expression is thought to be a major driver of chronic COVID-19 pathology. Although macrophages are not the primary target cells of SARS-CoV-2 infection in humans, viral RNA and antigens in activated monocytes and macrophages have been detected in post-mortem samples, and dysfunctional monocytes and macrophages have been hypothesized to contribute to a protracted hyper-inflammatory state in COVID-19 patients. In this study, we demonstrate that CD169, a myeloid cell specific I-type lectin, facilitated ACE2-independent SARS-CoV-2 fusion and entry in macrophages. CD169-mediated SARS-CoV-2 entry in macrophages resulted in expression of viral genomic and sub-genomic (sg) RNAs with minimal viral protein expression and no infectious viral particle release, suggesting a post-entry restriction of the SARS-CoV-2 replication cycle. Intriguingly this post-entry replication block was alleviated by exogenous ACE2 expression in macrophages. Restricted expression of viral gRNA and sgRNA in CD169^{+} macrophages elicited a pro-inflammatory cytokine expression (TNFα, IL-6 and IL-1β) in a RIG-I, MDA-5 and MAVS-dependent manner, which was suppressed by remdesivir pre-treatment. These findings suggest that *de novo* expression of SARS-CoV-2 RNA in macrophages contributes to the pro-inflammatory cytokine signature and that blocking CD169-mediated ACE2 independent infection and subsequent activation of macrophages by viral RNA might alleviate COVID-19-associated hyperinflammatory response.

Author Summary

Over-exuberant production of pro-inflammatory cytokine expression by macrophages has been hypothesized to contribute to severity of COVID-19 disease. Molecular mechanisms that contribute to macrophage-intrinsic immune activation during SARS-CoV-2 infection are not fully understood. Here we show that CD169, a macrophage-specific sialic-acid binding lectin, facilitates abortive SARS-CoV-2 infection of macrophages that results in innate immune sensing of viral replication intermediates and production of proinflammatory responses. We identify an ACE2-independent, CD169-mediated endosomal viral entry mechanism that results in cytoplasmic delivery of viral capsids and initiation of virus replication, but absence of infectious viral production. Restricted viral replication in CD169^{+} macrophages and detection of viral genomic and sub-genomic RNAs by cytoplasmic RIG-I-like receptor family members, RIG-I and MDA5, and initiation of downstream signaling via the adaptor protein MAVS, was required for innate immune activation. These studies uncover mechanisms important for initiation of innate immune sensing of SARS-CoV-2 infection in macrophages, persistent activation of which might contribute to severe COVID-19 pathophysiology.

65 **Introduction**

66 Severe acute respiratory syndrome coronavirus 2 (SARS-CoV-2) is the causative agent
67 of the COVID-19 pandemic, which has claimed nearly 6 million deaths worldwide
68 (https://coronavirus.jhu.edu/). Severe COVID-19 cases have been associated with
69 aberrant bronchioalveolar immune cell activation and persistently high levels of
70 proinflammatory cytokines, including IL-6, TNFα, and IL-1β (1, 2). This protracted immune
71 hyperactivation state marked by uncontrolled proinflammatory cytokine expression (3-6)
72 is a potential driver of acute respiratory distress syndrome (ARDS) in severe COVID-19.
73 Transcriptomic analysis of bronchioalveolar lavage fluid (BALF) samples from SARS-
74 CoV-2 infected individuals revealed extensive lung infiltration by inflammatory monocytes
75 and activated tissue-resident and BALF-associated macrophages with robust induction of
76 interferon-stimulated gene (ISG) expression (7), suggestive of a myeloid cell-intrinsic
77 cytokine signature contributing to ARDS and COVID-19 pathologies (8, 9). However,
78 whether SARS-CoV-2 can establish productive infection in monocytes and macrophages
79 has remained contentious (10-15), and importantly, the molecular mechanisms that
80 contribute to myeloid cell-intrinsic hyperinflammatory phenotype have remained unclear
81 (6, 16-19).

82 Studies on post-mortem tissues from patients, who succumbed to COVID-19,
83 showed that a subset of tissue-resident alveolar macrophages are enriched in SARS-
84 CoV-2 RNA (20, 21). Additionally, single-cell RNA-seq analysis revealed the presence of
85 viral mRNAs in inflammatory myeloid cell populations in autopsied lung tissues (22, 23).
86 Recent studies suggest that tissue-resident human macrophages are permissive to
87 SARS-CoV-2 infection in humanized mice models, and that inhibition of viral genome
88 replication or type-I interferon (IFN) signaling significantly attenuates chronic macrophage

89 hyperactivation and disease progression (24). However, whether the presence of viral
90 RNA in macrophages reflects phagocytosis of infected bystander cells or active virus
91 replication in tissue-resident macrophages has yet to be defined. In contrast, $CD14^+$
92 peripheral blood monocytes, monocyte-derived dendritic cells (MDDCs), or monocyte-
93 derived macrophages (MDMs) were not-permissive to productive SARS-CoV-2 replication
94 in vitro (10-12, 15). In permissive lung epithelial cells and those expressing the cognate
95 entry receptor, angiotensin-converting enzyme 2 (ACE2), SARS-CoV-2 utilizes its spike
96 (S) glycoprotein to interact with ACE2, which facilitates proteolytic cleavage, plasma or
97 endosomal membrane fusion, and cytosolic import of viral genome (25-27). Depending
98 on cell type, different host proteases such as furin, TMPRSS2, or cathepsins are required
99 for S cleavage and entry of SARS-CoV-2 (26, 28, 29). While circulating monocytes and
100 macrophages are not known to express ACE2 (30), these cells have been shown to
101 express low levels of endogenous surface TMPRSS2 (31), and moderate levels of
102 endosomal cathepsins (32) (33), although the relative expression of these cellular
103 proteases in the context of SARS-CoV-2 infection and inflammation is not well understood.
104 Recent reports have highlighted capture of SARS-CoV-2 virus particles by myeloid
105 cell-specific receptors, such as C-type lectins, in an ACE2-independent manner (16, 17,
106 19, 34, 35) though virus particle fusion or productive viral infection was not observed. We
107 and others have previously shown that CD169/Siglec-1 facilitates viral infections of
108 macrophages or dendritic cell (DC)-mediated trans infection of bystander cells (36-39).
109 CD169 binds to sialylated viral glycoproteins or viral membrane-associated gangliosides,
110 GM1 and GM3 (38-44). SARS-CoV-2 S protein is highly sialylated (45, 46), and a recent
111 report demonstrated that DC-mediated SARS-CoV-2 trans infection of $ACE2^+$ epithelial
112 cells was facilitated by CD169 (19). CD169 is highly expressed by splenic red pulp and

113 perifollicular macrophages, subcapsular sinus macrophages (47) and alveolar
114 macrophages (48, 49). Besides constitutive expression on tissue-resident macrophages,
115 CD169 expression can be upregulated on peripheral blood monocytes under inflammatory
116 conditions, especially in response to type I interferons (IFNs) (50-52). Since type I IFNs
117 are highly upregulated and CD169-expressing myeloid cells are elevated during SARS-
118 CoV-2 infection (53, 54), we reasoned that SARS-CoV-2 S mediated interactions with
119 CD169^{+} macrophages might play a crucial role in driving immunopathology of SARS-CoV-
120 2 infection.

121 In this study, we examined the role of CD169 in facilitating SARS-CoV-2 infection
122 of ACE2-deficient human macrophages and its effect on inducing pro-inflammatory
123 cytokine expression. Using two different human macrophage models, PMA-differentiated
124 THP1 cells (THP1/PMA) and primary monocyte-derived macrophages (MDMs), we show
125 that CD169 binds to SARS-CoV-2 S and mediates SARS-CoV-2 S-dependent viral entry
126 into macrophages, leading to restricted cytosolic expression of viral genomic and sub-
127 genomic (sg) RNA. Surprisingly, induced constitutive expression of ACE2 in macrophages
128 (THP1/PMA and MDMs) restored permissiveness to robust virus replication and
129 production of infectious progeny virions, suggesting that ACE2 expression overcomes a
130 post-entry block to SARS-CoV-2 infection in macrophages. While CD169-mediated,
131 ACE2-independent SARS-CoV-2 entry into macrophages resulted in negligible viral
132 protein expression and absence of infectious virus production, restricted expression of
133 viral negative strand RNA and sgRNAs induced pro-inflammatory cytokine expression via
134 retinoic acid-inducible gene I (RIG-I) and melanoma differentiation-associated gene 5
135 (MDA-5) dependent sensing of viral replication intermediates. Importantly, expression of
136 IL-6, TNFα and IL-1β was enhanced, whereas type I IFN responses were muted,

137 suggesting a novel CD169-mediated, macrophage-intrinsic amplification of pro-
138 inflammatory responses. These findings suggest that induction of pro-inflammatory
139 responses in SARS-CoV-2-exposed macrophages requires initial viral RNA synthesis and
140 that abortively infected macrophages might contribute to the hyperimmune phenotype and
141 pathophysiology of COVID-19.
142
143 **Results**
144 **SARS-CoV-2 Spike protein can mediate ACE2-independent entry into macrophages**
145 To examine the role of macrophages in SARS-CoV-2 infection and COVID-19
146 pathogenesis, we differentiated primary MDMs from multiple donors by culturing $CD14^+$
147 monocytes in the presence of human AB-serum and M-CSF for 6 days (55). Compared
148 to a control HEK293T/ACE2 cell line retrovirally transduced to stably express human
149 ACE2, ACE2 expression in primary human MDMs was under the detection limit (**Fig. 1A**
150 **and B**). However, similar to HEK293T/ACE2 cells (**Fig. 1C**), MDMs from multiple donors
151 were robustly infected with a SARS-CoV-2 S-pseudotyped lentivirus (**Fig. 1D**), suggesting
152 that macrophages can support ACE2-independent S-pseudotyped virus entry.
153 Furthermore, SARS-CoV-2 S-pseudotyped infections in MDMs were blocked by pre-
154 treatment with a cathepsin inhibitor (E64D) but not a TMPRSS2 inhibitor (Camostat) (**Fig.**
155 **1D**), suggesting that SARS-CoV-2 S facilitates endosomal viral entry into ACE2-deficient
156 MDMs. Preferential engagement of endosomal entry mechanism for SARS-CoV-2 S
157 pseudotyped lentiviruses (LVs) in MDMs correlated with lack of active and cleaved form
158 of serine protease TMPRSS2 expression in THP1/PMA and primary macrophages ((56),
159 **Fig. S1A**), and robust cathepsin-L expression in THP1/PMA and MDMs (**Fig. S1B**).
160 Strikingly, pre-treatment with neutralizing antibodies targeting the N-terminal domain

161 (NTD) of SARS-CoV-2 S that do not compete with ACE2 binding by S (57), led to
162 significant reduction in S-pseudotyped lentivirus infection of primary MDMs, suggesting
163 that specific interaction between SARS-CoV-2 S and ACE2-independent entry factors are
164 essential to mediate entry and endosomal fusion in macrophages (**Fig. S2**).
165

166 **CD169 is a SARS-CoV-2 attachment and entry factor in macrophages**

167 Expression of CD169, an ISG, is significantly upregulated in monocytes and alveolar
168 macrophages isolated from COVID-19 patients, and its expression enhancement
169 correlates with COVID-19 disease severity (7, 53). While co-expression of CD169 with
170 ACE2 can enhance ACE2-mediated SARS-CoV-2 S entry in HEK293T cells (16), whether
171 CD169 plays a role in SARS-CoV-2 infection of ACE2-deficient macrophages is unclear.
172 To address this question, THP1 cells stably expressing wildtype (wt) CD169, mutant
173 CD169/R116A which displays an attenuated ability to bind sialylated glycoconjugates (39,
174 58, 59), ACE2, or both wt CD169 and ACE2 (CD169/ACE2) (**Fig. S3A**) were incubated
175 with recombinant SARS-CoV-2 S protein, and relative S binding was determined by flow
176 cytometry. In contrast to parental THP1 monocytes, THP1 cells expressing wt CD169
177 (THP1/CD169) displayed robust S binding comparable to levels observed with
178 THP1/ACE2 cells (**Fig. 2A**). There was a significant reduction in S binding to
179 THP1/CD169-R116A cells, indicating that the sialylated S protein is recognized by CD169
180 (**Fig. 2A**). Co-expression of CD169 and ACE2 in THP1 cells further enhanced S binding
181 compared to cells expressing only ACE2 or CD169, suggestive of cooperative binding of
182 CD169 and ACE2 to SARS-CoV-2 S.

