VIP plasma levels associate with survival in severe COVID-19 patients, correlating with protective effects in SARS-CoV-2-infected cells.

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Short Title: Protective effects of VIP and PACAP in SARS-CoV-2 infection

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Abstract

Infection by SARS-CoV-2 may elicit uncontrolled and damaging inflammatory responses. Thus, it is critical to identify compounds able to inhibit virus replication and thwart the inflammatory reaction. Here, we show that the plasma levels of the immunoregulatory neuropeptide VIP are elevated in patients with severe COVID-19, correlating with reduced inflammatory mediators and with survival on those patients. In vitro, VIP and PACAP, highly similar neuropeptides, decreased the SARS-CoV-2 genome replication in human monocytes and viral production in lung epithelial cells, also reducing cell death. Both neuropeptides inhibited the production of proinflammatory mediators in lung epithelial cells and in monocytes. VIP and PACAP prevented in monocytes the SARS-CoV-2-induced activation of NF-kB and SREBP1 and SREBP2, transcriptions factors involved in proinflammatory reactions and lipid metabolism, respectively. They also promoted CREB activation, a transcription factor with antiapoptotic activity and negative regulator of NF-kB. Specific inhibition of NF-kB and SREBP1/2 reproduced the anti-inflammatory, antiviral and cell death protection effects of VIP and PACAP. Our results support further clinical investigations of these neuropeptides against COVID-19.

Introduction

Individuals with coronavirus disease 2019 (COVID-19), caused by the severe acute respiratory syndrome coronavirus 2 (SARS-CoV-2) [1], may present asymptomatic or mild disease to severe lung inflammation and acute respiratory distress syndrome (ARDS) [2,3], besides a variety of extrapulmonary manifestations [4]. Severe SARS-CoV-2 infection is characterized by elevated serum levels of proinflammatory mediators (hypercytokinemia, also known as cytokine storm) such

as, for example, IL-2, IL-6, TNF, IL-8, IL-1β, IFN-γ [2,3,5,6]. The dysregulated immune response and production of cytokines and chemokines are hallmarks of SARS-CoV-2 infection and have been pointed as the main cause of the severe lung damage and unfavorable clinical progression of patients with COVID-19 [3–8]. Also, the in vivo formation of neutrophil extracellular traps (NETs) in the lungs, SARS-CoV-2-induced inflammasome activation and cell death by pyroptosis, have also been considered as risk factors in critically ill COVID-19 patients [9–14].

During the inflammatory response to human pathogenic coronaviruses, circulating neutrophils and monocytes migrate and infiltrate the lungs [15,16] and other organs, contributing to potentiate and perpetuate the inflammation and eventually exacerbating the tissue damage [17–19]. Previous studies showed that MERS-CoV- and SARS-CoV-infected macrophages produce high levels of pro-inflammatory cytokines and chemokines [20,21], and, more recently, that lung monocytes from severe pneumonia caused by SARS-CoV-2 are potent producers of TNF-α and IL-6, whose levels were increased in the serum of the same patients [7]. Also, we and other authors have found that SARS-CoV-2 induces inflammasome activation and cell death by pyroptosis in monocytes, either by experimental or natural infection, which are associated with lung inflammation and are risk factors in critically ill COVID-19 patients [13,14].

Thus, it is critical to identify agents able to prevent the infection and concurrently thwart the prototypical dysregulated inflammatory reaction and tissue lesions secondary to SARS-CoV-2 infection. In this work, we evaluated whether the neuropeptides Vasoactive Intestinal Peptide (VIP) and Pituitary Adenylate Cyclase-Activating Polypeptide (PACAP) can present protective effects in SARS-CoV-2

infection. VIP and PACAP share many biological properties through their interaction with the G protein-coupled receptors VPAC1, VPAC2 and PAC1 [22], which are systemically distributed. They have well-characterized regulatory effects on the immune system and anti-inflammatory properties, including control of cell activation and differentiation, down-regulation of inflammatory cytokines and reactive oxygen species and induction of the anti-inflammatory cytokine IL-10 [23–28]. Based on their consistent anti-inflammatory and pro-homeostatic activities, both neuropeptides have been considered as promising therapeutic agents for autoimmune disorders and chronic inflammatory illnesses [29–32]. Therefore, based on the well-known properties of both neuropeptides to regulate inflammatory reactions, and on the dysregulated immune responses that affect COVID-19 patients, we investigated whether they could present protective roles during SARS-CoV-2 infection. We report here that VIP levels are elevated in the plasma of individuals with severe manifestations of COVID-19, which correlated with survival on critically ill patients. We also verified, in in vitro assays, that VIP and PACAP inhibit the production of proinflammatory mediators in SARS-CoV-2-infected monocytes and lung epithelial cells; and reduced viral production and cell death.

Materials and Methods

Cells, virus and reagents. African green monkey kidney cells (Vero, subtype E6) and human lung epithelial cell lines (Calu-3) were expanded in high glucose DMEM (Vero) or MEM (Calu-3) with 10% fetal bovine serum (FBS; Merck), with 100 U/mL penicillin and 100 µg/mL streptomycin (Pen/Strep; Gibco) at 37°C in a humidified atmosphere with 5% CO_2. Peripheral blood mononuclear cells (PBMCs) were isolated by density gradient centrifugation (Ficoll-Paque, GE Healthcare) from buffy-

coat preparations of blood from healthy donors. PBMCs (2 x 10^6 cells) were plated onto 48-well plates (NalgeNunc) in RPMI-1640 with 5% inactivated male human AB serum (Merck) for 3 hours. Non-adherent cells were removed and monocytes were maintained in DMEM (low-glucose) with 5% human serum and 100 U/mL penicillin and 100 µg/mL streptomycin. Purity of monocytes was above 90%, as determined by flow cytometry (FACScan; Becton Dickinson) using anti-CD3 (BD Biosciences) and anti-CD14 (BD Biosciences) antibodies. SARS-CoV-2 (GenBank accession no. MT710714) was expanded in Vero E6 cells. Viral isolation was performed after a single passage in a cell culture in a 150 cm^2 flasks with high glucose DMEM plus 2% FBS. Observations for cytopathic effects were performed daily and peaked 4 to 5 days after infection. All procedures related to virus culture were handled in biosafety level 3 (BSL3) multiuser facilities, according to WHO guidelines. Virus titers were determined as plaque forming units (PFU/mL), and virus stocks were kept in -80°C ultralow freezers. VIP and PACAP and the VPAC1 and VPAC2 agonists ($Ala^{11,22,28}$)-VIP and Bay 55-9837, respectively, were purchased from Tocris. The PAC1 agonist Maxadilan was kindly donated by Dr. Ethan A. Lerner (Department of Dermatology, Massachusetts General Hospital, MA, USA). All peptides and agonists were diluted in PBS. The inhibitors of the transcription factors SREBP (AM580) and NF-KB (Bay 11-7082) were purchased from Selleckchem.

Infections and virus titration. Infections were performed with SARS-CoV-2 at MOI of 0.01 (monocytes) or 0.1 (Calu-3) in low (monocytes) or high (Calu-3) glucose DMEM without serum. After 1 hour, viral input was removed and cells were washed and incubated with complete medium with treatments or not. For virus titration, monolayers of Vero E6 cells (2 x 10^4 cell/well) in 96-well plates were infected with serial dilutions of supernatants containing SARS-CoV-2 for 1 hour at 37°C. Semi-

129 solid high glucose DMEM medium containing 2% FBS and 2.4%
130 carboxymethylcellulose was added and cultures were incubated for 3 days at 37 °C.
131 Then, the cells were fixed with 10% formalin for 2 hours at room temperature. The
132 cell monolayer was stained with 0.04% solution of crystal violet in 20% ethanol for
133 1 hour. Plaque numbers were scored in at least 3 replicates per dilution by
134 independent readers blinded to the experimental group, and the virus titers were
135 determined by plaque-forming units (PFU) per milliliter.

136 **Molecular detection of virus RNA levels.** The total RNA was extracted from cells
137 using QIAamp Viral RNA (Qiagen), according to manufacturer's instructions.
138 Quantitative RT-PCR was performed using QuantiTect Probe RT-PCR Kit (Qiagen)
139 in a StepOnePlus™ Real-Time PCR System (Thermo Fisher Scientific).
140 Amplifications were carried out in 15 µL reaction mixtures containing 2× reaction
141 mix buffer, 50 µM of each primer, 10 µM of probe, and 5 µL of RNA template.
142 Primers, probes, and cycling conditions recommended by the Centers for Disease
143 Control and Prevention (CDC) protocol were used to detect the SARS-CoV-2 [33].
144 The standard curve method was employed for virus quantification. For reference to
145 the cell amounts used, the housekeeping gene RNAse P was amplified. The Ct
146 values for this target were compared to those obtained to different cell amounts, 10^7
147 to 10^2, for calibration.

148 **SDS-PAGE and Western blot for SREBPs.** After 24h of SARS-CoV-2 infection,
149 monocytes were harvested using ice-cold lysis buffer (1% Triton X-100, 2% SDS,
150 150 mM NaCl, 10 mM HEPES, 2 mM EDTA containing protease inhibitor cocktail -
151 Roche). Cell lysates were heated at 100 °C for 5 min in the presence of Laemmli
152 buffer (20% β-mercaptoethanol; 370 mM Tris base; 160 µM bromophenol blue; 6%

glycerol; 16% SDS; pH 6.8), and 20 µg of protein/sample were resolved by electrophoresis on SDS-containing 10% polyacrylamide gel (SDS-PAGE). After electrophoresis, the separated proteins were transferred to nitrocellulose membranes and incubated in blocking buffer (5% nonfat milk, 50 mM Tris-HCl, 150 mM NaCl, and 0.1% Tween 20). Membranes were probed overnight with the following antibodies: anti-SREBP-1 (Proteintech #14088-1-AP), anti-SREBP-2 (Proteintech #28212-1-AP) and anti-β-actin (Sigma, #A1978). After the washing steps, they were incubated with IRDye - LICOR or HRP-conjugated secondary antibodies. All antibodies were diluted in blocking buffer. The detections were performed by Supersignal Chemiluminescence (GE Healthcare) or by fluorescence imaging using the Odyssey system. Densitometries were analyzed using the Image Studio Lite Version 5.2 software.

Measurements of inflammatory mediators, cell death, NF-kBp65, CREB and neuropeptides. A multiplex biometric immunoassay containing fluorescent dyed microbeads was used to measure cytokines in plasma samples (Bio-Rad Laboratories). The following cytokines were quantified: Basic-FGF, CTRAK, Eotaxin, G-CSF, GRO-α, HGF, IFN-α2, IFN-β, IFN-γ, IL-1α, IL-1β, IL-1RA, IL-2, IL-2RA, IL-3, IL-4, IL-5, IL-6, IL-7, IL-8, IL-9, IP-10, IL-10, IL-12(p40), IL-13, IL-15, IL-16, IL-17A, IL-18, LIF, M-CSF, MCP-3, MIF, MIG, MIP-1β, PDGF-BB, RANTES, SCF, SCGF-1α, SCGF-β, TNFα, TNFβ, VEGF, β-NGF and PF4. Cytokine levels were calculated by Luminex technology (Bio-Plex Workstation; Bio-Rad Laboratories). The analysis of data was performed using software provided by the manufacturer (Bio-Rad Laboratories). A range of 0.51–8000 pg/mL recombinant cytokines was used to establish standard curves and the sensitivity of the assay. The levels of IL-6, IL-8, TNF-α and MIF were quantified in the supernatants from

uninfected and SARS-CoV-2-infected Calu-3 cells and monocytes by ELISA (R&D Systems), following manufacturer's instructions, and results are expressed as percentages relative to uninfected cells. Cell death was determined according to the activity of lactate dehydrogenase (LDH) in supernatants using CytoTox® Kit (Promega) according to the manufacturer's instructions. Supernatants were centrifuged at 5,000 rpm for 1 minute to remove cellular debris. Evaluation of NF-kBp65 and CREB activation was performed in infected or uninfected monocytes using NF-kB p65 (Total/Phospho) InstantOne™ and CREB (Total/Phospho) Multispecies InstantOne™ ELISA Kits (Thermo Fisher), according to manufacturer's instructions. VIP and PACAP levels were quantified in the plasma from patients or control volunteers using standard commercially available ELISA and EIA Kits, according to the manufacturer's instructions (Abelisa).

Human subjects. We prospectively enrolled patients with severe or mild/asymptomatic COVID-19 RT-PCR-confirmed diagnosis, and SARS-CoV-2-negative healthy controls. Blood and respiratory samples were obtained from 24 patients with severe COVID-19 within 72 hours from intensive care unit (ICU) admission in two reference centers (Instituto Estadual do Cérebro Paulo Niemeyer and Hospital Copa Star, Rio de Janeiro, Brazil). Severe COVID-19 was defined as those critically ill patients presenting viral pneumonia on computed tomography scan and requiring oxygen supplementation through either a nonrebreather mask or mechanical ventilation. Eight outpatients presenting mild self-limiting COVID-19 syndrome, and two SARS-CoV-2-positive asymptomatic subjects were also included. Patients had SARS-CoV-2 confirmed diagnostic through RT-PCR of nasal swab or tracheal aspirates. Peripheral vein blood was also collected from 10 SARS-CoV-2-negative healthy participants as tested by RT-PCR on the day of blood

sampling. Characteristics of severe (n=24), mild/asymptomatic (n=10) and healthy (n=10) participants are presented in **Table 1**. Mild and severe COVID-19 patients presented differences regarding age and presence of comorbidities, such as obesity, cardiovascular diseases and diabetes (**Table 1**), which is consistent with previously reported patient cohorts [2,34–36]. The SARS-CoV-2-negative control group included subjects of older age and chronic non-communicable diseases, so it is matched with mild and critical COVID-19 patients, except for hypertension (**Table 1**). All ICU-admitted patients received usual supportive care for severe COVID-19 and respiratory support with either noninvasive oxygen supplementation (n=5) or mechanical ventilation (n=19) (**Supplemental Table 1**). Patients with acute respiratory distress syndrome (ARDS) were managed with neuromuscular blockade and a protective ventilation strategy that included low tidal volume (6 mL/kg of predicted body weight) and limited driving pressure (less than 16 cmH2O) as well as optimal PEEP calculated based on the best lung compliance and PaO2/FiO2 ratio. In those patients with severe ARDS and PaO2/FiO2 ratio below 150 despite optimal ventilatory settings, prone position was initiated. Our management protocol included antithrombotic prophylaxis with enoxaparin 40 to 60 mg per day. Patients did not receive routine steroids, antivirals or other anti-inflammatory or anti-platelet drugs. The SARS-CoV-2-negative control participants were not under anti-inflammatory or anti-platelet drugs for at least two weeks. All clinical information was prospectively collected using a standardized form - ISARIC/WHO Clinical Characterization Protocol for Severe Emerging Infections (CCPBR). Clinical and laboratory data were recorded on admission in all severe patients included in the study and the primary outcome analyzed was 28-day mortality (n = 11 survivors and 13 non-survivors, **Supplemental Table 2**). Age and frequency of comorbidities were

not different between severe patients requiring mechanical ventilation or noninvasive oxygen supplementation neither between survivors and non-survivors (**Supplemental Table 1 and 2**).

Statistical analysis. Statistics were performed using GraphPad Prism software version 8. Numerical variables were tested regarding distribution using the Shapiro-Wilk test. One-way analysis of variance (ANOVA) was used to compare differences among 3 groups following a normal (parametric) distribution, and Tukey's post-hoc test was used to locate the differences between the groups; or Friedman's test (for non-parametric data) with Dunn's post-hoc test. Comparisons between 2 groups were performed using the Student t test for parametric distributions or the Mann-Whitney U test for nonparametric distributions. Correlation coefficients were calculated using Pearson's correlation test for parametric distributions and the Spearman's correlation test for nonparametric distributions.

Results

Plasma levels of VIP are elevated in patients with severe forms of COVID-19 and associate with survival. From April to May 2020, we followed up 24 critically ill COVID-19 patients, at the median age of 53-year-old (**Table 1**), presenting the most common infection symptoms and comorbidities, from whom we evaluated the plasma levels of the neuropeptides VIP and PACAP, comparing with patients with mild COVID-19 symptoms and non-infected healthy individuals. We found that patients affected by the most severe forms of infection had higher plasma levels of the neuropeptide VIP than uninfected healthy controls and asymptomatic/mild patients (**Fig. 1A**). Comparing the viral load in positive swab samples from mild and severe COVID-19 patients we found a modest positive correlation with VIP levels

(**Fig. 1B**). Following, we examined a possible correlation between VIP levels of severe patients and inflammatory markers. We identified that VIP negatively correlated with five pro-inflammatory factors (IL-8, IL-12p40, IL-17A, TNF-α and CXCL10/IP-10), and positively with two anti-inflammatory factors (IL-1RA and IL-10) (**Fig. 1C-I**). Next, severe COVID-19 patients were further subdivided between those requiring invasive mechanical ventilation or noninvasive O_2 supplementation or according to the 28-day mortality outcome as survivors or non-survivors. We did not find a significant difference when analyzing O2 supplementation versus mechanical ventilation (**Fig. 1J**), probably due to the low number of patients under the first condition. On the contrary, we observed that VIP plasma levels associated with survival of patients with severe COVID-19, being significantly higher in survivors than in non-survivors (**Fig. 1K**). For PACAP plasma levels, we did not find significant differences between the groups analyzed, inflammatory markers, viral load or with VIP levels (data not shown). The finding that survival of severe COVID-19 patients is associated with higher levels of circulating VIP, a molecule with pro-homeostasis and anti-inflammatory activities [32,37], moreover pointing to an application as a prognostic marker, also implies to a therapeutical potential of VIP in COVID-19. In fact, VIP has been approved for three clinical trials against COVID-19 in intravenous [38] and inhaled [39,40] formulations. Our initial clinical data prompted us to evaluate the effects of VIP (and of PACAP as well) on SARS-CoV-2-infected cells to better corroborate the use of VIP as therapeutical agent in COVID-19 patients.

VIP and PACAP reduce SARS-CoV-2 RNA synthesis in human primary monocytes and viral replication in pulmonary cells, protecting them from virus-mediated cytopathic effects. Upon identifying the association of VIP with survival of critical COVID-19 patients and considering that, in the setting of COVID-

19, the main affected cells are those present in the lung epithelium, including the immune cells recruited upon infection, we sought to investigate the in vitro effects of VIP and PACAP in SARS-CoV-2-infected cells. To this end, we initially evaluated the SARS-CoV-2 RNA synthesis in monocytes (as the infection by SARS-CoV-2 in this cell is non-productive [41,42]) and the viral replication in Calu-3 cells (a lineage of lung epithelial cells highly susceptible to SARS-CoV-2) exposed to VIP or PACAP). We found that VIP reduced the SARS-CoV-2 RNA synthesis in monocytes, achieving up to 40% and 50% inhibition at 5 nM and 10 nM, respectively (**Fig. 2A**). PACAP similarly decreased the levels of viral RNA synthesis with 5 nM and 10 nM (up to 50% for both doses) (**Fig. 2B**). We next evaluated whether VIP and PACAP could also be able to restrict virus production in pulmonary cells, one of the major targets of SARS-CoV-2. We found that VIP reduced viral replication, reaching up to 50% and 40% inhibition with 1 nM and 5 nM, respectively (**Fig. 2C and Supp Fig. 1A**). PACAP also diminished virus production up to 40% and 50% at concentrations equivalent to 10 nM and 50 nM (**Fig. 2D and Supp Fig. 1B**). In parallel, VIP and PACAP protected monocytes and Calu-3 cells from SARS-CoV-2-mediated cytopathic effect, as measured by LDH activity in supernatants (**Fig. 2E and 2F**). Overall, these results show that cells exposed to VIP or PACAP present decreased viral output and resistance to damages induced by the infection.