183 We next sought to determine the role of CD169 in mediating SARS-CoV-2 infection
184 of macrophages. PMA-differentiated THP1 macrophages expressing wt or mutant CD169,

185 ACE2, or CD169/ACE2 were infected with SARS-CoV-2 S-pseudotyped lentiviruses.
186 Expression of wt CD169 on THP1/PMA macrophages enhanced S-pseudotyped lentiviral
187 infection by ~30-fold compared to parental THP1/PMA macrophages, similar to the levels
188 of infection observed with $ACE2^+$ THP1/PMA macrophages (**Fig. 2B**). In contrast
189 expression of CD169/R116A did not enhance S-pseudotyped lentiviral infection of
190 THP1/PMA cells, confirming that recognition of sialylated motifs on SARS-CoV-2 S is
191 essential for CD169-mediated infection of macrophages (**Fig. 2B**). Co-expression of wt
192 CD169 and ACE2 further enhanced S-pseudotyped lentiviral infection by greater than 11-
193 fold and 3-fold when compared to cells expressing CD169 or ACE2, respectively (**Fig. 2B**),
194 confirming that CD169 facilitates S-mediated entry into macrophages in the absence of
195 ACE2 and enhances entry in the presence of ACE2. To confirm the role of CD169 in
196 SARS-CoV-2 S-mediated infection in primary human MDMs, and given the relatively low
197 and variable expression of endogenous CD169 in primary MDMs (**Fig. S3B**), we used
198 lentiviral transduction to overexpress either wt CD169 or ACE2 (**Fig. S3C and D**).
199 Following infection of transduced primary macrophages with S-pseudotyped lentivirus, we
200 observed that CD169 or ACE2 overexpression in MDMs from multiple donors significantly
201 enhanced SARS-CoV-2 S-pseudotyped lentivirus infection compared to control MDMs
202 transduced with empty vector (**Fig. 2C**). Crucially, pre-treatment with anti-CD169 blocking
203 mAb (7D2) prior to infection with S-pseudotyped lentivirus significantly attenuated
204 infection of untransduced primary MDMs when compared to non-specific IgG1
205 pretreatment (**Fig. 2D**). These findings suggest that CD169 facilitates SARS-CoV-2 S-
206 dependent fusion and entry into both THP1/PMA macrophages and primary MDMs in the
207 absence of ACE2.
208

209 **SARS-CoV-2 establishes abortive infection in macrophages lacking ACE2**

210 To investigate whether CD169 expression is sufficient to establish productive SARS-CoV-
211 2 infection and replication in ACE2-deficient macrophages, we infected THP1/PMA and
212 primary MDMs overexpressing CD169, ACE2, or parental cells (lacking both CD169 and
213 ACE2) with replication-competent SARS-CoV-2 (Washington isolate, NR-52281), as
214 previously described (60). To evaluate productive infection, we examined the temporal
215 expression of double-stranded RNA (dsRNA), a viral replication intermediate (61), as well
216 as viral nucleocapsid (N) protein. SARS-CoV-2-infected THP1/PMA macrophages were
217 fixed at various time points post infection and subjected to immunofluorescence analysis
218 using antibodies against dsRNA and SARS-CoV-2 N. In contrast to parental THP1/PMA
219 macrophages that showed background staining of dsRNA and no expression of SARS-
220 CoV-2 N at any time point post infection (**Fig. 3A**), CD169-expressing THP1/PMA cells
221 showed low levels of dsRNA production and small puncta staining of SARS-CoV-2 N that
222 did not significantly increase over the course of infection (**Fig. 3B**). However, both ACE2$^+$
223 (**Fig. 3C**) and CD169/ACE2 double-positive (**Fig. 3D**) THP1/PMA macrophages showed
224 robust dsRNA and SARS-CoV-2 N production starting as early as 2-4 hours post infection
225 (hpi), which significantly increased over the course of infection. There was a clear
226 distinction in the spatial distribution of viral N protein in infected ACE2$^+$ and
227 CD169$^+$/ACE2$^+$ THP1/PMA macrophages over time, as noted by a transition from 6 hpi
228 onward from small cytosolic N protein puncta to homogenous distribution throughout the
229 cytosol (**Fig. 3C** and **D**). Furthermore, there was extensive co-localization between peri-
230 nuclear dsRNA foci and N staining in ACE2$^+$ and CD169$^+$/ACE2$^+$ THP1/PMA
231 macrophages at 6 and 24 hpi. In accordance with our S-pseudotyped lentivirus infection
232 data (**Fig. 2B**), co-expression of CD169 and ACE2 led to an increase in SARS-CoV-2

233 infection compared to ACE2-expressing cells, with higher levels and slightly earlier
234 production of dsRNA and SARS-CoV-2 N (compare **Fig. 3C** and **D**). In contrast, N protein
235 staining was not dispersed in the cytoplasm of CD169^{+} THP1/PMA macrophages and
236 remained as small cytosolic puncta over the course of infection with minimal co-
237 localization with dsRNA staining (**Fig. 3B**). These findings suggest that CD169-mediated
238 SARS-CoV-2 entry in THP1/PMA macrophages results in initiation of viral transcription
239 and moderate viral protein production.

240 Similar to our findings in THP1/PMA macrophages, we observed SARS-CoV-2 N
241 expression in primary MDMs overexpressing ACE2, whereas we were not able to detect
242 N protein in primary untransduced MDMs or those overexpressing CD169 at 24 hpi (**Fig.**
243 **S4**). The lack of detection of either N (**Fig. S4**) or dsRNA (data not shown) in primary
244 MDMs compared to the low level of N and dsRNA expression observed in THP1/CD169
245 macrophages (**Fig. 3B**) could be explained by the inefficient lentivector transduction
246 efficiency and low expression of CD169 in primary MDMs (**Fig. S3B** and **C**) compared to
247 the robust CD169 expression in retrovirally transduced THP1 cells (**Fig. S3A**). We further
248 quantified infectious SARS-CoV-2 particle production from both THP1/PMA macrophages
249 (**Fig. 3E**) and primary MDMs (**Fig. 3F**) by TCID50 assay and detected no infectious virions
250 in culture supernatants from CD169-expressing cells. However, both THP1/PMA and
251 primary MDMs expressing ACE2 showed robust production of infectious SARS-CoV-2
252 particles, with a marked increase in infectious virus production in THP1/PMA cells co-
253 expressing CD169 and ACE2 compared to ACE2 alone (**Fig. 3E**). These results suggest
254 an absence of post-entry restrictions to SARS-CoV-2 replication in macrophages, if virus
255 entry is mediated by ACE2.
256

257 **CD169-mediated SARS-CoV-2 infection of macrophages results in *de novo***
258 **expression of viral mRNAs**

259 To explore the spatial and temporal distribution of SARS-CoV-2 RNA at single cell level,
260 single-molecule RNA FISH (smFISH) analysis (62) was performed in infected THP1/PMA
261 macrophages. Individual fluorescent spots corresponding to viral gRNAs were detected
262 in CD169$^+$, ACE2$^+$ and CD169$^+$/ACE2$^+$ THP1/PMA macrophages, as early as 1 hpi (**Fig.**
263 **S5**). By 6 hpi, we observed diffuse cytosolic staining and perinuclearly localized bright
264 gRNA foci (**Fig. S5**), which further increased in in ACE2$^+$ and CD169$^+$/ACE2$^+$ but not
265 CD169$^+$ THP1/PMA macrophages (**Fig. S5**). In order to distinguish between gRNAs and
266 N gene transcripts, we probed cells at 24 hpi with two probe sets labeled with
267 distinguishable dyes one against SARS-CoV-2 ORF1a and the other against N gene. The
268 former detects only gRNA and the later reports both gRNA and N sub-genomic transcripts
269 **(Fig. 4A)**. The staining, particularly that of N gene, showed diffused cytoplasmic
270 distribution, only in ACE2$^+$ and CD169$^+$/ACE2$^+$ THP1/PMA macrophages, especially in
271 the advanced stages of infection.

272 Dispersion of N transcripts (gRNA and sgRNA) in the cytosol of ACE2$^+$ and
273 CD169$^+$/ACE2$^+$ THP1/PMA macrophages mirrors the temporal localization phenotype of
274 viral N protein (**Fig. 3C** and **D**), and might be indicative of formation of N positive viral
275 replication compartments (63). While a majority of virus-exposed CD169$^+$ THP1/MA
276 macrophages expressed fluorescent puncta (gRNA) at 24 hpi (indicated by the white
277 arrowheads showing both ORF1a and N expression**, Fig. 4A and B**), transition to bright
278 gRNA foci or cytosolic expansion was not observed, suggesting that CD169 expression
279 in THP1/PMA cells increased uptake of virus, but without ACE2, failed to establish viral
280 replication foci. It should be noted that the formation of distinct fluorescent puncta in

281 CD169^{+} THP1/PMA macrophages at 24 hpi is suggestive of *de novo* RNA synthesis and
282 not virus inoculum, since these puncta were not detected at 1 hpi (**Fig. S5**). While viral
283 RNAs in the CD169-expressing cells are localized in few distinct granulated puncta,
284 ACE2-expressing cells exhibited inclusion-like structures, suggesting that differential
285 engagement of viral entry receptors (such as CD169 and ACE2) leads to altered fate of
286 the incoming viral genome and subsequent steps in the viral replication cycle.

287 To further investigate the step at which SARS-CoV-2 replication is restricted in
288 macrophages, THP1/PMA macrophages or those expressing either CD169, ACE2, or
289 both CD169 and ACE2 were infected with SARS-CoV-2 and cells lysed and harvested at
290 2, 4, 6, and 24 hpi to quantify the level of total SARS-CoV-2 N transcripts, +gRNA and
291 sgRNA, as well as negative sense antigenomic RNA, by RT-qPCR. We detected
292 increasing levels of total SARS-CoV-2 N transcripts at early time points (2-6 hpi) in
293 THP1/PMA macrophages expressing CD169, ACE2, or both CD169 and ACE2, whereas
294 parental THP1/PMA macrophages showed no significant increase in viral N RNA levels
295 compared to mock infection controls (**Fig. 4C**). Furthermore, there were no significant
296 differences in gRNA levels at early times post infection (up to 6 hpi) between CD169^{+},
297 ACE2^{+} or CD169^{+}/ACE2^{+} THP1/PMA macrophages suggesting an absence of cell-
298 intrinsic restrictions to early steps of SARS-CoV-2 replication, such as attachment and
299 fusion, in CD169+ THP1/PMA macrophages. Interestingly, SARS-CoV-2 N transcripts
300 peaked at 6 hpi in CD169+ THP1/PMA cells, followed by a progressive decline at 24 hpi
301 (**Fig. 4C**). In contrast, there was a temporal increase in SARS-CoV-2 N transcripts in cells
302 expressing ACE2, with markedly higher expression at 24 hpi compared to CD169-
303 expressing cells. In concordance with SARS-CoV-2 N protein expression (**Fig. 3D**),

304 THP1/PMA cells expressing both CD169 and ACE2 expressed the highest levels of
305 SARS-CoV-2 N transcripts at 24 hpi compared to those expressing ACE2 or CD169 alone.
306 After virus entry and capsid uncoating, the next steps in the SARS-CoV-2
307 replication cycle are translation of the viral gRNA followed by the formation of viral
308 replication-transcription complexes, which enables synthesis of the negative sense
309 antigenomic RNA (64). Negative sense antigenomic RNAs are present at significantly
310 lower levels than +gRNA and sgRNA, and are templates for synthesis of additional
311 positive sense gRNA and sgRNAs (64). We employed strand-specific RT-qPCR analysis
312 to detect negative sense viral RNA (ORF1b) and confirmed viral replication (at 2 hpi) in
313 CD169$^+$ THP1/PMA cells, compared to complete absence of negative sense viral RNAs
314 in parental THP1/PMA macrophages (**Fig. 4D**). Interestingly, negative sense RNA
315 expression in CD169$^+$ THP1/PMA macrophages plateaued at 6 hpi, suggesting that
316 CD169-mediated SARS-CoV-2 entry promotes initial steps of viral replication. In contrast,
317 there was a progressive increase in negative sense RNA levels in ACE2$^+$ THP1/PMA
318 macrophages particularly at 24 hpi, and a further enhancement was observed upon co-
319 expression of CD169 and ACE2 in THP1/PMA macrophages at later times post infection
320 (**Fig. 4D**).
321 To confirm that temporal increases in viral transcripts in CD169$^+$ or ACE2$^+$
322 THP1/PMA macrophages were generated from ongoing virus transcription, THP1/PMA
323 cells (±CD169 ±ACE2) were pre-treated with remdesivir (RDV), a known inhibitor of
324 SARS-CoV-2 RNA synthesis, prior to infection with SARS-CoV-2 (24, 63). RT-qPCR
325 analysis of both gRNA (N transcripts) (**Fig. 4E**) and sgRNA (E transcripts) (**Fig. 4F**)
326 transcripts harvested at 24 hpi revealed that RDV pre-treatment completely blocked the
327 increase in viral RNA expression in THP1/PMA macrophages expressing CD169, ACE2,

328 or both CD169 and ACE2, to levels observed in parental THP1/PMA macrophages.
329 Furthermore, levels of viral gRNA (**Fig. 4G**) and sgRNA (**Fig. 4H**) in SARS-CoV-2 infected
330 untransduced MDMs progressively increased over time, and these increases in viral
331 gRNA and sgRNAs were also suppressed upon RDV pre-treatment. Notably, primary
332 MDMs harbored higher levels of viral transcripts compared to parental THP1/PMA
333 macrophages at all times post infection (**Fig. 4E-H**), suggesting that endogenous CD169
334 expression was sufficient to facilitate entry and initiation of virus replication in primary
335 MDMs. The marked lower levels of viral transcripts in primary MDMs (**Fig. 4G** and **H**)
336 compared to CD169$^+$ THP1/PMA macrophages (**Fig. 4E** and **F**) might be correlated to the
337 lower CD169 expression in primary MDMs compared to CD169$^+$ THP1/PMA
338 macrophages cells which were selected for high CD169 expression (**Fig. S3A**). Taken
339 together, these results suggest that CD169-mediated viral entry enables initiation of viral
340 RNA replication and transcription in ACE2-deficient CD169$^+$ macrophages even in the
341 absence of establishment of robust viral RNA replication foci in macrophages, and that
342 SARS-CoV-2 infection of macrophages is restricted at a post-entry step of virus replication.
343

344 **Low level expression of SARS-CoV-2 genomic and sub-genomic RNAs is sufficient**
345 **to induce pro-inflammatory cytokines in non-productively infected macrophages**

346 Since CD169 expression in macrophages was sufficient to permit SARS-CoV-2 entry and
347 initiate restricted viral RNA expression, we investigated whether *de novo* viral RNA
348 synthesis in the absence of productive virus replication can trigger innate immune
349 responses. SARS-CoV-2 infected THP1/PMA cells (±CD169 ±ACE2) were lysed at 24 hpi,
350 and total RNA was analyzed by RT-qPCR for inflammatory cytokine expression (**Fig. 5**).
351 We observed significant induction of expression of IL-6, TNFα, IL-1β, and IL-18 mRNA in

352 non-productively infected CD169$^+$ THP1/PMA macrophages compared to the parental
353 THP1/PMA cells (**Fig. 5A**). IL-6 and TNFα mRNA expression in SARS-CoV-2 infected
354 THP1/CD169 cells was similar to the levels observed in productively infected THP1/ACE2,
355 but lower than that observed in THP1/CD169/ACE2 cells. Intriguingly, induction of pro-
356 inflammatory cytokines, IL-1β and IL-18, was only consistently observed in non-
357 productively infected THP1/CD169 macrophages but not in the productively infected
358 THP1/ACE2 or THP1/CD169/ACE2 macrophages (**Fig. 5A**). A delayed or impaired type I
359 IFN response is thought to be a critical mechanism for COVID-19 pathogenesis, though
360 impaired induction of type I IFN response has mostly been reported in infected lung
361 epithelial cells (65). Interestingly, we observed muted induction of IFNβ, IP-10 and Viperin
362 in SARS-CoV-2 infected CD169$^+$ THP1/PMA macrophages. In contrast, IFNβ, IFNλ1, IP-
363 10 and Viperin mRNA expression was dramatically upregulated upon establishment of
364 productive SARS-CoV-2 infection in THP1/ACE2 and THP1/CD169/ACE2 macrophages
365 (**Fig. 5A**) and correlated with the extent of viral RNA expression and virus replication in
366 these cells (**Fig. 3**).