Receptor contribution for the VIP and PACAP mediated inhibition of SARS-CoV-2 replication. The different optimal concentrations of VIP and PACAP to reduce SARS-CoV-2 replication in Calu-3 cells might be explained by the relative abundance of the neuropeptide receptors, since it has been shown that these cells express only VPAC1 [43]. However, all three receptors are reported to be expressed in lungs, with some studies showing that VPAC1 levels are higher than VPAC2 or

PAC1 (to which PACAP binds with higher affinity than to VPAC1 and VPAC2 [22,44–46]). With that in mind, we evaluated the role of the individual receptors in the neuropeptide-mediated inhibition of SARS-CoV-2 in both cells. To this end, monocytes were treated with specific agonists to VPAC1, VPAC2 and PAC1 (Ala-VIP, Bay 55-9837 and Maxadilan, respectively), and then infected with SARS-CoV-2. Activation of VPAC1 at 1 nM, 5 nM and 10 nM, and of VPAC2 at 1 nM, significantly reduced the SARS-CoV-2 genome replication (**Fig. 3A**). We also verified that VPAC1 is the main receptor involved the inhibition of SARS-CoV-2 in Calu-3 cells, resembling the level of inhibition achieved with VIP, while the exposure to a VPAC2 agonist resulted in a more modest inhibition (**Fig. 3B**). The stimulus with a PAC1 agonist had no effect on viral replication (**Fig. 3A and 3B**). As a whole, these findings suggest that VPAC1 receptor is the main contributor for the VIP- and PACAP-mediated SARS-CoV-2 inhibition in monocytes and Calu-3 cells, and that activation of this receptor can lead to a diminished viral replication similar to that induced by the own neuropeptides.

VIP and PACAP reduce the production of proinflammatory cytokines by SARS-CoV-2-infected monocytes and Calu-3 cells. Controlling the production of proinflammatory cytokines may be critical for reducing SARS-CoV-2 replication and limiting tissue damages, and based on evidence that VIP and PACAP can regulate the inflammatory response [27,47], we next evaluated whether both neuropeptides could attenuate the production of proinflammatory mediators by SARS-CoV-2-infected monocytes or lung epithelial cells. As shown in **Fig. 4A**, SARS-CoV-2-infected monocytes produced large amounts of the proinflammatory mediators IL-6, IL-8, TNF and MIF relative to uninfected cells (15, 4, 12 and 18 times more, respectively). In contrast, the treatment of SARS-CoV-2-infected monocytes with

either neuropeptide reduced to 66%, 50%, 66% and 50% the cellular production of IL-6, IL-8, TNF and MIF, respectively. Furthermore, VIP and PACAP reverted by approximately the same degree the release of IL-6 and IL-8 by Calu-3 cells (**Fig. 4B**), implying that VIP and PACAP may offer a critical protection to inflamed lungs affected by SARS-CoV-2 replication. Because proinflammatory cytokines may favor SARS-CoV-2 replication, which, in turn, can amplify the cellular synthesis of these mediators, these findings may support our assumption that VIP and PACAP offer tissue protection by inhibiting virus replication and regulating the boost of cytokine production.

VIP and PACAP regulate the activation of transcription factors in SARS-CoV-2-infected monocytes. Given that the transcription factor NF-kB is critically involved in the cellular production of inflammatory mediators [48], and our own findings showing that VIP and PACAP can inhibit its activation in HIV-1-infected macrophages [49], we investigated whether both neuropeptides would exert this same effect on SARS-CoV-2-infected monocytes. We found that activated NF-kB is up-modulated in infected cells (as measured by the increased amount of phosphorylated NF-kBp65 subunit), and that VIP and PACAP were able to reduce NF-KBp65 phosphorylation (**Fig. 5A**). Following, we analyzed the effects of both neuropeptides on the activation of CREB, a transcription factor induced by several GPCR ligands, including VIP and PACAP [50], and also involved in the induction of anti-inflammatory cytokines [51,52]. CREB and NF-kB share the CREB-binding protein/p300 (CBP/p300 protein) as a cofactor, and CREB activation results in the inhibition of NF-kB [53]. We found that activation of CREB was diminished in SARS-CoV-2-infected monocytes (**Fig. 5B**), a result coherent with NF-kB activation in the same cells. Consistent with this finding, VIP and PACAP promoted CREB activation

(as measured by increase of CREB phosphorylation) in those infected monocytes, a result matching the inhibition of NF-kB and the reduction of cellular production of proinflammatory cytokines. We also evaluated in SARS-CoV-2-infected monocytes the expression of the active form of SREBP-1 and SREBP-2, transcription factors that also interact with CBP/p300 [54], and are crucial for the replication of several viruses, including coronaviruses [55–57]. In fact, we and other authors reported that SARS-CoV-2 infection promotes the activation of SREBP, and that this activation is associated with enhanced viral replication [58,59] and COVID-19 disease severity [60]. We detected that the levels of both isoforms of SREBP in active state are increased in SARS-CoV-2-infected monocytes and that VIP or PACAP treatment prevented this augmentation, lowering them to the same basal levels found in uninfected monocytes (**Fig. 5C and 5D, Supp. Fig. 2**).

Inhibition of NF-kB and SREBP in monocytes reduces SARS-CoV-2 RNA synthesis, production of proinflammatory mediators and protects the cells from virus-mediated cytopathic effects. To directly connect these latter findings with viral replication and production of pro-inflammatory mediators, we treated SARS-CoV-2-infected monocytes with pharmacological inhibitors of NF-KB (Bay 11-7082) or SREBP (AM580) [55,59], together or not with VIP and PACAP. We found that the sole inhibition of SREBP decreased viral RNA synthesis and production of TNF-α and IL-6, and reduced cell death, measurements that were all amplified when the inhibitors were associated with either neuropeptide (Fig. 6, A-D). Except for viral RNA synthesis, the sole inhibition of NF-KB, or in combination with VIP or PACAP, produced similar results (Fig. 6, A-D). Importantly, the protecting effects mediated by VIP or PACAP alone were identical to those seen

when the signaling pathways triggered by NF-KB or SREBP activation were specifically inhibited.

Together, our data suggest that the restriction of SARS-CoV-2 replication in monocytes and in pulmonary cells by VIP and PACAP can be the outcome of the intrinsic modulation of inflammatory mediators and transcription factors that are involved directly and indirectly with the viral replication. Considering that VIP and PACAP regulate inflammatory reactions, it is possible that their increased circulating amounts reflect a counter-regulatory effect elicited by the dysregulated immune response typical of the more severe clinical status of COVID-19 patients. Since SARS-CoV-2-induced NF-kB and SREBP activation are key events involved in the elevated production of proinflammatory cytokines in COVID-19 [58,60,61], the inhibition of these transcription factors, associated with the reduction of proinflammatory cytokines and with the decrease of viral replication by VIP and PACAP, strengthen the potential of these neuropeptides as possible therapeutical candidates for COVID-19.

Discussion

In this work, we identified that the plasma levels of the neuropeptide VIP are elevated in patients with severe forms of COVID-19, correlating with viral load, associated with reduced inflammation, and that the elevated VIP levels at ICU admission predicted patients' favorable outcome, including association with patient survival. In in vitro SARS-CoV-2-infected monocytes and epithelial lung cells, the neuropeptides VIP and PACAP, endogenous molecules presenting anti-inflammatory properties, reduced the exacerbated synthesis of proinflammatory mediators, coupled with the inhibition of SARS-CoV-2 replication. Our findings

400 support and encourage clinical trials with VIP in COVID-19 patients, which are in
401 progress with intravenous [38] and inhaled [39,40] formulations and are expected to
402 be full disclosed this year and next. An initial release of the data, as preprint, shows
403 an increase in survival rates and reduction of IL-6 levels on those who received
404 intravenous Aviptadil (VIP) [62]. Our present data may substantiate additional larger
405 trials with VIP, an overlooked molecule associated with antiviral, anti-inflammatory
406 and enhanced survival activities.

407 Both neuropeptides regulate the inflammatory response due to their ability to
408 decrease the production of proinflammatory mediators, and to elicit the production
409 of anti-inflammatory molecules. Given that VIP and PACAP and their receptors are
410 systemically distributed, including lungs [22,63], brain, and gut, we believe that the
411 anti-SARS-CoV-2 effects of both neuropeptides would not be restricted to the
412 respiratory tract, as shown by many studies in other chronic inflammatory illnesses.

413 VIP and PACAP decreased SARS-CoV-2 genome replication in monocytes,
414 while protecting them from virus-induced cytopathicity. By diminishing the
415 intracellular levels of viral RNA and other viral molecules, VIP and PACAP could
416 prevent the cell death by pyroptosis, which has been described as one of the main
417 causes of cell damage during SARS-CoV-2 infection [13,14]. VIP and PACAP also
418 diminished the production of the proinflammatory cytokines IL-6, IL-8, TNF-α and
419 MIF by these cells, in agreement with the reported ability of these neuropeptides to
420 regulate the inflammatory response [24–27,64]. We found similar results with lung
421 epithelial cells, supporting that VIP and PACAP may offer a critical protection to
422 inflamed lungs affected by SARS-CoV-2 replication. It is possible that the higher

423 amounts of VIP in patients with severe forms of infection may reflect a counter-
424 regulatory feedback elicited by the dysregulated immune response of these patients.

425 We detected that the transcription factor CREB, which can act as a negative
426 regulator of NF-kB [65,66], is down-regulated in SARS-CoV-2-infected monocytes,
427 in opposition to NF-kB activation in the same cells, and that VIP and PACAP
428 reversed both phenomenon in infected monocytes. In some models [67–72], CREB
429 activation is related to induction of anti-inflammatory cytokines concomitant with
430 reduction of pro-inflammatory molecules and through competition with NF-kB by
431 their shared co-activator protein CBP/p300 [51,65,66,72]. CREB activation is also
432 involved with the anti-apoptotic response in monocytes and macrophages, during
433 differentiation and inflammatory stimuli [73,74]. The imbalance between CREB and
434 NF-kB, either as a direct effect of infection by SARS-CoV-2 or a consequence of
435 exposure of bystander cells to viral products and inflammatory molecules, could be
436 an important target for inhibition of SARS-CoV-2 deleterious effects, at least in
437 monocytes and probably also in lung cells, as a similar imbalance between CREB
438 and NF-kB was observed in an acute inflammatory pulmonary condition [53].

439 Induction of SREBP activity by SARS-CoV-2 was consistent with data
440 showing its increase and association with COVID-19 severity in patients [60].
441 SREBP1 regulates the expression of genes of fatty acid biosynthesis, whilst
442 SREBP2 regulates genes involved in cholesterol biosynthesis, intracellular lipid
443 movement and lipoprotein import [75]. While crucial for metabolic homeostasis, both
444 transcription factors are involved in pathologies when misbalanced or overactivated
445 [75], and several viruses are reported to induce their activation, as the up-regulation
446 of host lipid biosynthesis is a requirement for their optimal replication [55–57]. As

reported by our group [58] and others authors [59], recently reported that SARS-CoV-2 activates SREBP-1 and other pathways of lipid metabolism in human cells, and that lipid droplets enhance viral replication and production of inflammatory mediators. Similar to NF-kB and CREB, the association of SREBPs with CBP/p300 [54] makes its function susceptible to the availability of this co-factor, which abundance can be low or high depending on the state of activation of NF-kB and CREB. Thus, the modulation of each one of these factors by VIP and PACAP can reflect a fine tuning of the transcriptional regulation of metabolic and inflammatory pathways, which in turn can affect the replication of SARS-CoV-2. Our results with inhibitors of SREBPs and NF-KB, used alone or in combination with either neuropeptide, provide further connection between the ability of VIP and PACAP to regulate the activity of these transcription factors and to control viral replication and production of pro-inflammatory mediators, as well as to reduce SARS-CoV-2-induced cell damages. The decline of viral genome replication and production of inflammatory cytokines secondary to SREBP blockage are in agreement with previous reports showing that this transcription factor is essential for replication of a broad range of viruses, including coronaviruses in Calu-3 cells [55–57,59] and contributes to cytokine storm in COVID-19 patients [60]. The diminished production of TNF-α and lL-6 in our assays due to NF-KB inhibition agrees with its well-known role to eliciting inflammatory responses. Overall, we believe that the protecting role of VIP and PACAP against SARS-CoV-2 infection in vitro can be explained, at least in part, by their ability to simultaneously regulate the signaling pathways elicited by these transcription factors. Our findings are summarized in the model presented in Fig. 7.

Because VIP and PACAP signaling outcome is dependent of the combined action of the receptors activated by them (VIP and PACAP receptors can elicit cell signaling in homo and hetero dimers; 72), we evaluated whether they were involved in the final outcome analyzed. Our assays suggest that signaling through the receptors VPAC1 and VPAC2 contributed for VIP- and PACAP-mediated reduction of SARS-CoV-2 RNA synthesis in monocytes and viral production in Calu-3 cells, with VPAC1 activation alone being able to reproduce the SARS-CoV-2 inhibition promoted by the natural neuropeptides. The inhibition profile of SARS-CoV-2 by VIP and PACAP in Calu-3 cells may be biased regarding the expected action in the lungs, since Calu-3 cells appear to express only VPAC1 [43]. However, lung tissues, while reported to express high levels of VPAC1, also express VPAC2 and PAC1 [44,46], and, more specifically, VPAC2 mRNA was detected in airway epithelial, glandular, and immune cells of the lung [45]. Therefore, while the inhibition curve of SARS-CoV-2 by VIP and PACAP in Calu-3 cells points to different optimal doses than those obtained for monocytes, it is possible that in normal lung cells and tissue, VIP and PACAP could present a broader range of action in the inhibition of SARS-CoV-2. In fact, VIP and specific agonists for VPAC1 or VPAC2 have been proposed and tested for respiratory conditions, such as asthma [77–79], pulmonary arterial hypertension (PAH) [77,80,81] and chronic obstructive pulmonary disease (COPD) [77,78,82], demonstrating that the anti-inflammatory actions of VIP and PACAP can be achieved in lung tissues. Future studies should define which of these receptors would preferentially be activated by specific agonists to restrain SARS-CoV-2 replication in lungs or other sites. Also, as G-coupled receptors ligands, it is expected that VIP and PACAP curve profiles be subject to variation due receptor density in cell, receptor isoforms, and subtypes of associated G proteins. Those

496 factors can influence the threshold and outcome of activation, and have been
497 described for a variety of G-coupled receptors, including VIP/PACAP receptors [83–
498 85]. Together with the possible differences of receptor expression and self-
499 regulatory characteristics of GPCRs, a third regulation level of VIP and PACAP
500 action on pulmonary cells can be achieved by the activity of proteases and
501 peptidases, as lungs are described to express high levels of several of them in both
502 normal and pathological conditions [86–88]. Some of these peptidases could target
503 VIP and PACAP, thus altering the ligand/receptor ratio and modulating the signaling
504 pathways.

505 Since our results were obtained with the pandemic SARS-CoV-2 D614G, we cannot
506 assure that the VIP and PACAP protective effects will also prevail against emerging
507 variants. Nonetheless, given that both neuropeptides regulate cellular mechanisms,
508 actions that might be independent of virus genotypes, we suppose that their
509 protective effects will likely be replicated against SARS-CoV-2 variants.

510 As up to now the availability of antivirals specific to SARS-CoV-2 is limited, and that
511 the hyper-inflammation may persist in COVID-19 patients even after the lowering of
512 the viral load, the searching for compounds that target the aberrant production of
513 proinflammatory cytokines and, simultaneously, the own viral replication, should be
514 stimulated. Our present results showing that VIP and PACAP hold these two critical
515 activities point these neuropeptides or their analogue molecules as potential
516 therapeutic agents for COVID-19.

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Statement of Ethics

Experimental procedures involving human cells from healthy donors were performed with samples obtained after written informed consent and were approved by the Institutional Review Board (IRB) of the Oswaldo Cruz Institute/Fiocruz (Rio de Janeiro, RJ, Brazil) under the number 49971421.8.0000.5248. The National Review Board approved the study protocol (CONEP 30650420.4.1001.0008) for clinical samples, and informed consent was obtained from all participants or patients' representatives.

Conflict of Interest Statement

The authors declare no competing financial interests.

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Author Contribution

Conceived the study: JRT, TMLS, DCBH; Designed the experiments: JRT, PTB, TMLS, DCBH; Performed the experiments: JRT, CQS, NFR, CRRP, CSF, SSGD, ACF, MM, VCS, LT, IGAQ, EDH, PK; Analyzed the data: JRT, PTB, IGAQ, EDH, PK, FAB, TMLS, DCBH; Wrote the paper: JRT, PTB, TMLS, DCBH. All authors reviewed and approved the manuscript.

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Figure legends

Figure 1. **Plasma levels of VIP are elevated in patients with severe forms of COVID-19 and associates with reduced levels of inflammatory markers and with survival.** The levels of VIP (**A**) in the plasma of SARS-CoV-2-negative control participants, SARS-CoV-2-positive asymptomatic subjects, or symptomatic patients presenting mild to severe COVID-19 were quantified by ELISA. Correlation between levels of VIP and viral load (**B**) or inflammation markers (**C-I**). Severe COVID-19 patients admitted to the ICU were sub-divided between those requiring invasive mechanical ventilation or noninvasive O_2 supplementation (**J**) and according to the 28-day mortality outcome as survivors or non survivors (**K**). Linear regression (with the 95% confidence interval) and Spearman's correlation were calculated according to the distribution of the data. Dots represent: Controls, grey; Asymptomatics, blue; Mild, brown; Severe, red). The horizontal lines in the box plots represent the median, the box edges represent the interquartile ranges, and the whiskers indicate the minimal and maximal value in each group. *$p \leq .05$; **$p \leq .01$.

Figure 2. VIP and PACAP reduce SARS-CoV-2 RNA synthesis in human primary monocytes and viral replication in pulmonary cells, protecting them from virus-mediated cytopathic effects. Monocytes (**A, B**) and Calu-3 cells (**C, D**) were exposed (overnight) or not to the indicated concentrations of VIP (**A, C**) or PACAP (**B, D**). Culture medium was removed and then cells were infected with SARS-CoV-2. After infection, viral input was removed and cells were washed, then re-exposed to the neuropeptides. Viral RNA synthesis was evaluated by qPCR in monocytes 24 hours after infection. In Calu-3 cells, supernatants were collected at 48 hours after infection, and viral replication was evaluated by quantifying PFUs in

872 Vero E6 plaque assays. Cellular viability was analyzed by measuring LDH release
873 in the supernatants of uninfected or SARS-CoV-2-infected monocytes (**E**) treated or
874 not with VIP or PACAP (10 nM), and Calu-3 cells (**F**) treated or not with VIP (1 nM)
875 or PACAP (50 nM). Data in (**A, B**) are shown normalized to infected cells kept only
876 with culture medium, and in (**C, D, E, F**) represent means ± SD of absolute values.
877 *$p \leq .05$; **$p \leq .01$; (A, B, E) n=6; (C, D, F) n=5. Each dot represents an independent
878 assay with three replicates.