367 Since previous reports have suggested that macrophage exposure to recombinant
368 S protein may trigger inflammatory cytokine production (17, 66), we infected parental,
369 CD169$^+$, ACE2$^+$, or CD169$^+$/ACE2$^+$ THP1/PMA cells with S-pseudotyped lentivirus but
370 observed no induction of pro-inflammatory cytokines (IL-6, TNFα, IL-1β, and IFNλ1) (**Fig.
371 S6**). To confirm that the induction of pro-inflammatory cytokine and ISG expression was
372 due to viral replication and sensing of viral RNA, we infected THP1/PMA macrophages
373 with SARS-CoV-2 in the presence of RDV. Pre-treatment with RDV which abolished virus
374 replication (**Fig. 4E** and **F**) completely abrogated IL-6, TNFα, IL-1β and IFNλ1 induction
375 in CD169$^+$, ACE2$^+$, and CD169$^+$/ACE2$^+$ THP1/PMA macrophages (**Fig. 5B**), suggesting

376 that *de novo* viral RNA transcription and sensing of virus replication intermediates are
377 required for the induction of pro-inflammatory cytokines and ISGs in macrophages.
378 Temporal analysis of inflammatory cytokine induction revealed that while SARS-CoV-2
379 infection of parental THP1/PMA cells did not result in induction of pro-inflammatory
380 responses (**Fig. 5C**), infection of CD169$^+$ THP1/PMA cells led to rapid induction of IL-6,
381 TNFα, IL-1β, and IFNλ1 mRNA expression (**Fig. 5D**). In fact, fold-induction in levels of
382 pro-inflammatory cytokines at early times post infection (4-6 hpi) was similar between
383 CD169$^+$ and ACE2$^+$ macrophages (**Fig. 5D** and **E**), indicating that early viral RNA
384 production is the key trigger of innate immune activation. Accelerated kinetics and highest
385 magnitude of induced IFNλ1 expression was observed in SARS-CoV-2 infected
386 CD169$^+$/ACE2$^+$ THP1/PMA macrophages (**Fig. 5F,** note difference in scale on y axis),
387 which correlated with greater level of negative sense antigenomic RNA (**Fig. 4D**) and
388 highest levels of virus replication in CD169$^+$/ACE2$^+$ THP1/PMA macrophages (**Fig. 3E**).
389 To further confirm the findings obtained from CD169$^+$ THP1/PMA macrophages,
390 we pre-treated primary MDMs from multiple donors with RDV for 30 minutes prior to
391 infection with SARS-CoV-2. Total RNA was harvested and subsequently analyzed by RT-
392 qPCR to determine fold-induction of IL-6, TNFα, IL-1β, and IFNλ1 mRNA expression at
393 indicated timepoints (**Fig. 5G**). Similar to the observations in CD169$^+$ THP1/PMA
394 macrophages (**Fig. 5B**), SARS-CoV-2 infection induced IL-6, TNFα, IL-1β, and IFNλ1
395 mRNA in primary MDMs (**Fig. 5G**), with proinflammatory cytokine induction observed as
396 early as 2 hpi. Furthermore, induction of pro-inflammatory responses in primary MDMs
397 was significantly suppressed by RDV pre-treatment (**Fig. 5G**), confirming that
398 establishment of infection and initiation of viral transcription is required for macrophage-
399 intrinsic innate immune activation. Collectively, these findings suggest that CD169-

400 mediated restricted SARS-CoV-2 infection of macrophages induces robust inflammatory
401 responses.
402
403 **Cytosolic RNA sensing by RIG-I and MDA-5 is required for SARS-CoV-2 induced**
404 **inflammation in macrophages**
405 Since innate immune activation in THP1/CD169 cells and primary MDMs requires the
406 expression of *de novo* viral RNAs (**Fig. 5B** and **G**), we next sought to delineate the nucleic
407 acid sensing mechanism required for the detection of SARS-CoV-2 gRNA and sgRNAs in
408 CD169^{+} THP1/PMA macrophages. Depending on the specific pathogen-derived cytosolic
409 nucleic acids, numerous host sensors can detect and trigger innate immune activation via
410 the MAVS and/or STING pathways (67). Viral RNAs can be sensed by RIG-I-like receptors
411 (RLRs) or endosomal toll-like receptors (TLRs) to activate MAVS or TRIF, respectively,
412 leading to induction of pro-inflammatory cytokines (68). Innate immune sensing of SARS-
413 CoV-2 RNAs by RLRs such as RIG-I and MDA-5, or endosomal TLRs (TLR7/8), has been
414 previously proposed (69, 70). It has also been hypothesized that SARS-CoV-2-induced
415 mitochondrial damage and release of mitochondrial DNA into the cytosol, a cellular stress
416 response, could trigger cGAS/STING sensing pathway in infected cells (71, 72). To
417 investigate which of the nucleic acid sensing pathways are involved in sensing abortive
418 SARS-CoV-2 infection in macrophages, we stably knocked-down expression of either
419 RIG-I, MDA-5, UNC93B1 (a protein required for TLR3/7/9 trafficking to endosomes, (73)),
420 MAVS or STING in CD169^{+} THP1/PMA cells through shRNA-based lentiviral transduction.
421 Upon successful selection of transduced cells targeted for knockdown of individual host
422 proteins, we observed robust decrease in both mRNA (**Fig. 6A**) and protein (**Fig. 6B**)
423 expression. Knock-down of RIG-I, MDA-5, UNC93B1, MAVS or STING in THP1/CD169

424 macrophages did not impact infection efficiency of SARS-CoV-2, as shown by RT-qPCR
425 analysis of viral gRNA and sgRNAs in each cell line (**Fig. 6C** and **D**). While knockdown of
426 UNC93B1 in virus-infected THP1/PMA CD169$^+$ cells had negligible impact on induction of
427 pro-inflammatory cytokines (IL-6, TNFα, IL-1β and IFNλ1) compared to scramble control
428 cells, depletion of either RIG-I or MDA-5 led to dramatic reduction in pro-inflammatory
429 cytokine expression to near background levels, suggesting both cytosolic viral RNA
430 sensors, but not endosomal TLRs, are required for innate immune sensing of SARS-CoV-
431 2 transcripts (**Fig. 6E-H**). Furthermore, knock-down of MAVS but not STING, completely
432 abrogated SARS-CoV-2- induced innate immune activation in THP1/PMA macrophages,
433 further confirming the requirement of cytosolic viral RNA sensing for induction of pro-
434 inflammatory cytokines.
435
436 **MAVS is essential for SARS-CoV-2 RNA-induced innate immune activation in both**
437 **non-productively and productively infected THP1/PMA macrophages**
438 We next sought to determine if MAVS was required for induction for pro-inflammatory
439 responses not only in CD169-mediated abortive infection but also in ACE2-mediated
440 productive infection of macrophages with SARS-CoV-2. Parental THP1 cells or those
441 expressing CD169, ACE2, or both CD169 and ACE2 were transduced with lentivectors
442 expressing scramble shRNAs (control) or MAVS-specific shRNAs, which led to robust
443 knock-down of MAVS protein expression in all cell lines (**Fig. 7A**). While MAVS depletion
444 did not affect subsequent SARS-CoV-2 infection of CD169$^+$, ACE2$^+$ or CD169$^+$/ACE2$^+$
445 THP1/PMA cells, as quantified by total SARS-CoV-2 N gRNA transcripts (**Fig. 7B**),
446 induction of pro-inflammatory cytokines (IL-6, TNFα, IL-1β and IFNλ1) was significantly
447 attenuated in both productively (ACE2$^+$, CD169$^+$/ACE2$^+$) and abortively (CD169$^+$) infected

448 THP1/PMA macrophages upon MAVS knockdown (**Fig. 7C**). These results suggest that
449 MAVS plays a pivotal role in pro-inflammatory cytokine induction in both ACE2-dependent
450 and independent (CD169-mediated) SARS-CoV-2 infection of THP1/PMA macrophages.
451 Taken together, these findings suggest that CD169-dependent establishment of abortive
452 SARS-CoV-2 infection in macrophages triggers RIG-I/MDA-5 mediated sensing of viral
453 gRNA and sgRNAs and MAVS-dependent inflammatory cytokines induction, which might
454 contribute to the dysregulated hyper-immune phenotype of inflammatory macrophages
455 and severity of COVID-19 disease.
456

457 **Discussion**

458 Though monocytes and macrophages have not been directly implicated in productive
459 SARS-CoV-2 infection, several reports have provided evidence of SARS-CoV-2 RNA and
460 antigen in circulating monocytes, macrophages, and tissue-resident alveolar
461 macrophages, although these cells are not known to express ACE2 (**Fig. 1** and (30).
462 Importantly, macrophage-intrinsic inflammatory phenotype in lung BALF samples has
463 been associated with COVID-19 disease severity (7). In this study, we examined the
464 mechanisms by which macrophages potentially contribute to inflammation during SARS-
465 CoV-2 infection, using THP1/PMA and primary human macrophages expressing a
466 myeloid cell-specific receptor, CD169, in the presence or absence of ACE2. We showed
467 that CD169 expression mediated entry and fusion of SARS-CoV-2 S-pseudotyped
468 lentivirus in both CD169^{+} THP1/PMA and primary macrophages. It was recently reported
469 that CD169 expressed on dendritic cells captures SARS-CoV-2 particles via binding to
470 gangliosides exposed on the viral membrane, such as GM1, and mediates trans infection
471 of bystander cells (19). Our results, however, suggest that CD169 can also bind the

472 sialylated SARS-CoV-2 S protein. Other studies, including ours, have also described
473 glycan-dependent interactions of SARS-CoV-2 S protein with C-type lectin receptors (DC-
474 SIGN, LSIGN) and Tweety family member 2 (TTYH2) (17, 19, 74). While ACE2-
475 independent mechanisms of SARS-CoV-2 interactions with myeloid cells can be mediated
476 by diverse virus particle-associated antigens (gangliosides, mannosylated S and
477 sialylated S), our results suggest that CD169-S interaction is sufficient to promote virus
478 entry and fusion in macrophages in an ACE2-independent manner.

479 Pre-treatment with antibodies targeting SARS-CoV-2 S NTD and inhibition of
480 endosomal cathepsins markedly attenuated S-pseudotyped lentiviral infection in CD169^{+}
481 macrophages, suggesting that S interaction with CD169 and virus entry mechanisms are
482 distinct to those targeted by ACE2. This is in agreement with recent data suggesting that
483 binding epitopes for myeloid cell-specific receptors are found outside the ACE2 binding
484 domain in the spike receptor binding domain (RBD) (17). Consequently, the results
485 presented here have implications for antibody treatment in COVID-19 patients, as current
486 therapies are primarily focused on RBD-binding antibodies (57, 75-78). Targeting non-
487 RBD epitopes to disrupt ACE2-independent entry in CD169^{+} myeloid cells could serve as
488 a potential mechanism for preventing myeloid cell-intrinsic immune activation. Indeed,
489 broadly neutralizing nanobodies and potent NTD-targeting neutralizing antibodies from
490 COVID-19 patients that block both ACE2-dependent and ACE2-independent entry were
491 recently described (57, 75-78) and might provide potential benefit in also suppressing
492 macrophage-intrinsic inflammatory signature.

493 Efficiency of CD169-mediated S-pseudotyped infection in macrophages was
494 similar to that mediated by ACE2 (**Fig. 2**). Importantly, CD169-mediated SARS-CoV-2
495 entry was also similarly efficacious to that mediated by ACE2 in THP1/PMA macrophages,

496 as evident by the similar number of viral gRNA copies at 6 hpi (**Fig. 4C**), though viral
497 gRNA and sgRNA expression in THP1/CD169+ macrophages was attenuated at later
498 times post infection (**Fig. 4E** and **F**). SARS-CoV-2 RNA synthesis occurs within ER-
499 derived double-membrane vesicles (DMVs). The establishment of viral replication
500 factories within DMVs in the cytoplasm of infected cells is induced by viral proteins, in
501 concert with cellular factors (64). Previous reports have utilized dsRNA staining to
502 visualize these viral replication organelles (79). While viral dsRNA+ cells were observed
503 in a minor percentage of THP1/CD169^{+} macrophages at 6 hpi (**Fig. 3B**), no further
504 increase was observed. In contrast, majority of the virus-exposed THP1/ACE2 and
505 THP1/CD169/ACE2 macrophages were dsRNA+ by 24 hpi (**Fig. 3C** and **D**). Since this
506 staining strategy requires expression of high levels of viral dsRNA, the paucity of dsRNA
507 positivity in SARS-CoV-2 infected CD169^{+} macrophages might reflect selective
508 impairment of formation of DMVs. However, expression of ACE2 in THP-1/PMA and
509 primary MDMs restored infectious virus particle production, suggesting that macrophages
510 are permissive to SARS-CoV-2 replication when entry is facilitated by ACE2. Considering
511 that both CD169 and ACE2 mediated virus entry resulted in similar levels of SARS-CoV-
512 2 gRNA at 6 h pi but only ACE2-mediated virus entry resulted in productive virus infection,
513 these results implicate a hitherto unappreciated post-entry role for ACE2 in virus life cycle
514 in macrophages. Interestingly, expression of both CD169 and ACE2 in macrophages led
515 to enhanced kinetics and magnitude of infection, reflecting an entry-enhancing effect of
516 CD169 even in the context of ACE2-mediated infection, though the mechanism of
517 enhanced kinetics of SARS-CoV-2 replication in CD169^{+}/ACE2^{+} macrophages remains
518 unclear.

519 Despite lack of productive infection, cytoplasmic viral RNA expression in CD169$^+$
520 macrophages potently induced expression of pro-inflammatory cytokines and chemokines.
521 Thus, CD169-mediated viral entry does not simply enable viral uptake by macrophages
522 but also initiates SARS-CoV-2 replication and triggers inflammatory cytokine expression.
523 Critically, pre-treatment with RDV not only blocked *de novo* viral RNA expression but also
524 significantly reduced pro-inflammatory cytokine expression in non-productively infected
525 CD169$^+$ macrophages (**Fig. 5**), suggesting that neither S protein interaction with cell
526 surface receptors nor TLR-mediated sensing of incoming viral genome in the endosomal
527 lumen is sufficient to trigger robust innate immune activation. Rather newly synthesized
528 viral RNAs (negative sense gRNA, dsRNA, and/or sgRNAs) are the key drivers of innate
529 immune activation in non-productively infected macrophages. While mRNA expression of
530 type I and III IFNs peaked at 24 hpi and correlated with the extent of virus replication
531 (marked by high levels of IFNλ1 mRNA expression at 24 hpi, **Fig. 5A**), pro-inflammatory
532 cytokines, IL-6 and TNFα mRNAs were induced to comparable levels in both productively
533 (ACE2$^+$ and CD169$^+$/ACE2$^+$) and non-productively (CD169$^+$) infected macrophages (**Fig.**
534 **5A**). Interestingly, significant induction of IL-1β and IL-18 was only observed in CD169+
535 THP1/PMA and primary macrophages (**Fig. 5D** and **G**), suggesting that CD169-mediated
536 virus entry and infection establishment uncouples induction of inflammatory responses
537 from robust viral replication. Since transcriptional priming of the inflammasome
538 components, IL-1β and IL-18, was only observed in abortively infected CD169$^+$
539 THP1/PMA macrophages (**Fig. 5A**), SARS-CoV-2 infected and primed macrophages
540 might thus uniquely contribute to the inflammasome activation upon delivery of secondary
541 activation signals and perpetuate the hyper-inflammatory inflammatory phenotype.

542 Previous reports have implicated both RIG-I and MDA-5 in cytosolic sensing of
543 SARS-CoV-2 RNAs (80, 81), although the primary RNA sensor might be cell-type
544 dependent. For instance, recent studies have implicated MDA-5 as the primary viral RNA
545 sensor in lung epithelial cells (82), while other studies have found both MDA-5 and RIG-I
546 sense SARS-CoV-2 infection in Calu-3 cells (81, 83). Our results implicate both RIG-I and
547 MDA-5 in SARS-CoV-2 RNA sensing in macrophages, as knockdown of either RIG-I or
548 MDA-5 significantly attenuated inflammatory cytokine induction in CD169^{+} macrophages.
549 Despite previous studies suggesting that induction of IL-6 and TNFα might be MAVS-
550 independent (84), knock-down of MAVS abrogated viral RNA sensing and induction of
551 NF-κB-dependent inflammatory cytokines (IL-6, TNFα, IL-1β, IL-18) in productively
552 infected (ACE2^{+}) and abortively infected (CD169^{+}) macrophages. Thus, we propose a co-
553 sensing requirement of both RIG-I and MDA-5 for detecting viral replication intermediates
554 and a pivotal role of MAVS in signal transduction in non-productively infected CD169^{+}
555 macrophages. Intriguingly, induction of RIG-I/MDA-5/MAVS-dependent IFNβ and ISG
556 expression was muted compared to the robust upregulation of NF-kB-dependent pro-
557 inflammatory cytokines in SARS-CoV-2 infected CD169^{+} macrophages. Since RLR
558 relocalization to the mitochondrial, peroxisomal or ER membranes is thought to initiate
559 robust MAVS-dependent IRF3 activation (85-87), it is tempting to speculate that during
560 restricted SARS-CoV-2 infection and diminished expression of viral RNAs, cytosolic
561 retention or altered intracellular localization of RLRs might control the strength and
562 specificity of downstream responses and favor NF-kB-dependent proinflammatory
563 cytokine expression. Future studies will need to address spatiotemporal dynamics of RIG-
564 I/MDA-5/MAVS interactions upon SARS-CoV-2 RNA sensing in macrophages.

565 SARS-CoV-2 RNA infection of lung epithelial cells can contribute to innate immune
566 activation, inflammation, recruitment of inflammatory monocytes and macrophages to the
567 alveolar space, and activation of tissue-resident alveolar macrophages (80, 81). Alveolar
568 macrophages and airway epithelial cell-associated macrophages, which are uniquely
569 positioned as gatekeepers to intercept invading pathogens from the bronchiolar airways,
570 constitutively express CD169 (58, 88), an ISG, whose expression can be further induced
571 by type I and type III IFNs (39, 50, 51, 89). While therapeutic use of both type I and III
572 IFNs have been proposed, clinical benefit has proven inconclusive (90-92), presumably
573 related to timing of the IFN response. For instance, a delayed and persistent type I IFN
574 response without resolution has been correlated with disease severity and mortality in
575 patients with COVIID-19 (68). As was recently suggested (93), the pathological outcomes
576 associated with a delayed type I IFN response might be partly due to the type I IFN-
577 induced expression of SARS-CoV-2 entry receptors, such as CD169, in
578 monocytes/macrophages and increased virus uptake and amplification of inflammatory
579 responses.

580 Treatment of COVID-19 patients with remdesivir has been shown to significantly
581 shorten recovery time and reduce lower respiratory tract infections, despite having
582 minimal impact on viremia (94, 95). Notably, combination therapy with Baricitinib, an anti-
583 inflammatory drug led to further improvement in clinical status and significantly lowered
584 serious adverse events (96). Therefore, targeting macrophage-intrinsic innate immune
585 activation by either blocking macrophage-specific receptors which can mediate SARS-
586 CoV-2 uptake, or through administration of RIG-I/MDA-5 antagonists present a novel
587 therapeutic strategy for combating hyperinflammation in COVID-19 patients. However,
588 further research is needed to better understand the mechanisms of ACE2-independent

589 CD169-mediated SARS-CoV-2 infection of macrophages, the post-entry restrictions to
590 virus replication, and the viral determinants that trigger innate immune activation.

591

592 **Figure Legends**

593 **Figure 1. ACE2-independent SARS-CoV-2 entry in macrophages.**

594 (**A-B**) Representative ACE2 mRNA expression (**A**) and flow cytometry profiles showing
595 ACE2 surface expression (**B**) of HEK293T cells stably expressing ACE2 and primary
596 MDMs from multiple donors. (**C-D**) Parental (vector) and transduced (ACE2) HEK293T
597 cells (**C**) and primary MDMs from 3 donors (**D**) were infected with S-pseudotyped lentivirus
598 (20 ng based on $p24^{Gag}$), in the absence or presence of cathepsin inhibitor (E64D) or
599 TMPRSS2 inhibitor (Camostat), and infection was quantified by measuring luciferase
600 activity at day 3 post-infection. Mock: no virus added, DMSO: no-treatment. The means ±
601 SEM from at least 3 independent experiments are shown. *P*-values: paired t-test, two-
602 tailed comparing to vector control (**C**), or one-way ANOVA followed by the Dunnett's post-
603 test comparing to DMSO (**D**). ***: $p < 0.001$, ****: $p < 0.0001$, ns: not significant.

604

605 **Figure 2. CD169 is a SARS-CoV-2 attachment and entry factor in macrophages.**

606 (**A**) Binding of SARS-CoV-2 S protein (Wuhan isolate) to THP1 monocytes expressing wt
607 CD169, mutant CD169 (R116A), ACE2, or both wt CD169 and ACE2 (CD169/ACE2). (**B**)
608 THP1/PMA macrophages were infected with S-pseudotyped lentivirus (20 ng $p24^{Gag}$), and
609 infection was quantified by measuring luciferase activity at 3 dpi. Relative light units
610 (RLUs) from each cell line were normalized to no virus control (mock). The means ± SEM
611 are shown from at least five independent experiments. (**C**) Primary MDMs from three
612 donors overexpressing either CD169 or ACE2, or control were infected with S-

613 pseudotyped lentivirus (20 ng $p24^{Gag}$) for 3 days, followed by analysis of luciferase activity
614 in whole cell lysates. (**D**) Untransduced primary MDMs (representative of 3 donors) were
615 pre-treated with anti-CD169 mAb (20 µg/ml, 7D2), IgG1, or empty media for 30 min at 4°C
616 prior to infection with S-pseudotyped lentivirus (20 ng $p24^{Gag}$) for 3 days, followed by
617 analysis of luciferase activity. RLUs from each donor in each group were normalized to
618 no virus control (mock). The means ± SEM from at least 3 independent experiments are
619 shown. *P*-values: paired t-test, two-tailed (**A**), one-way ANOVA followed by the Dunnett's
620 post-test (**B**) or Tukey's post-test comparing to parental (THP1) cells (**C**) or each pre-
621 treatment condition (D). ***: $p < 0.001$, ****: $p < 0.0001$, ns: not significant.
622
623 **Figure 3. SARS-CoV-2 establishes restricted infection in $CD169^{+}$ macrophages.**
624 (**A-D**) Representative immunofluorescence images (100x) of THP1/PMA macrophages
625 infected with SARS-CoV-2 (MOI=1) and stained for nucleus (DAPI, blue), SARS-CoV-2
626 dsRNA (green), and SARS-CoV-2 nucleocapsid (red), at indicated timepoints post
627 infection. Images shown for each THP1 cell line; untransduced control (parental, **A**),
628 CD169-expressing (**B**), ACE2-expressing (**C**), and CD169/ACE2 double expressing (**D**).
629 Bar=25 µm. (**E-F**) Culture supernatants from SARS-CoV-2 infected THP1/PMA cells (**E**)
630 and primary MDMs (**F**) were harvested at 24 hpi and viral titers determined by $TCID_{50}$
631 assay. The means ± SEM from at least 3 independent experiments are shown. LOD: limit
632 of detection of assay.
633
634 **Figure 4. CD169-mediated SARS-CoV-2 infection of macrophages results in**
635 **restricted viral RNA expression.**

636 (**A**) Single molecule RNA FISH analysis for viral RNAs using ORF1a specific probe set
637 (labeled with Texas Red) and N specific probe set (labelled with TMR) in SARS-CoV-2
638 infected THP1/PMA macrophages (MOI=10, 24 hpi) (**B**) Percentage of infected cells
639 based on the presence of SARS-CoV-2 RNAs determined from 10-20 independent fields,
640 (representative field shown in **A**). Data are representative of 2 independent experiments.
641 Bar=25 μm. (**C-F**) THP1/PMA macrophages infected with SARS-CoV-2 (MOI=1) in the
642 absence (**C-D**) or presence (**E-F**) of remdesivir (RDV, 1 μM). Total RNA was harvested at
643 indicated times post-infection and expression of viral transcripts was quantified by RT-
644 qPCR. Replication kinetics of SARS-CoV-2 was quantified by (**C**) total N amplification
645 (values from each group normalized to mock (uninfected) or (**D**) negative strand genome
646 from strand-specific reverse-transcription and ORF1b amplification (mean Ct values for
647 each condition). Expression of total N mRNA (**E**) and Envelope sgRNA (**F**) transcripts in
648 THP1/PMA cells pretreated with RDV was analyzed at 24 hpi. Values from each group
649 normalized to mock (uninfected). (**G-H**) MDMs from multiple donors were infected with
650 SARS-CoV-2 (MOI=1), in the absence or presence of RDV (1 μM), and viral replication
651 kinetics analyzed by RT-qPCR at indicated timepoints for total N mRNA (**G**), Envelope
652 sgRNA (**H**) transcripts. The means ± SEM are shown from at least 3 independent
653 experiments, each symbol represents a different donor. Significant differences between
654 groups were determined by one-way ANOVA followed by the Dunnett's post-test (**E-F**),
655 comparing to control parental THP1 cells. *P*-values: *<0.1; **<0.01; ***<0.001; ****<0.0001.
656

657 **Figure 5. Restricted expression of SARS-CoV-2 gRNA and sgRNA induces pro-**
658 **inflammatory responses in non-productively infected macrophages**

659 (**A-B**) PMA-differentiated THP1 cells from parental (THP1) or those expressing CD169,
660 ACE2, or CD169/ACE2 were infected with SARS-CoV-2 (MOI=1, 24 hpi) in the absence
661 or presence of RDV (1 μM, 30 mins), and total RNA was quantified by RT-qPCR for pro-
662 inflammatory cytokines and ISGs. Values were normalized to mock-infected control for
663 each group. Fold-induction for indicated pro-inflammatory cytokines (**A**, top panel) and
664 ISGs (**A**, bottom panel) in the absence of RDV, or in the presence of RDV (**B**). (**C-F**)
665 Kinetics of pro-inflammatory cytokine/ISG mRNA expression in the absence of RDV in
666 parental (**C**), CD169-expressing (**D**), ACE2-expressing (**E**), and CD169/ACE2-expressing
667 (**F**) PMA-differentiated THP1 cells. (**G**) MDMs from multiple donors were infected with
668 SARS-CoV-2 (MOI=1, 24 hpi) and total RNA analyzed by RT-qPCR. MDMs were pre-
669 treated with DMSO (control) or RDV (1 μM, 30 mins) prior to infection, and fold-induction
670 of indicated cytokine mRNAs normalized to mock-infected controls from each donor. RDV:
671 Remdesivir, ISGs: interferon-stimulated genes. Minus sign represents DMSO, and plus
672 sign represents RDV pre-treatment. The means ± SEM from at least 3 independent
673 experiments are shown. Significant differences between groups were determined by one-
674 way ANOVA followed by the Dunnett's post-test between groups (**A**) or Tukey's multiple
675 comparisons test within groups (**B** and **G**), comparing to parental THP1 (**A**) or DMSO-
676 treated (**B**, **G**) in each group. *P*-values: *<0.1; **<0.01; ***<0.001; ****<0.0001, ns: not
677 significant.
678
679 **Figure 6. Cytosolic RNA sensing by RIG-I and MDA-5 is required for SARS-CoV-2**
680 **induced innate immune responses in macrophages**
681 (**A-B**) CD169-expressing THP1 monocytes were transduced with lentivectors expressing
682 shRNA against non-specific control (scramble), or specific sequences against STING,

683 UNC93B1, MAVS, RIG-I, and MDA-5. Knockdown of host proteins targeted by shRNAs
684 compared to scramble analyzed by RT-qPCR (**A**), and immune blotting (**B**). (**C-H**) CD169$^+$
685 THP1 cells with stable knockdown of target genes were PMA-differentiated and infected
686 with SARS-CoV-2 (MOI=1, 24 hpi), and total RNA was analyzed by RT-qPCR for total
687 nucleocapsid (gRNA) (**C**), sgRNA (Envelope) (**D**), and pro-inflammatory cytokines/ISGs,
688 IL6, TNFα, IL-1β and IFNλ1 (**E-F**), normalized to mock-infected controls for each group.
689 Each knockdown is represented by different colors as in **A**. The means ± SEM from 3
690 independent experiments are shown, and significant differences were determined by one-
691 way ANOVA followed by the Dunnett's post-test comparing to scramble THP1 (**C**-**D**), or
692 by two-way ANOVA followed by Bonferroni post-test comparing Mock to CoV-2$^+$ in each
693 group (**E**-**H**). *P*-values: *<0.1; **<0.01; ***<0.001; ****<0.0001), ns: not significant.
694
695 **Figure 7. MAVS is essential for SARS-CoV-2 RNA-induced inflammatory responses**
696 **in macrophages.**
697 (**A**) Parental (THP1) monocytes and those expressing CD169, ACE2, or CD169/ACE2
698 were transduced with lentivectors expressing shRNA against scrambled sequence (-), or
699 MAVS sequence (+), and knockdown of MAVS in each cell line analyzed by immune
700 blotting (**A**, left panel), and quantified (**A**, right panel). (**B-C**) THP1 monocytes with stable
701 MAVS knockdown were PMA-differentiated and infected with SARS-CoV-2 (MOI=1, 24
702 hpi), and total RNA analyzed by RT-qPCR for (**B**) total viral transcripts (nucleocapsid),
703 and (**C**) IL6, TNFα, IL-1β and IFNλ1 mRNA expression, normalized to mock-infected
704 controls for each group. The means ± SEM from 3 independent experiments are shown,
705 and significant differences were determined by one-way ANOVA followed by the Tukey-