879 **Figure 3**. **Receptor contribution for the VIP and PACAP mediated inhibition of**
880 **SARS-CoV-2 replication.** Monocytes (**A**) and Calu-3 cells (**B**) were treated
881 (overnight) or not with agonists for VIP and PACAP receptors, as indicated, at
882 different concentrations. Culture medium was removed and then cells were infected
883 with SARS-CoV-2. After infection, viral input was removed, and cells were washed,
884 and then re-exposed to the receptor agonists. Viral RNA synthesis was evaluated
885 by qPCR in monocytes 24 hours after infection. In Calu-3 cells, supernatants were
886 collected at 48 hours after infection, and viral replication was evaluated by
887 quantifying PFUs in Vero E6 plaque assays. Data in (**A**) are shown normalized to
888 infected cells kept only with culture medium, and in (**B**) represents means ± SD of
889 absolute values. *$p \leq .05$; **$p \leq .01$; ***$p \leq .001$; (A, B) n=4. Each dot represents an
890 independent assay with three replicates.

891 **Figure 4**. **VIP and PACAP reduce the production of proinflammatory mediators**
892 **by SARS-CoV-2-infected monocytes and Calu-3 cells.** Monocytes (**A**) and Calu-
893 3 cells (**B**) were treated (overnight) or not with VIP or PACAP (10 nM each for
894 monocytes, 1 nM of VIP or 50 nM of PACAP for Calu-3 cells). Culture medium was
895 removed and then cells were infected with SARS-CoV-2. After infection, viral input

was removed and cells were washed, and then re-exposed to the neuropeptides. The levels of IL-6, IL-8, TNF-α and MIF were measured in culture supernatants of monocytes after 24 hours (**A**), and of IL-6 and IL-8 after 48 hours for Calu-3 cells (**B**), by ELISA. Data represent means ± SD. *$p \leq .05$; **$p \leq .01$; (A) n=6; (B) n=4. Each dot represents an independent assay with three replicates.

Figure 5. **VIP and PACAP regulate the activation of transcription factors in SARS-CoV-2-infected monocytes.** Monocytes were treated (overnight) or not with to VIP or PACAP (10 nM), culture medium was removed and then cells were infected with SARS-CoV-2. After infection, viral input was removed, and cells were washed and then re-exposed to the neuropeptides. After 24 hours, cells were lysed and the ratios between phosphoNF-kBp65 and total NF-kBp65 (**A**), phosphoCREB and total CREB (**B**), active SREBP-1 and β-actin (**C**), and active SREBP-2 and β-actin (**D**) were quantified by ELISA (**A, B**) or by western blot (**C, D**) in the cell lysates. Data represent means ± SD. *$p \leq .05$; **$p \leq .01$; ***$p \leq .001$; (A, B) n=3; (C, D) n=4. Each dot represents an independent assay with three replicates.

Figure 6. **Inhibition of NF-kB and SREBP in monocytes reduces SARS-CoV-2 RNA synthesis, production of proinflammatory mediators and protects the cells from virus-mediated cytopathic effects.** Monocytes were treated (overnight) or not with to VIP or PACAP (5 nM), culture medium was removed and then cells were infected with SARS-CoV-2. After infection, viral input was removed, and cells were washed and then re-exposed to the neuropeptides associated or not with inhibitors of SREBP (AM580, 10 uM) or NF-kB (Bay 11-7082, 10 uM). Viral RNA synthesis (A), cellular viability (B) and levels of TNF-α and IL-6 **(C, D)** were evaluated by qPCR, ELISA and LDH release, respectively, in the culture

supernatants 24 hours after infection. Data in (**A**) are shown normalized to infected cells kept only with culture medium, and in (B, C, D) represent means ± SD of absolute values. *$p \leq .05$; **$p \leq .01$; ***$p \leq .001$; (A - D) n=6. Each dot represents an independent assay with three replicates.

Figure 7. **Graphical summary of study data.** In severe COVID-19 patients, VIP plasma levels correlated with decreased inflammatory markers and survival. In in vitro assays with monocytes and lung epithelial cells, VIP and PACAP were found to decrease SARS-CoV-2 RNA synthesis (monocytes) and viral replication (lung epithelial cells). Both neuropeptides also reduced inflammatory factors and cell death of infected cells. Created with BioRender.com

Table 1: Characteristics of COVID-19 patients and control subjects.

Characteristics[1]	Control (n=10)	Asymptomatic/ Mild (n=10)	Severe/critical (n=24)
Age, years	53 (32 – 60)	43 (24 – 52)	58 (48 – 66)
Sex, male	4 (40%)	4 (40%)	12 (50%)
Respiratory support			
Oxygen supplementation	0 (0%)	0 (0%)	5 (20.8%)
Mechanical ventilation	0 (0%)	0 (0%)	19 (79.2%)
SAPS 3	-	-	60 (55 – 71)
PaO2/FiO2 ratio	-	-	154 (99 – 373)
Vasopressor	-	-	10 (41.6%)
Time from symptom onset to blood sample, days	-	6 (-1 – 8)[2]	14 (8 – 17)
28-day mortality	-	-	13 (54.2%)
Comorbidities			
Obesity	1 (10%)	1 (10%)	5 (20.8%)
Hypertension	1 (10%)	2 (20%)	6 (25%)
Diabetes	0 (0%)	0 (0%)	9 (37.5%)
Cancer	0 (0%)	0 (0%)	3 (12.5%)
Heart disease[3]	0 (0%)	0 (0%)	2 (8.3%)
Presenting symptoms			
Cough	0 (0%)	3 (30%)	17 (70.8%)
Fever	0 (0%)	5 (50%)	18 (75%)
Dyspnea	0 (0%)	0 (0%)	20 (83.3%)
Headache	0 (0%)	4 (40%)	3 (12.5%)

Anosmia	0 (0%)	4 (40%)	8 (33.3%)
Laboratory findings on admission			
Leukocytes, x 1000/µL	-	-	138 (102 – 180)
Lymphocyte, cells/µL	-	-	1,167 (645 – 1,590)
Monocytes, cells/µL	-	-	679 (509 – 847)
Platelet count, x 1000/µL	-	-	169 (137 – 218)
C Reactive Protein, mg/L[4]	0.1 (0.1 – 0.18)	0.2 (0.1 – 0.13)	178 (74 – 308)*
Fibrinogen, mg/dL[4]	281 (232 – 302)	248 (182 – 341)	528 (366 – 714)*
D-dimer, IU/mL[4]	292 (225 – 476)	191 (187 – 313)	4836 (2364 – 10816)*

[1]Numerical variables are represented as the median and the interquartile range, and qualitative variables are represented as the number and the percentage.
[2]Day of sample collection after the onset of symptoms was not computed for asymptomatic subjects.
[3]Coronary artery disease or congestive heart failure.
[4]Reference values of C reactive Protein (0.00 – 1.00), Fibrinogen (238 – 498 mg/dL) and D-dimer (0 – 500 ng/mL).
*$p < 0.05$ compared to control. The qualitative variables were compared using the two tailed Fisher exact test, and the numerical variables using the t test for parametric and the Mann Whitney U test for nonparametric distributions.