706 Kramer post-test within groups (**B**, and **C**), or Dunnett's post-test between groups (**C**). *P*-
707 values: *<0.05; **<0.01; ***<0.001; ****<0.0001, ns: not significant.
708

709 ## Supplementary Figure Legends

710 **Figure S1. Expression of endogenous TMPRSS2 and Cathepsin-L in human**
711 **macrophages**

712 (**A-B**) Western blot analysis for total TMPRSS2 (**A**) and Cathepsin-L (**B**) expression in
713 wildtype and transduced HT-29 cells (control), HEK293T, THP-1/PMA, and primary MDMs
714 from multiple donors. β-actin was probed as a loading control.
715

716 **Figure S2. Infection of primary MDMs by S-pseudotyped lentivirus is blocked by**
717 **anti-SARS-CoV-2 NTD antibodies.**

718 SARS-CoV-2 S-pseudotyped lentivirus (20 ng) was pre-incubated with indicated anti-
719 Spike neutralizing antibodies for 30 mins at 37°C, followed by infection of primary MDMs
720 for 3 days. Relative infection quantified by luciferase activity from whole cell lysates. NT:
721 no-treatment with neutralizing antibody. Data are representative of 2 independent
722 experiments, from 3 different donors each. Mock: no virus added, PBS: no-pre-incubation
723 of virus with antibody. The means ± SEM are shown. *P*-values: one-way ANOVA followed
724 by the Dunnett's post-test comparing to untreated (PBS) control, *: $p < 0.05$, **: $p < 0.01$,
725 ***: $p < 0.001$, ****: $p < 0.0001$.
726

727 **Figure S3. Expression profiles of human CD169 and ACE2 in THP1 monocytes and**
728 **primary MDMs.**

729 (**A**) Representative flow cytometry profiles of different THP1 cell lines and primary
730 MDMs stained for surface expression of CD169 and ACE2. (**A**) Transduced THP1 cell
731 lines stably expressing wild type (wt) CD169, mutant (R116A) CD169, ACE2, or both wt
732 CD169 and ACE2. (**B**) Untransduced primary MDMs from multiple donors showing
733 differential expression of endogenous CD169. After 5-6 days of macrophage
734 differentiation, cells were either unstained or stained with anti-human CD169 antibody,
735 and surface expression analyzed by flow cytometry. (**C-D**) Representative flow
736 cytometry profiles of primary MDMs transduced with wt CD169 (**C**) or ACE2 (**D**)
737 lentiviruses compared to negative (vector only) control.
738
739 **Figure S4. Exogenous expression of ACE2 in primary MDMs rescues SARS-CoV-2**
740 **replication.**
741 Representative immunofluorescence images (20x) of primary MDMs infected with SARS-
742 CoV-2 (MOI=1) and stained for nucleus (DAPI, blue), and SARS-CoV-2 nucleocapsid
743 protein (red), at 24 hpi. Images from primary MDMs overexpressing either CD169 or ACE2
744 compared to vector-only control were captured and represent at least 3 independent
745 donors. Bar = 25 μm.
746
747 **Figure S5. CD169 and ACE2-dependent temporal enhancement of SARS-CoV-2**
748 **RNAs in THP1/PMA macrophages.**
749 Single molecule FISH analysis of viral +gRNA using high fidelity probes in SARS-CoV-2
750 (MOI=10) infected THP1/PMA macrophages at the indicated timepoints. Representative
751 fields of cells were hybridized at indicated times with 7 sets of smFISH probes labeled

752 with Quasar670 targeting the + strand of SARS-CoV-2 ORF1a (NSP1-3) and N
753 transcripts. Data are representative of 2 independent experiments. Bar = 50μM
754
755 **Figure S6. Lack of pro-inflammatory cytokine expression in THP1/PMA**
756 **macrophages infected with SARS-CoV-2 S-pseudotyped lentiviruses.**
757 PMA-differentiated THP1 cell lines infected with SARS-CoV-2 S-pseudotyped lentivirus
758 (20 ng) and total RNA harvested at 2 dpi, followed by qRT-PCR analysis. Fold expression
759 of indicated cytokines normalized to mock (uninfected) condition in each group. Data are
760 representative of at least 3 independent experiments. The means ± SEM from 3
761 independent experiments are shown.
762

763 **Materials & Methods**

764 **Ethics statement.** This research has been determined to be exempt by the Institutional
765 Review Board of the Boston University Medical Center since it does not meet the definition
766 of human subjects research, since all human samples were collected in an anonymous
767 fashion and no identifiable private information was collected.

768

769 **Plasmids**

770 The SARS-CoV-2 S/gp41 expression plasmid was a gift from Dr. Nir Hachoen at the Broad
771 Institute, and has previously been described (74). For ACE2 lentiviral transduction in
772 THP1 cells, we used a lentiviral plasmid expressing ACE2 and the puromycin resistant
773 gene (Addgene #145839, hereafter pLenti-ACE2-IRES-puro). Generation of wildtype and
774 mutant (R116A) human CD169 plasmids (LNC-CD169) was previously described and
775 validated (39). For transduction of primary MDMs, a 3' LTR-restored lentiviral expression
776 vector (Addgene #101337, hereafter LV-3'LTR) expressing a GFP reporter was used to
777 express ACE2 or CD169. For ACE2 cloning, the NotI-XhoI fragment from pLenti-ACE2-
778 IRES-puro was inserted into the LV-3'LTR backbone. For cloning CD169 into LV-3'LTR
779 vector, a BglII-AgeI fragment from LNC-CD169 was inserted into LV-3'LTR vector. HIV-1
780 packaging plasmid psPAX2 and VSV-G expression constructs have been previously
781 described (39). All lentiviral vectors (pLKO.1) expressing shRNAs used for knockdown of
782 host proteins were purchased from Sigma.

783

784 **Cells**

785 HEK293T cells (ATCC) were maintained in DMEM (Gibco) containing 10% heat-
786 inactivated fetal bovine serum (FBS) (Gibco) and 1% pen/strep (Gibco) (39, 40, 97). Vero

787 E6 cells (ATCC CRL-1586) were maintained in DMEM supplemented with 10% FBS and
788 100 µg/mL primocin. THP1 cells (ATCC) were maintained in RPMI/1640 (Gibco)
789 containing 10% FBS and 1% pen/strep (50). THP1 cells stably expressing CD169 have
790 previously been described (39). To generate HEK293T/ACE2$^+$, THP1/ACE2$^+$ and
791 THP1/CD169$^+$/ACE2$^+$ cells, HEK293T, THP1 or THP1/CD169 cells were transduced with
792 pLenti-ACE2-IRES-puro lentivector and cultured in puromycin-containing media (2 µg/ml).
793 Cells with robust surface expression of ACE2 and CD169/ACE2 (double-positive) were
794 sorted using a MoFlo cell sorter (Beckman Coulter) and cultured in puromycin-
795 supplemented media. All cell lines are routinely tested for mycoplasma contamination and
796 confirmed negative. For THP1 monocyte to macrophage differentiation, THP1 cells were
797 stimulated with 100 nM PMA (Sigma-Aldrich) for 48 hours. Human monocyte-derived
798 macrophages (MDMs) were derived from CD14$^+$ peripheral blood monocytes by culturing
799 cells in RPMI/1640 (Gibco) media containing 10% heat-inactivated human AB serum
800 (Sigma-Aldrich) and recombinant human M-CSF (20 ng per ml; Peprotech) for 5-6 days,
801 (55). To generate MDMs expressing ACE2 or overexpressing CD169, cells were co-
802 infected with ACE2 or CD169 expressing lentiviruses (100 ng based on p24^{gag} ELISA per
803 1x10^6 cells) and SIV3+ (Vpx expressing) VLPs. ACE2 and CD169 surface expression was
804 determined by flow cytometry 3 days post transduction.
805
806 **Viruses**
807 SARS-CoV-2 stocks (isolate USA_WA1/2020, kindly provided by CDC's Principal
808 Investigator Natalie Thornburg and the World Reference Center for Emerging Viruses and
809 Arboviruses (WRCEVA)) were grown in Vero E6 cells (ATCC CRL-1586) cultured in
810 Dulbecco's modified Eagle's medium (DMEM) supplemented with 2% fetal FBS and 100

811 μg/mL primocin. To remove confounding cytokines and other factors, viral stocks were
812 purified by ultracentrifugation through a 20% sucrose cushion at 80,000xg for 2 hours at
813 4°C (60). SARS-CoV-2 titer was determined in Vero E6 cells by tissue culture infectious
814 dose 50 ($TCID_{50}$) assay using the Spearman Kärber algorithm. All work with SARS-CoV-
815 2 was performed in the biosafety level 4 (BSL4) facility of the National Emerging Infectious
816 Diseases Laboratories at Boston University, Boston, MA following approved SOPs.
817 Generation of SARS-CoV-2 S-pseudotyped lentiviruses expressing spike glycoprotein
818 has previously been described (74). Briefly, HEK293T cells were co-transfected with HIV-
819 1 reporter plasmid containing a luciferase reporter gene in place of the *nef* ORF and
820 SARS-CoV-2 S (74). To generate ACE2 or CD169 expressing recombinant lentiviruses,
821 LV-3'LTR lentivectors expressing either empty vector, ACE2, or CD169, were co-
822 transfected with psPax2 (HIV Gag-pol packaging plasmid) and H-CMV-G (VSV-G
823 envelope-expressing plasmid) in HEK293T cells by calcium phosphate-mediated
824 transfection (98). Virus-containing supernatants were harvested 2 days post-transfection,
825 cleared of cell debris by centrifugation (300xg, 5 min), passed through 0.45 μm filters,
826 aliquoted and stored at -80 °C until use. Lentivirus titers were determined by a $p24^{gag}$
827 ELISA (98).
828
829 **Infection**
830 For RNA analysis, $1x10^6$ cells (THPI/PMA, MDMs, HEK293T) were seeded in 12-well
831 plates. For smFISH analysis, $1x10^6$ cells were seeded in 6-well plates containing 3-4
832 coverslips per well. The next day, cells were infected with purified SARS-CoV-2 at the
833 indicated multiplicity of infection (MOI). At indicated time points, the cells were either lysed
834 with TRIzol (for total RNA analysis) or fixed in 10% neutral buffered formalin for at least 6

835 hours at 4°C and removed from the BSL-4 laboratory for staining and imaging analysis in
836 accordance with approved SOPs. For SARS-CoV-2 S-pseudotyped lentiviral infections of
837 THP1/PMA macrophages or MDMs, $1x10^5$ cells were seeded in 96-well plates, and
838 infected via spinoculation the following day with 10-20 ng ($p24^{Gag}$) of purified S-
839 pseudotyped lentivirus and SIV_{mac} Vpx VLPs (1 hr at RT and 1100 x g), as previously
840 described (55). Incubation with virus was continued for 4 additional hours at 37˚C, cells
841 were then washed to remove unbound virus particles, and cultured for 2-3 days. For
842 CD169 blocking experiments, primary MDMs from 3 different donors were pre-incubated
843 with 20 µg/ml anti-CD169 antibody (HSn 7D2, Novus Biologicals) or IgG1k (P3.6.2.8.1,
844 eBioscience) for 30 min at 4˚C prior to infection. For anti-spike neutralizing experiments,
845 virus-containing media were pre-incubated with antibodies targeting SARS-CoV-2 spike
846 NTD for 30 min at 37˚C prior to infection. At indicated timepoints, cells are lysed, cell
847 lysates were analyzed for luciferase activity using the Bright-Glo luciferase assay kit
848 (Promega), as previously described (36). The SARS-CoV-2 neutralizing antibodies was
849 previously characterized (57) and were a kind gift from Dr. Duane Wesemann at Harvard
850 Medical School.
851
852 **S binding**
853 To evaluate SARS-CoV-2 S binding to various THP1 monocytes expressing different
854 surface receptors, approximately $0.25x10^6$ cells from parental THP1 or those expressing
855 wt CD169, mutant CD169 (R116A), ACE2, or both wt CD169 and ACE2 were incubated
856 for 30 min at 4 °C with 2 µg of spike glycoprotein (stabilized) from Wuhan-Hu-1 SARS-
857 CoV-2 containing a C-terminal Histidine Tag, recombinant from HEK293F cells (BEI
858 resources, #NR-52397). This is followed by secondary staining for 30 min at 4˚C with

859 APC-conjugated mouse anti-His antibody (BioLegend, #362605, 1:50) or isotype control.
860 Cells were fixed with 4% PFA (Boston Bioproducts) for 30 min, and analyzed with BD
861 LSRII (BD). Data analysis was performed using FlowJo software (FlowJo).
862
863 **Immunofluorescence**
864 In brief, the cells were permeabilized with acetone-methanol solution (1:1) for 10 min at -
865 20°C, incubated in 0.1 M glycine for 10 min at room temperature and subsequently
866 incubated in 5% goat serum (Jackson ImmunoResearch) for 20 minutes at room
867 temperature. After each step, the cells were washed three times in PBS. The cells were
868 incubated overnight at 4°C with a rabbit antibody directed against the SARS-CoV
869 nucleocapsid protein (Rockland; 1:1000 dilution in 5% goat serum), which cross-reacts
870 with the SARS-CoV-2 nucleocapsid protein, as previously described (99). The cells were
871 washed four times in PBS and incubated with goat anti-rabbit antibody conjugated with
872 AlexaFluor594 for 1 hour at room temperature (Invitrogen; 1:200 dilution in blocking
873 reagent). 4',6-diamidino-2-phenylindole (DAPI; Sigma-Aldrich) was used at 200 ng/ml for
874 nuclei staining. For dsRNA staining (61), anti-dsRNA (Pan-Enterovirus Reagent, clone
875 9D5, Light Diagnostics, Millipore) antibody was used 1:2 overnight and anti-mouse-AF488
876 (Invitrogen) 1:200 dilution as secondary antibody with DAPI. Images were acquired using
877 a Nikon Eclipse Ti2 microscope with Photometrics Prime BSI camera and NIS Elements
878 AR software.
879
880 **RNA isolation and RT-qPCR**
881 Total RNA was isolated from infected cells using TRIzol reagent (Invitrogen). Reverse
882 transcription (RT) from purified RNAs was performed using oligo$(dT)_{20}$ primer (Superscript

883 III, Invitrogen) or strand-specific RT primers as previously described (100). Target mRNAs
884 were quantified using Maxima SYBR Green (Thermo Scientific), using the primer sets
885 shown in **Table 1**. Primer sequences for GAPDH, IL-6, TNFα, IL-1β, IP-10, IFNλ1, IL-18,
886 Viperin and IFNβ have been described previously (97). The C_T value was normalized to
887 that of GAPDH and represented as a relative value to a 'mock' control using the $2^{-\Delta\Delta C_T}$
888 method as described (97, 101).
889
890 **shRNA mediated knockdown**
891 Stable knockdown of host proteins in THP1 cells was carried out by transduction with
892 lentivectors expressing individual shRNAs (pLKO.1, 400 ng $p24^{Gag}$ (as measured by
893 ELISA) per 1×10^6 cells) in the presence of polybrene (Millipore). Cells were washed and
894 cultured for 5-7 days in the presence of puromycin (2 µg/ml, InvivoGen). Selected cells
895 were expanded, and knockdown confirmed and quantified by RT-qPCR or western
896 blotting, prior to any downstream experiments. All shRNA target sequences are listed in
897 **Table 2**.
898
899 **Flow cytometry**
900 To examine cell surface expression of CD169 or ACE2 in transduced THP1 or primary
901 MDMs, approximately 0.5×10^6 cells were harvested with CellStripper (Corning), stained
902 with Zombie-NIR (BioLegend, #423105, 1:250) followed by staining for 30 min at 4˚C with
903 the following antibodies; Alexa647-conjugated mouse anti-CD169 antibody (BioLegend,
904 #346006, 1:50), Alexa647-conjugated mouse anti-ACE2 antibody (R&D systems, 1:200),
905 or unconjugated goat anti-ACE2 polyclonal antibody (R&D systems, #AF933, 1:200)
906 followed by Alexa488-conjugated chicken anti-goat antibody (Invitrogen, #A-21467,

907 1:100). Cells were fixed with 4% PFA (Boston Bioproducts) for 30 min, and analyzed with
908 BD LSRII (BD). Data analysis was performed using FlowJo software (FlowJo).
909
910 **smFISH**
911 *Probe designs*. smFISH probes used to detect different RNA segments of the SARS-CoV-
912 2 genome (NCBI reference sequence: NC_045512.2) consisted of a set of 48
913 oligonucleotides, each with length of 20 nt and labeled with different fluorophores (*see*
914 *Table. 3 in supplementary information*) for target genes and sequences for each of the
915 probe sets). Probes were designed using Stellaris™ Probe Designer by LGC Biosearch
916 Technologies and purchased from Biosearch Technologies. The 3'-end of each probe was
917 modified with an amine group and coupled to either tetramethylrhodamine (TMR; Thermo
918 Fisher Scientific), Texas Red-X (Thermo Fisher Scientific), Quasar 670 (Biosearch
919 Technologies) or Cy5 (Lumiprobe). Coupled probes were ethanol precipitated and purified
920 on an HPLC column to isolate oligonucleotides linked to the fluorophore via their amine
921 groups, as previously described by *Raj et.al.* (62).
922 *Hybridization*. Cells were cultured on glass coverslips, fixed at appropriate times with 10%
923 neutral buffered formalin and permeabilized with 70% methanol. Coverslips were
924 equilibrated with hybridization wash buffer (10% formamide, 2X SSC), and then immersed
925 in 50 µL of hybridization buffer, which consisted of 10% dextran sulphate (Sigma-Aldrich),
926 1 mg/mL *Escherichia coli* transfer RNA (Sigma-Aldrich), 2 mM ribonucleoside vanadyl
927 complexes (New England Biolabs, Ipswich, MA), 0.02% ribonuclease-free bovine serum
928 albumin (Thermo Fisher Scientific), 10% formamide, 2X SSC, and conjugated probes with
929 appropriate concentration (25 ng of pooled probes). This hybridization reaction mixture
930 was first added as a droplet onto a stretched-out piece of Parafilm (Bemis in North

931 America, Oshkosh, WI) over a glass plate, and then a coverslip containing the cells was
932 placed faced down onto the droplet, followed by incubation at 37ºC overnight in a humid
933 chamber. Following hybridization, the coverslips were washed twice for 10 minutes each
934 in 1 mL of hybridization wash buffer at room temperature. The coverslips were then
935 equilibrated with mounting buffer (2X SCC, 0.4% glucose) and mounted in the mounting
936 buffer supplemented with 1 µL of 3.7 mg/mL glucose oxidase and 1 µL of catalase
937 suspension (both from Sigma-Aldrich) for each 100 µL preparation. After removing the
938 excess mounting medium by gently blotting with a tissue paper, the coverslips were sealed
939 with clear nail polish, and then imaged on the same day.
940 *Image acquisition, pre-processing, analysis and mRNA quantification.* Images were
941 acquired using Zeiss Axiovert 200M (63x oil immersion objective; numerical aperture 1.4)
942 controlled by Metamorph image acquisition software (Molecular Devices, San Jose, CA).
943 Stacks of images of 16 layers with 0.2 µm interval at 100- to 2,000-milisecond exposure
944 times were used in each fluorescence color channel including DAPI. Two representative
945 coverslips per sample/group were selected and 10-20 regions/fields of interest were
946 imaged. For cell fluorescence intensity measurements, region of interest was drawn
947 manually around each cell using DIC and DAPI channels, then average intensity was
948 measure within the area of each cell using RNA-specific florescence channels.
949
950 **Immunoblot Analysis**
951 To assess expression of endogenous or transduced proteins, cell lysates containing 30-
952 40 µg total protein were separated by SDS-PAGE, transferred to nitrocellulose
953 membranes and the membranes were probed with the following antibodies: mouse anti-
954 TMPRSS2 (Santa Cruz, #515727, 1:1000), mouse anti-Cathepsin-L (Santa Cruz,

955 #32320, 1:1000), goat anti-ACE-2 (R&D systems, #AF933, 1;1000), rabbit anti-STING
956 (Cell Signaling, #13647, 1:1000), rabbit anti-MAVS (Thermo Fisher, #PA5-17256,
957 1:1000), mouse anti-RIG-I (AdipoGen, #20B-0009, 1:1000), rabbit anti-MDA-5
958 (Proteintech, #21775-1-AP, 1:1000), rabbit anti-UNC93B1 (Invitrogen, #PA5-83437,
959 1:1000), rabbit anti-IRF1 (Cell Signaling, #8478S, 1:1000). Specific staining was
960 visualized with secondary antibodies, goat anti-mouse-IgG-DyLight 680 (Thermo
961 Scientific, #35518, 1:20000), goat anti-rabbit-IgG-DyLight 800 (Thermo Scientific, #SA5-
962 35571, 1:20000), or a donkey anti-goat-IgG-IR-Dye 800 (Licor, #926-32214, 1:20000).
963 As loading controls, actin or tubulin expression was probed using a rabbit anti-actin
964 (Sigma-Aldrich, A2066, 1:5000), mouse anti-actin (Invitrogen, #AM4302, 1:5000), or
965 rabbit anti-tubulin (Cell Signaling, #3873, 1;5000). Membranes were scanned with an
966 Odessy scanner (Li-Cor).
967
968 **Statistics**
969 All the statistical analysis was performed using GraphPad Prism 9. *P*-values were
970 calculated using one-way ANOVA followed by the Tukey-Kramer post-test (symbols for *p*-
971 values shown with a line) or the Dunnett's post-test (comparing to mock), symbols for *p*-
972 values shown with a bracket), or a two-tailed paired t-test (comparing two samples,
973 symbols for two-tailed *p*-values shown with a line bracket). Symbols represent, *: $p < 0.05$,
974 **: $p < 0.01$, ***: $p < 0.001$, ****: $p < 0.0001$. No symbol or ns: not significant ($p \geq 0.05$).
975
976 **Data availability**
977 The authors declare that the data that support the findings of this study are available within
978 the paper and from the corresponding author upon reasonable request.

979

980 **Table 1**

981 **qRT-PCR primers:**

Gene	Forward	Reverse
GAPDH	CAAGATCATCAGCAATGCCT	AGGGATGATGTTCTGGAGAG
IL-6	TCTCCACAAGCGCCTTCG	CTCAGGGCTGAGATGCCG
TNFα	CCCAGGGACCTCTCTCTAATCA	GCTACAGGCTTGTCACTCGG
IL-1β	AAACAGATGAAGTGCTCCTTCC	AAGATGAAGGGAAAGAAGGTGC
IL-18	GACCAAGGAAATCGGCCTCTA	ACCTCTAGGCTGGCTATCTTTATACATAC
IFNβ	ATTCTAACTGCAACCTTTCG	GTTGTAGCTCATGGAAAGAG
IP-10	AAAGCAGTTAGCAAGGAAAG	TCATTGGTCACCTTTTAGTG
Viperin	TGGGTGCTTACACCTGCTG	GAAGTGATAGTTGACGCTGGTT
IFNλ1	GGACGCCTTGGAAGAGTCAC	AGCTGGGAGAGGATGTGGT
SARS-CoV-2_ negative strand	ACAGCACCCTAGCTTGGTAGCCGAACAACTGGACTTTATTGA	
nCoVsg_E.rtF	CGAACTTATGTACTCATTCGTTTCGG	
nCoVsg_E.rtR	AGAAGGTTTTACAAGACTCACGTT	
SARS-CoV-2 Nucleocapsid	CACATTGGCACCCGCAATC	GAGGAACGAGAAGAGGCTTG
SARS-CoV-2 Envelope (E)	ACAGGTACGTTAATAGTTAATAGCGT	ATATTGCAGCAGTACGCACACA
TRS 5' leader (forward)	ACCAACCAACTTTCGATCTCTTGT	
N 3' reverse	CACTGCGTTCTCCATTCTGG	
ACE-2	CGAAGCCGAAGGCCTGTTCTA	GGGCAAGTGTGGACTGTTCC
TMPRSS2	CAAGTGCTCCAACTCTGGGAT	AACACACCGATTCTCGTCCTC
STING	ACTGTGGGGTGCCTGATAAC	TGGCAAACAAAGTCTGCAAG
MAVS	GTACCCGAGTCTCGTTTC	GCAGAATCTCTACAACATCC
RIG-I	ATCCCAGTGTATGAACAGCAG	GCCTGTAACTCTATACCCATGTC
MDA-5	GGCATGGAGAATAACTCATCAG	CTCTTCATCTGAATCACTTCCC
UNC93B1	TGATCCTGCACTACGACGAG	GCGAGGAACATCATCCACTT

982

983 **Table 2**

984 **shRNA sequences:**

Gene	Sequence	Reference
STING	GCCCGGATTCGAACTTACAAT	Sigma (TRCN0000163296)

MAVS	ATGTGGATGTTGTAGAGATTC	Sigma (TRCN0000236031)
RIG-I	CCAGAATTATCCCAACCGATA	Sigma (TRCN0000153712)
MDA-5	CCAACAAAGAAGCAGTGTATA	Sigma (TRCN0000050849)
UNC93B1	CAAGGAGAGACAGGACTTCAT	Sigma (TRCN0000138268)

Table 3

smFISH probe sequences:

See attached excel sheet.

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Author Contributions

S.J., J.O., E.M. and S.G. designed the experiments. S.J., J.O, J.B., A.N., E.L., M.L., H.A., Y.B., and S.T., performed the experiments and analyzed the data. S.J., J.O., E.M. and S.G. wrote the manuscript.

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1308

Figure 1

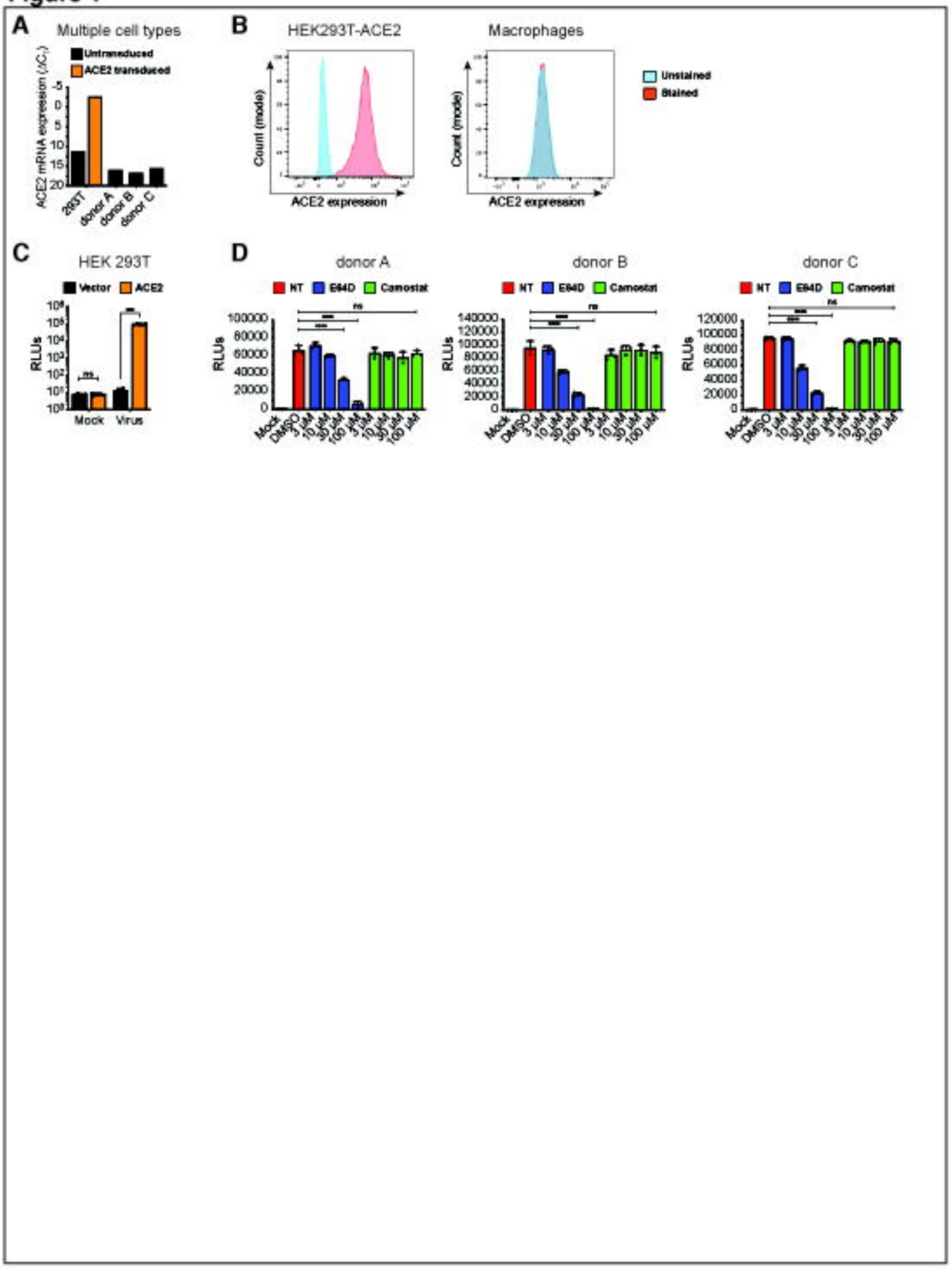

A
Multiple cell types
Untransduced
ACE2 transduced
ACE2 mRNA expression (ΔCt)
293T
donor A
donor B
donor C
B
HEK293T-ACE2
Macrophages
Count (mode)
ACE2 expression
Unstained
Stained
C
HEK 293T
Vector
ACE2
RLUs
Mock
Virus
D
donor A
donor B
donor C
NT
E64D
Camostat
RLUs
Mock
DMSO
3 μM
10 μM
30 μM
100 μM