Figure 1

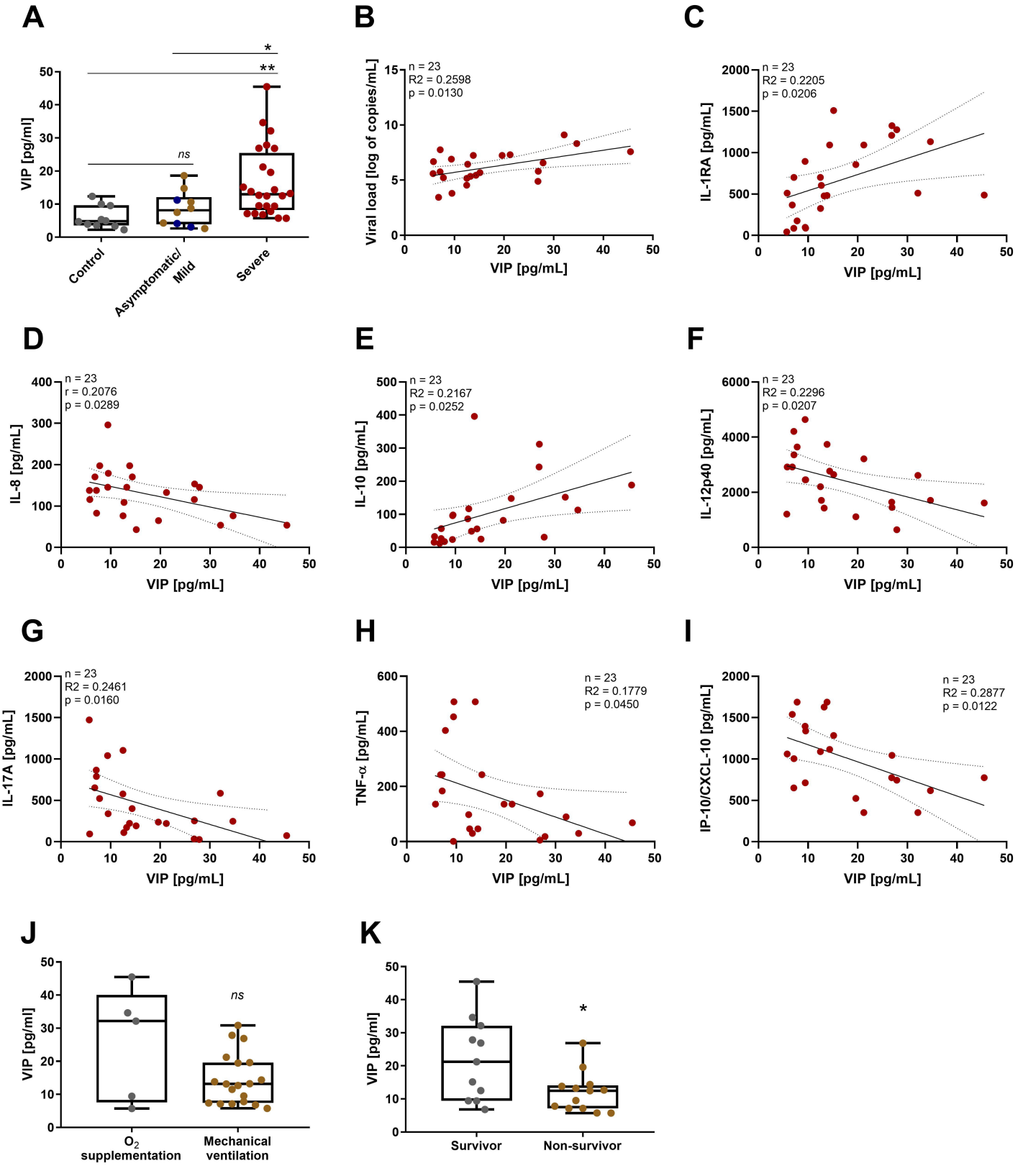

A
VIP [pg/ml]
Control
Asymptomatic/ Mild
Severe
ns
*
**
B
Viral load [log of copies/mL]
n = 23
R2 = 0.2598
p = 0.0130
VIP [pg/mL]
C
IL-1RA [pg/mL]
n = 23
R2 = 0.2205
p = 0.0206
VIP [pg/mL]
D
IL-8 [pg/mL]
n = 23
r = 0.2076
p = 0.0289
VIP [pg/mL]
E
IL-10 [pg/mL]
n = 23
R2 = 0.2167
p = 0.0252
VIP [pg/mL]
F
IL-12p40 [pg/mL]
n = 23
R2 = 0.2296
p = 0.0207
VIP [pg/mL]
G
IL-17A [pg/mL]
n = 23
R2 = 0.2461
p = 0.0160
VIP [pg/mL]
H
TNF-α [pg/mL]
n = 23
R2 = 0.1779
p = 0.0450
VIP [pg/mL]
I
IP-10/CXCL-10 [pg/mL]
n = 23
R2 = 0.2877
p = 0.0122
VIP [pg/mL]
J
VIP [pg/ml]
ns
O2 supplementation
Mechanical ventilation
K
VIP [pg/ml]
*
Survivor
Non-survivor

Figure 2

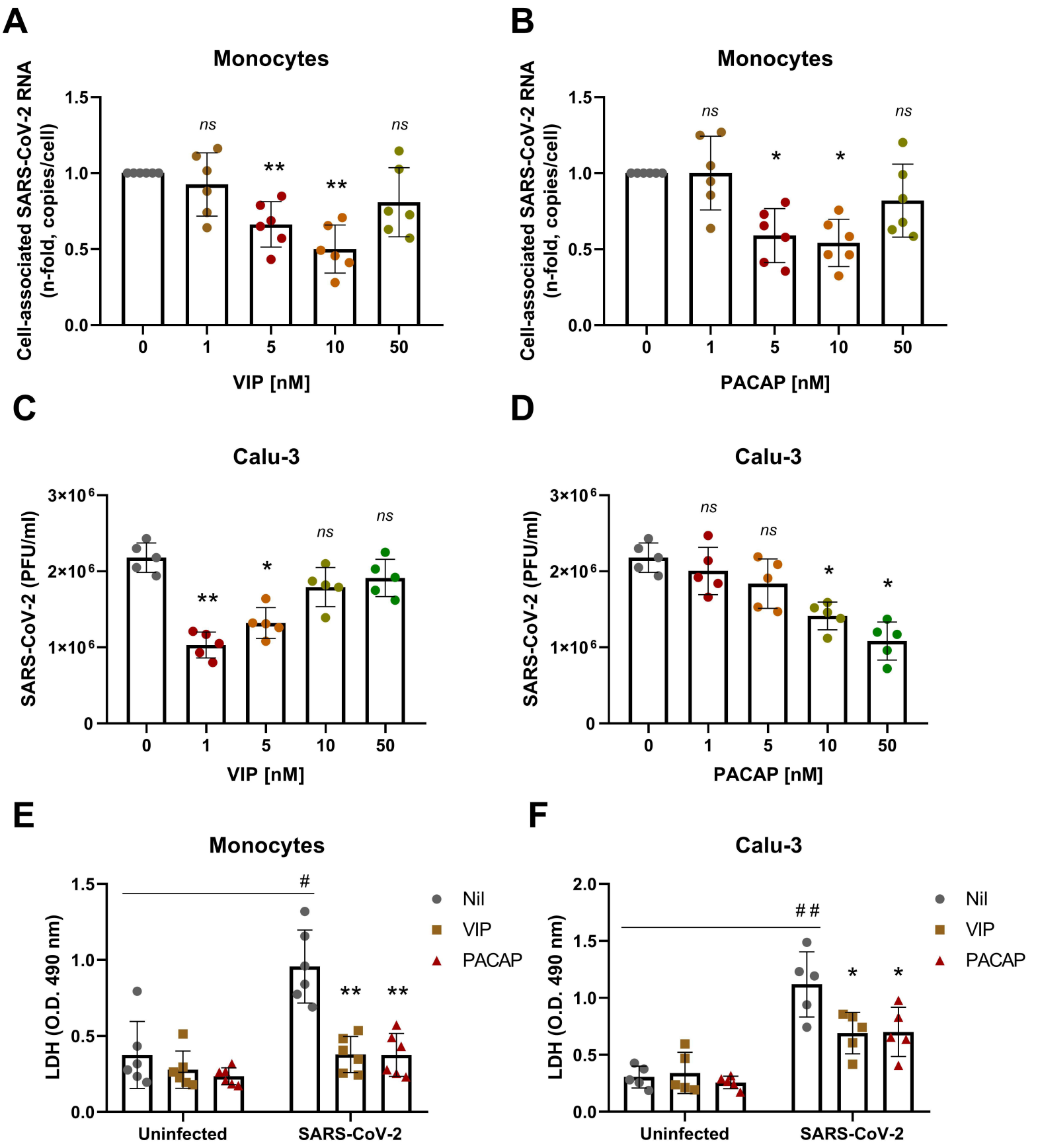

A
Monocytes
Cell-associated SARS-CoV-2 RNA (n-fold, copies/cell)
1.5
1.0
0.5
0.0
ns
**
**
ns
0
1
5
10
50
VIP [nM]
B
Monocytes
Cell-associated SARS-CoV-2 RNA (n-fold, copies/cell)
1.5
1.0
0.5
0.0
ns
*
*
ns
0
1
5
10
50
PACAP [nM]
C
Calu-3
SARS-CoV-2 (PFU/ml)
3×10⁶
2×10⁶
1×10⁶
0
**
*
ns
ns
0
1
5
10
50
VIP [nM]
D
Calu-3
SARS-CoV-2 (PFU/ml)
3×10⁶
2×10⁶
1×10⁶
0
ns
ns
*
*
0
1
5
10
50
PACAP [nM]
E
Monocytes
LDH (O.D. 490 nm)
1.5
1.0
0.5
0.0
#
**
**
Nil
VIP
PACAP
Uninfected
SARS-CoV-2
F
Calu-3
LDH (O.D. 490 nm)
2.0
1.5
1.0
0.5
0.0
##
*
*
Nil
VIP
PACAP
Uninfected
SARS-CoV-2

Figure 3

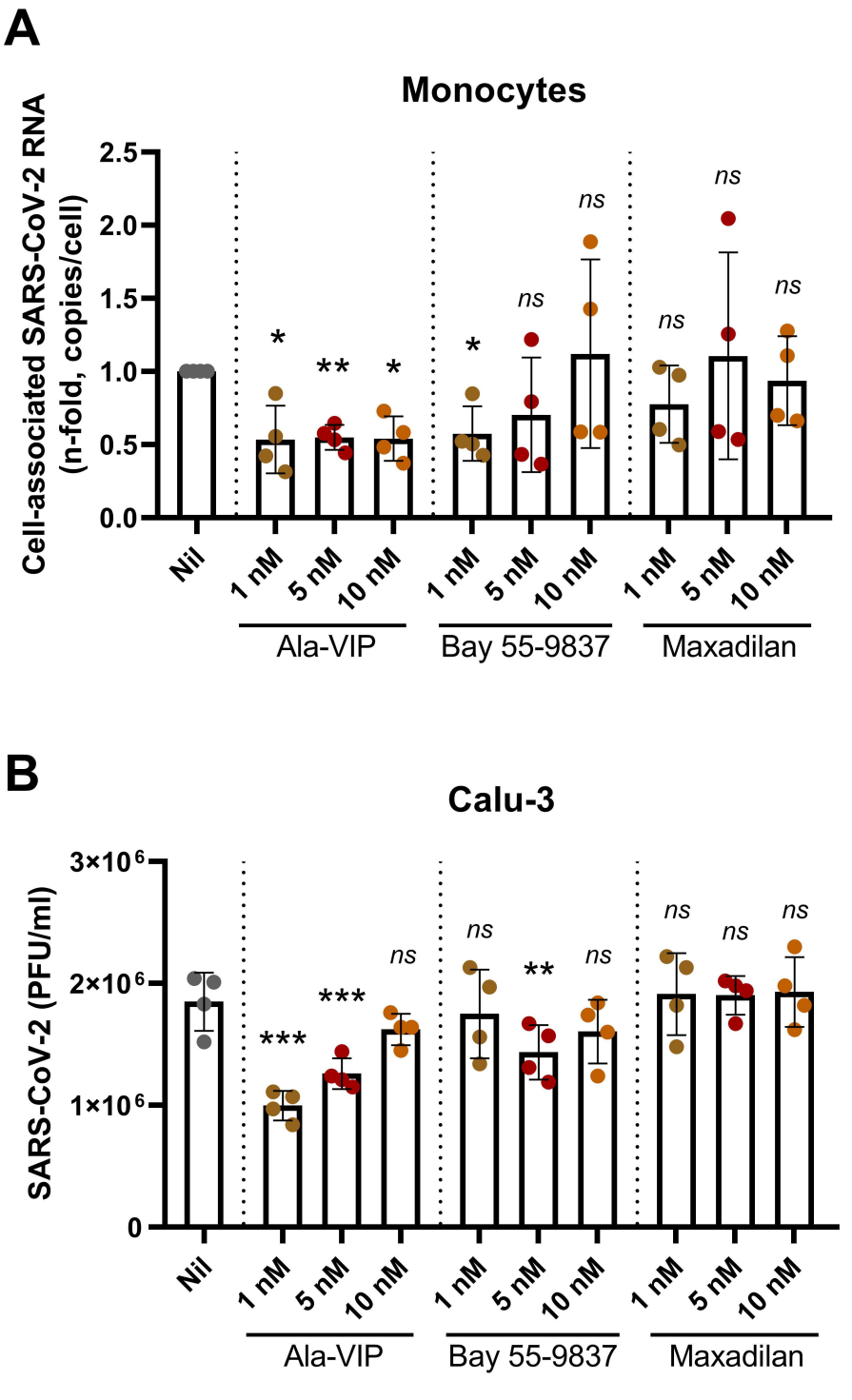

A
Monocytes
Cell-associated SARS-CoV-2 RNA (n-fold, copies/cell)
2.5
2.0
1.5
1.0
0.5
0.0
*
**
*
*
ns
ns
ns
ns
ns
Nil
1 nM
5 nM
10 nM
1 nM
5 nM
10 nM
1 nM
5 nM
10 nM
Ala-VIP
Bay 55-9837
Maxadilan
B
Calu-3
SARS-CoV-2 (PFU/ml)
3×10⁶
2×10⁶
1×10⁶
0
***
***
ns
ns
**
ns
ns
ns
ns
Nil
1 nM
5 nM
10 nM
1 nM
5 nM
10 nM
1 nM
5 nM
10 nM
Ala-VIP
Bay 55-9837
Maxadilan

Figure 4

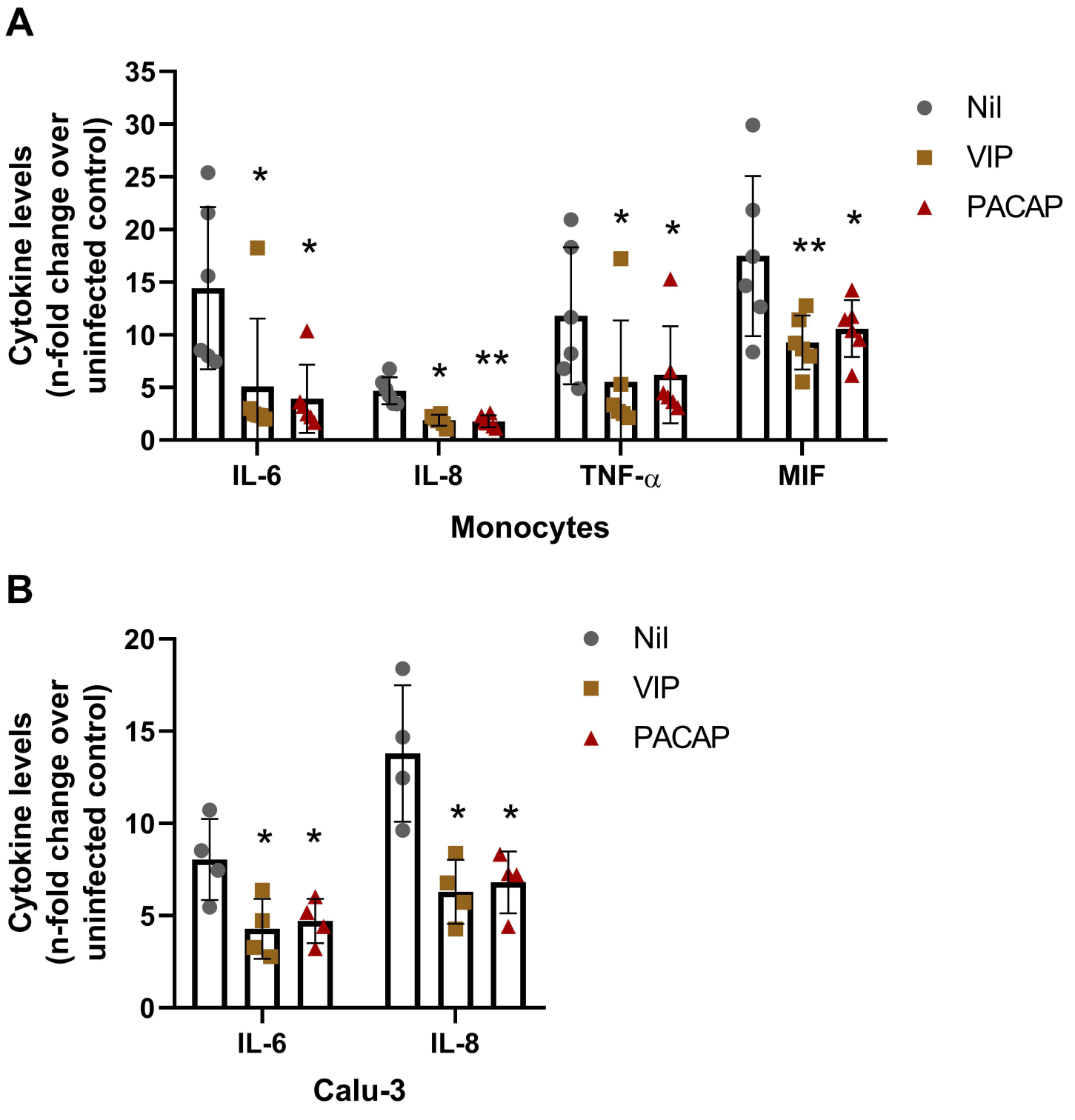

A
Cytokine levels (n-fold change over uninfected control)
35
30
25
20
15
10
5
0
*
*
*
**
*
*
**
*
IL-6
IL-8
TNF-α
MIF
Monocytes
Nil
VIP
PACAP
B
Cytokine levels (n-fold change over uninfected control)
20
15
10
5
0
*
*
*
*
IL-6
IL-8
Calu-3
Nil
VIP
PACAP