Figure 2

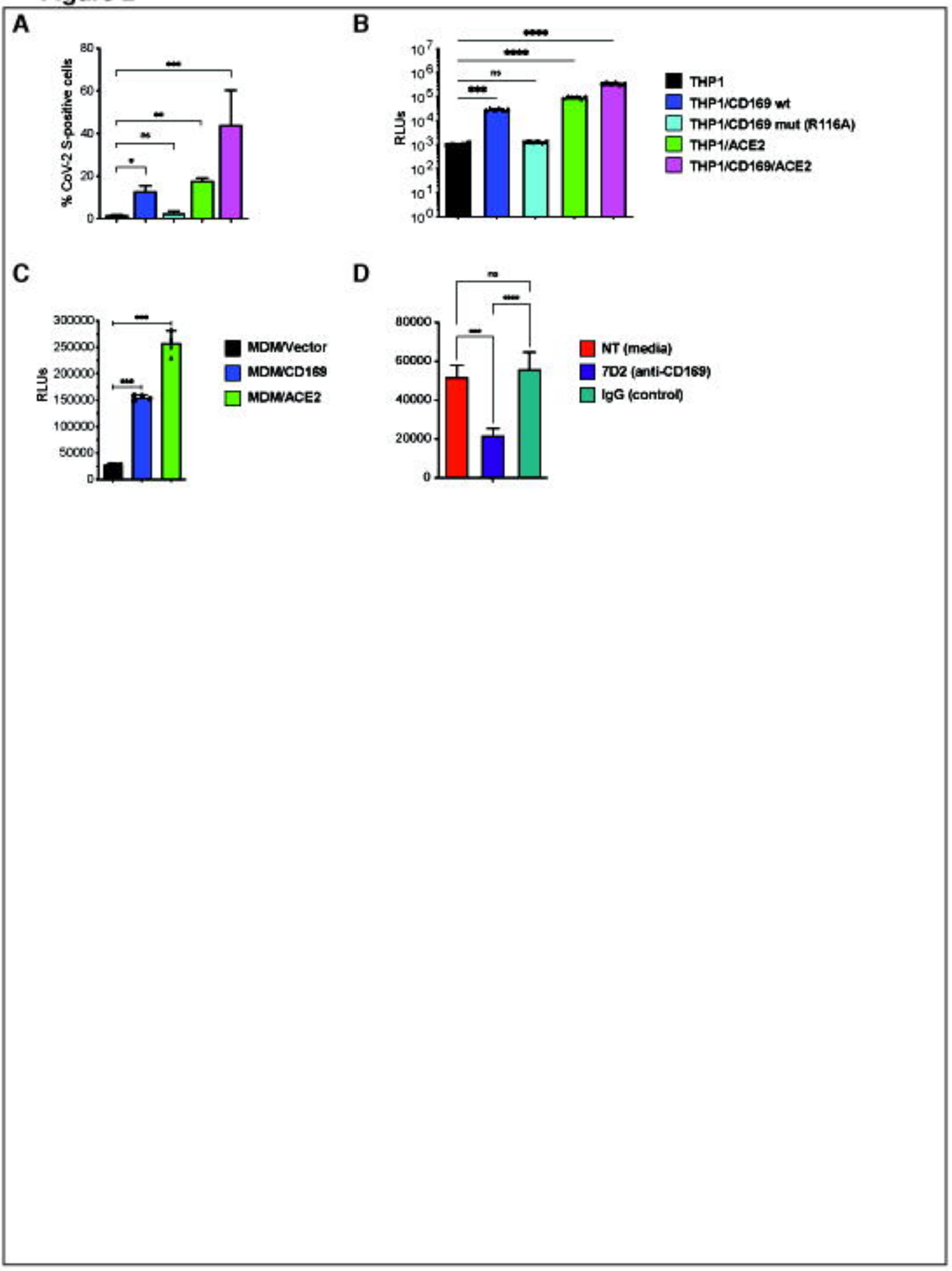

A
% CoV-2 S-positive cells
0
20
40
60
80
B
RLUs
THP1
THP1/CD169 wt
THP1/CD169 mut (R116A)
THP1/ACE2
THP1/CD169/ACE2
C
RLUs
MDM/Vector
MDM/CD169
MDM/ACE2
D
NT (media)
7D2 (anti-CD169)
IgG (control)

Figure 3

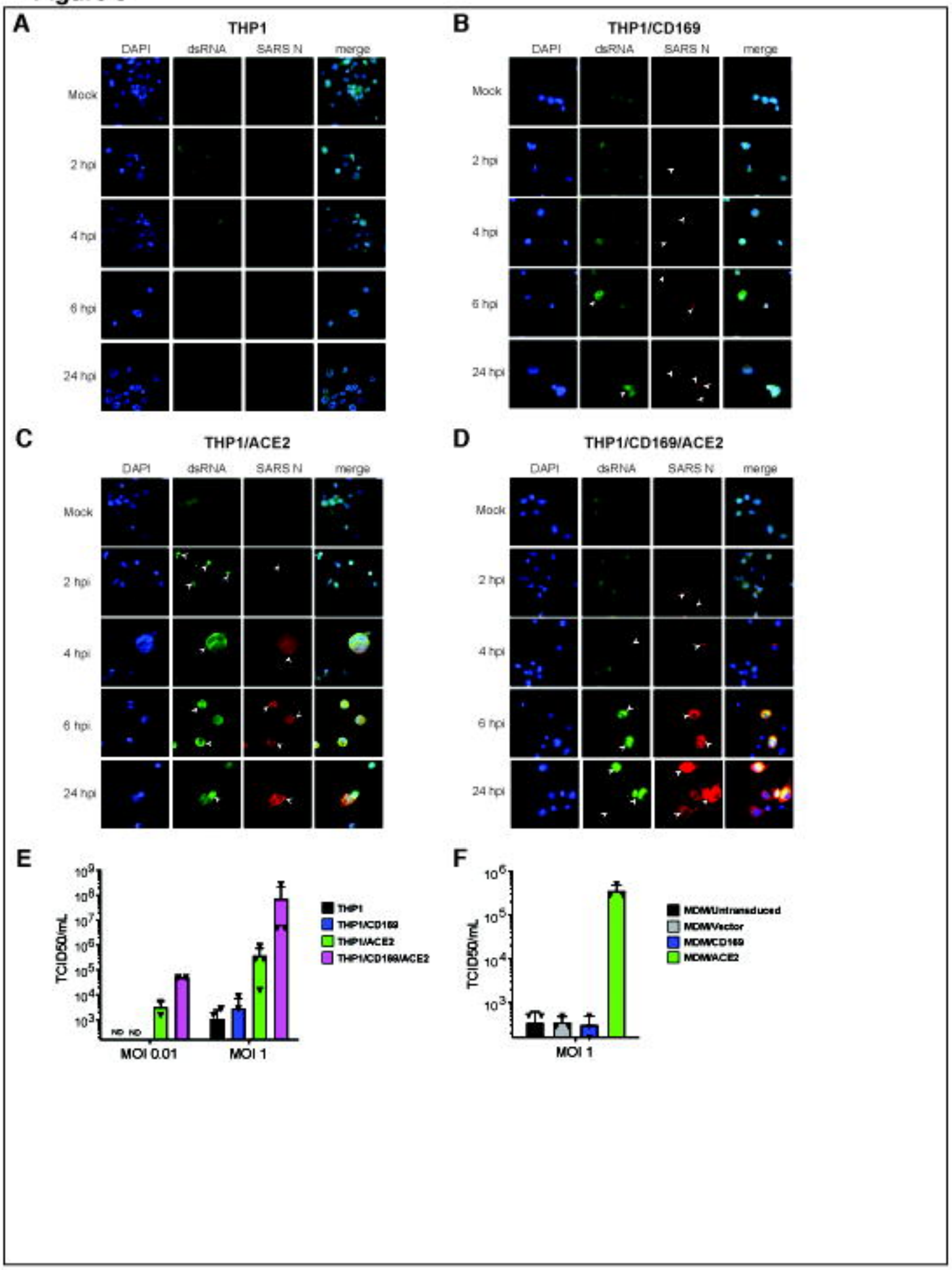

A
THP1
DAPI
dsRNA
SARS N
merge
Mock
2 hpi
4 hpi
6 hpi
24 hpi
B
THP1/CD169
C
THP1/ACE2
D
THP1/CD169/ACE2
E
TCID50/mL
ND
MOI 0.01
MOI 1
THP1
THP1/CD169
THP1/ACE2
THP1/CD169/ACE2
F
MDM/Untransduced
MDM/Vector
MDM/CD169
MDM/ACE2

Figure 4

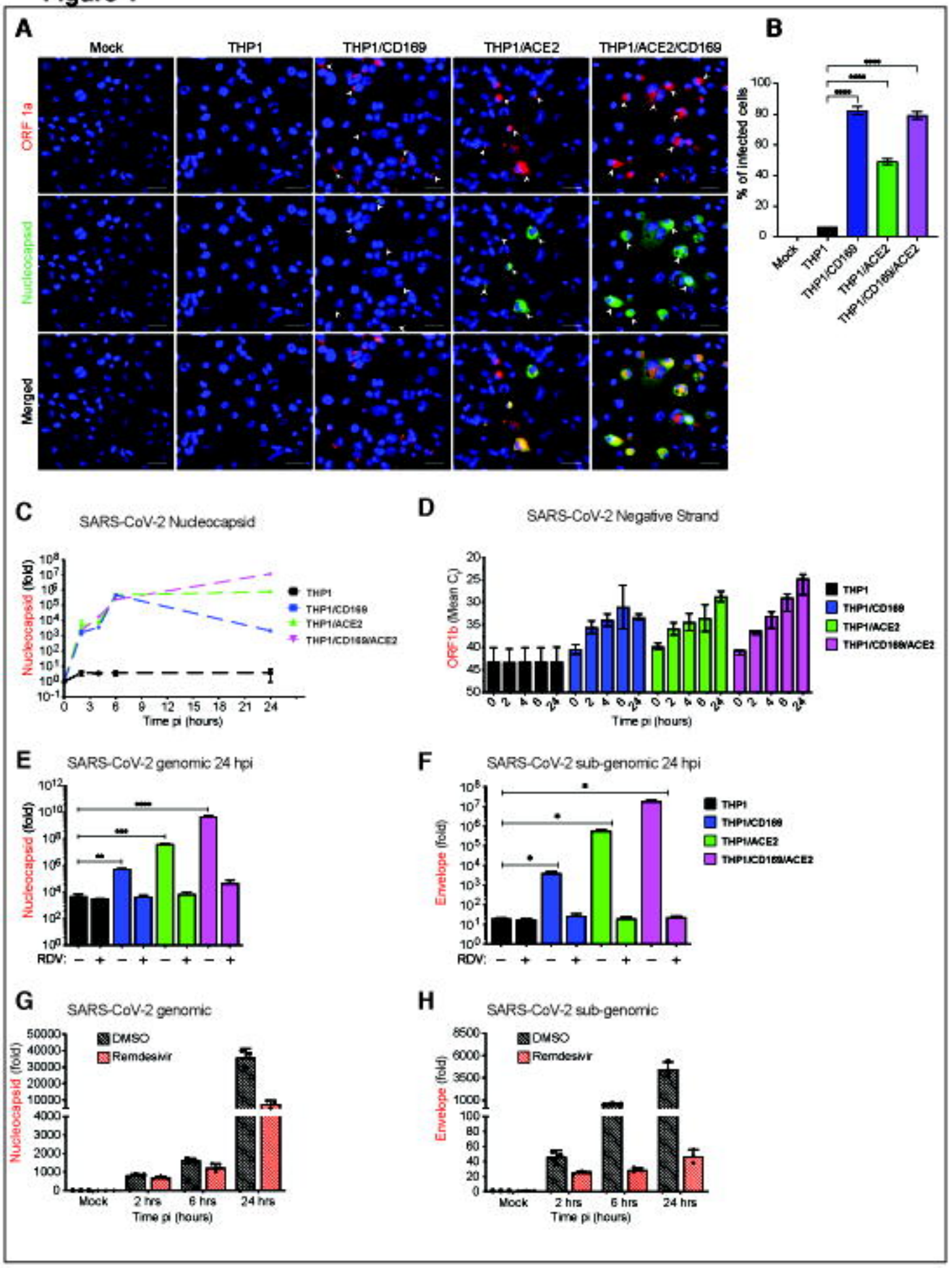

A
Mock
THP1
THP1/CD169
THP1/ACE2
THP1/ACE2/CD169
ORF 1a
Nucleocapsid
Merged
B
% of infected cells
Mock
THP1
THP1/CD169
THP1/ACE2
THP1/CD169/ACE2
C
SARS-CoV-2 Nucleocapsid
Nucleocapsid (fold)
Time pi (hours)
THP1
THP1/CD169
THP1/ACE2
THP1/CD169/ACE2
D
SARS-CoV-2 Negative Strand
ORF1b (Mean Ct)
Time pi (hours)
THP1
THP1/CD169
THP1/ACE2
THP1/CD169/ACE2
E
SARS-CoV-2 genomic 24 hpi
Nucleocapsid (fold)
RDV:
F
SARS-CoV-2 sub-genomic 24 hpi
Envelope (fold)
RDV:
THP1
THP1/CD169
THP1/ACE2
THP1/CD169/ACE2
G
SARS-CoV-2 genomic
Nucleocapsid (fold)
DMSO
Remdesivir
Mock
2 hrs
6 hrs
24 hrs
Time pi (hours)
H
SARS-CoV-2 sub-genomic
Envelope (fold)
DMSO
Remdesivir
Mock
2 hrs
6 hrs
24 hrs
Time pi (hours)