Figure 5

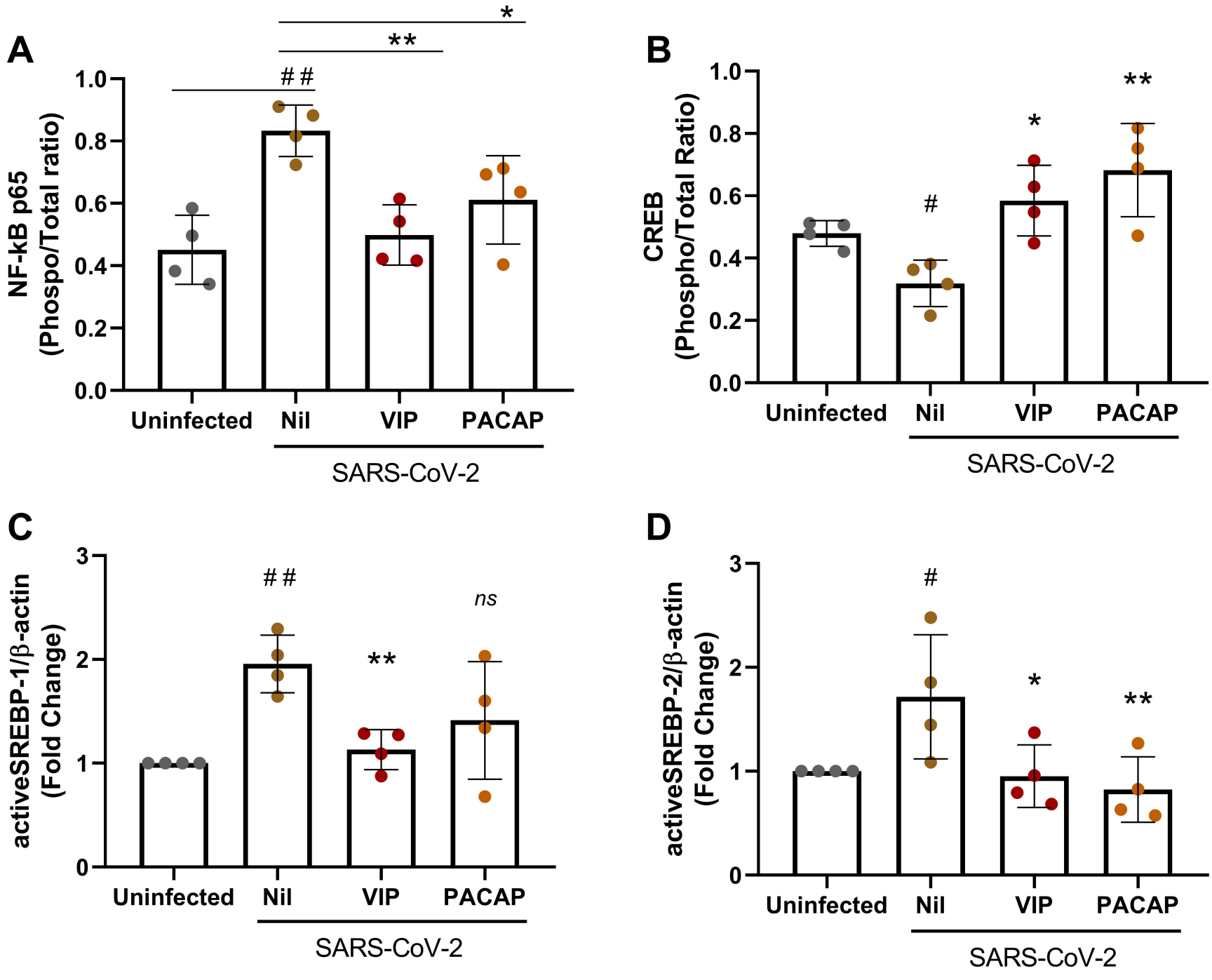
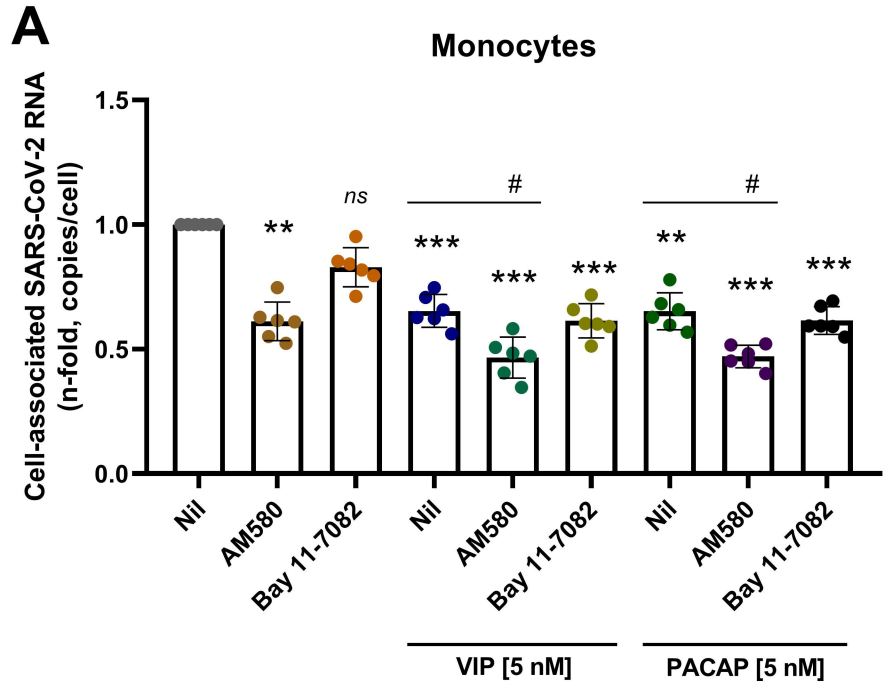
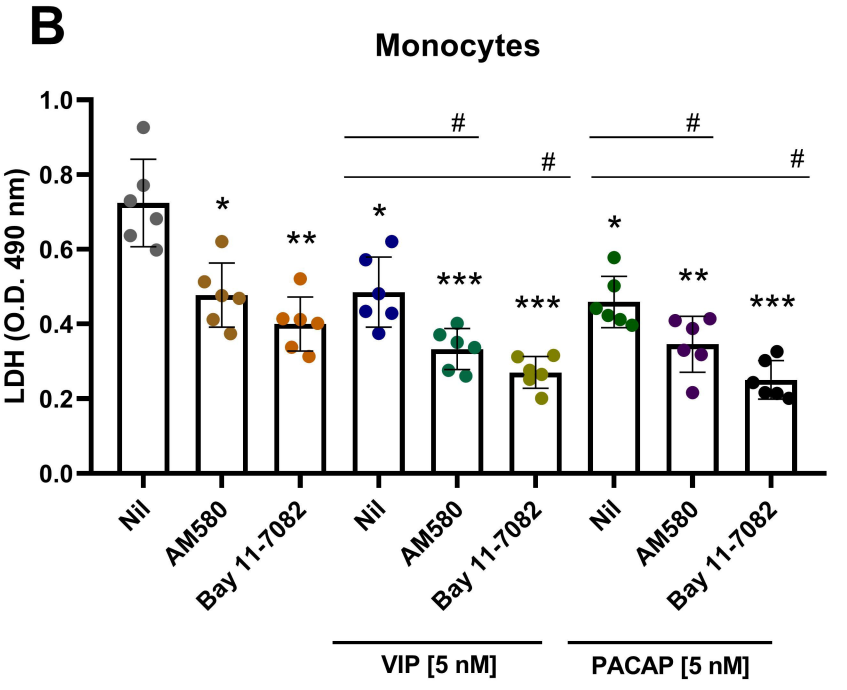
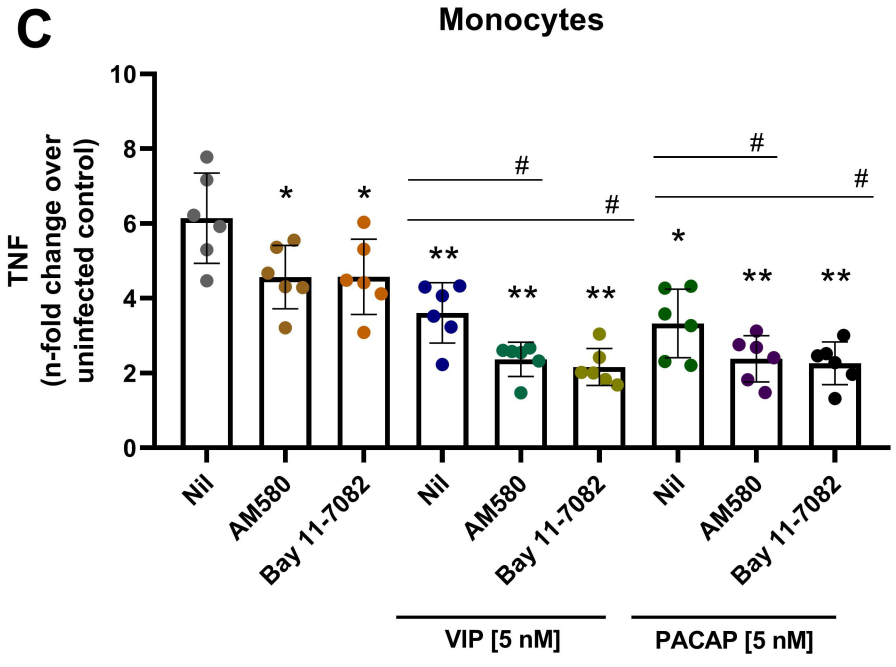

A
NF-kB p65 (Phospo/Total ratio)
1.0
0.8
0.6
0.4
0.2
0.0
##
**
*
Uninfected
Nil
VIP
PACAP
SARS-CoV-2
B
CREB (Phospho/Total Ratio)
1.0
0.8
0.6
0.4
0.2
0.0
#
*
**
Uninfected
Nil
VIP
PACAP
SARS-CoV-2
C
activeSREBP-1/β-actin (Fold Change)
3
2
1
0
##
**
ns
Uninfected
Nil
VIP
PACAP
SARS-CoV-2
D
activeSREBP-2/β-actin (Fold Change)
3
2
1
0
#
*
**
Uninfected
Nil
VIP
PACAP
SARS-CoV-2

Figure 6


A
Monocytes
Cell-associated SARS-CoV-2 RNA (n-fold, copies/cell)
1.5
1.0
0.5
0.0
ns
**
***
***
***
**
***
***
#
#
Nil
AM580
Bay 11-7082
Nil
AM580
Bay 11-7082
Nil
AM580
Bay 11-7082
VIP [5 nM]
PACAP [5 nM]


B
Monocytes
LDH (O.D. 490 nm)
1.0
0.8
0.6
0.4
0.2
0.0
*
**
*
***
***
*
**
***
#
#
#
#
Nil
AM580
Bay 11-7082
Nil
AM580
Bay 11-7082
Nil
AM580
Bay 11-7082
VIP [5 nM]
PACAP [5 nM]


C
Monocytes
TNF (n-fold change over uninfected control)
10
8
6
4
2
0
*
*
**
**
**
*
**
**
#
#
#
#
Nil
AM580
Bay 11-7082
Nil
AM580
Bay 11-7082
Nil
AM580
Bay 11-7082
VIP [5 nM]
PACAP [5 nM]

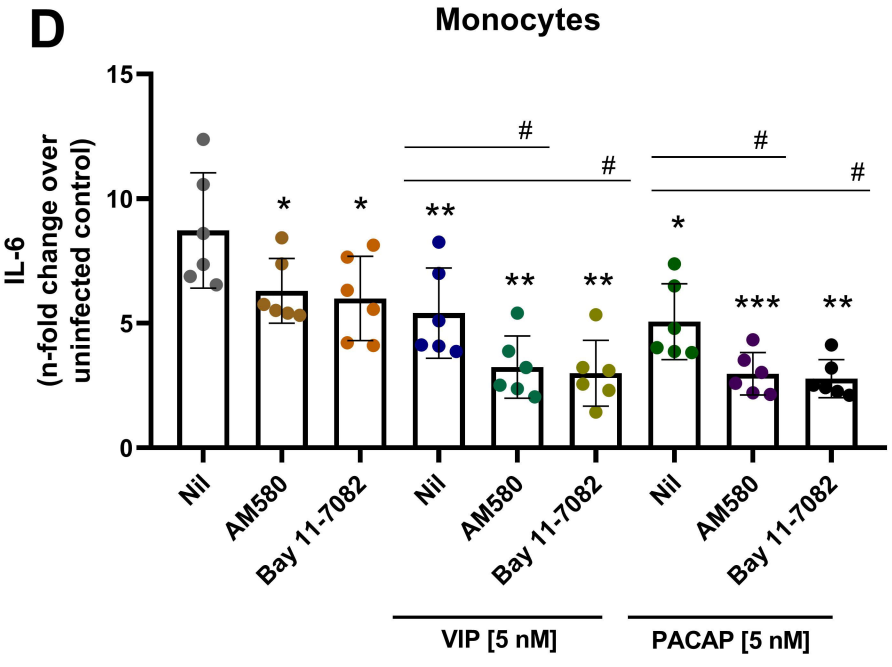