Figure 5

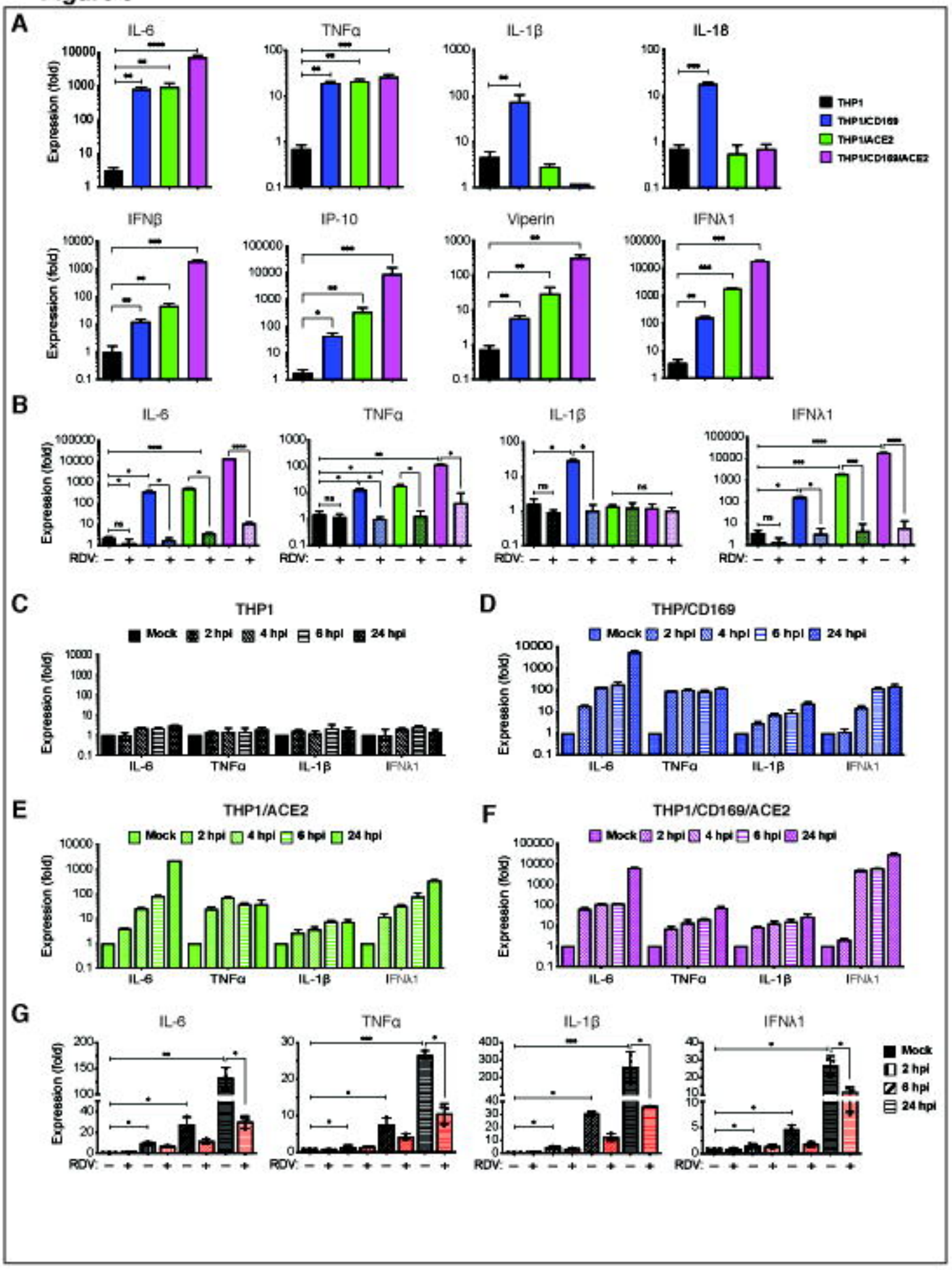

A
IL-6
TNFα
IL-1β
IL-18
IFNβ
IP-10
Viperin
IFNλ1
Expression (fold)
THP1
THP1/CD169
THP1/ACE2
THP1/CD169/ACE2
B
RDV:
C
THP1
D
THP/CD169
E
THP1/ACE2
F
THP1/CD169/ACE2
Mock
2 hpi
4 hpi
6 hpi
24 hpi
G

Figure 6

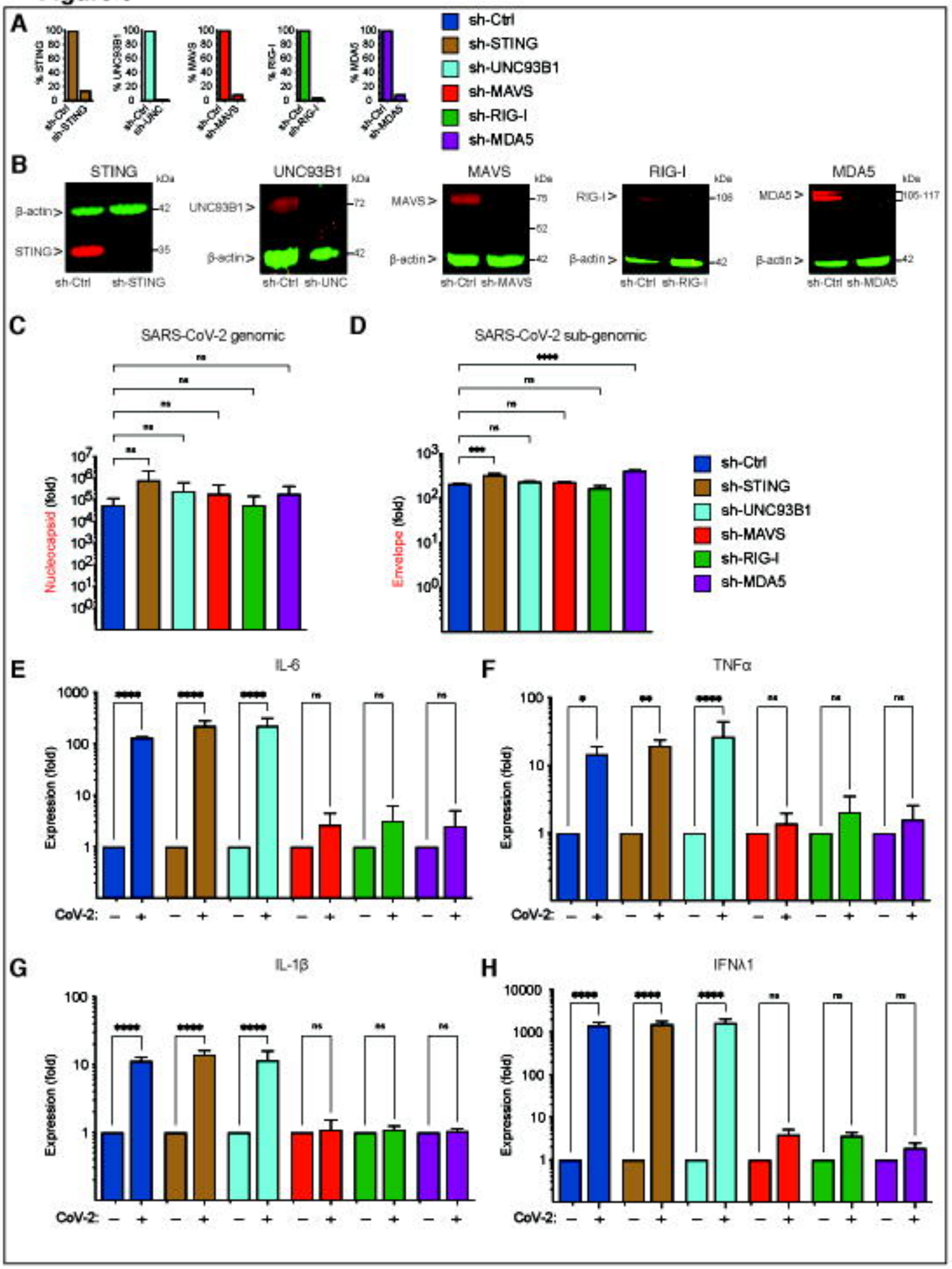
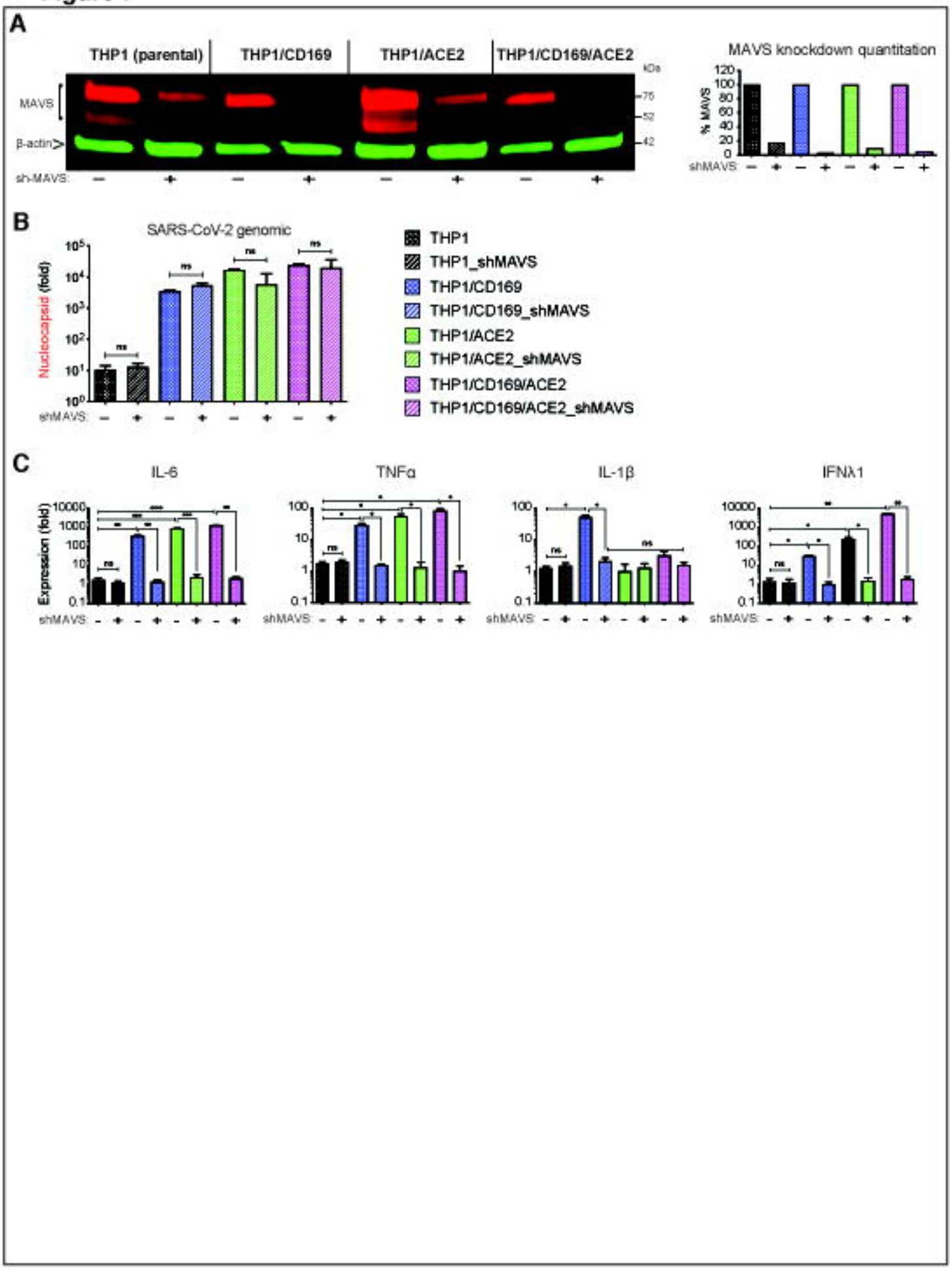

A
% STING
% UNC93B1
% MAVS
% RIG-I
% MDA5
sh-Ctrl
sh-STING
sh-UNC93B1
sh-MAVS
sh-RIG-I
sh-MDA5
B
STING
UNC93B1
MAVS
RIG-I
MDA5
kDa
β-actin
STING
UNC93B1
MAVS
RIG-I
MDA5
sh-Ctrl sh-STING
sh-Ctrl sh-UNC
sh-Ctrl sh-MAVS
sh-Ctrl sh-RIG-I
sh-Ctrl sh-MDA5
C
SARS-CoV-2 genomic
Nucleocapsid (fold)
D
SARS-CoV-2 sub-genomic
Envelope (fold)
E
IL-6
Expression (fold)
F
TNFα
G
IL-1β
H
IFNA1
CoV-2: − +

Figure 7


A
THP1 (parental)
THP1/CD169
THP1/ACE2
THP1/CD169/ACE2
kDa
MAVS
β-actin
75
52
42
sh-MAVS:
MAVS knockdown quantitation
% MAVS
shMAVS:
B
SARS-CoV-2 genomic
Nucleocapsid (fold)
shMAVS:
THP1
THP1_shMAVS
THP1/CD169
THP1/CD169_shMAVS
THP1/ACE2
THP1/ACE2_shMAVS
THP1/CD169/ACE2
THP1/CD169/ACE2_shMAVS
C
IL-6
TNFα
IL-1β
IFNλ1
Expression (fold)
shMAVS: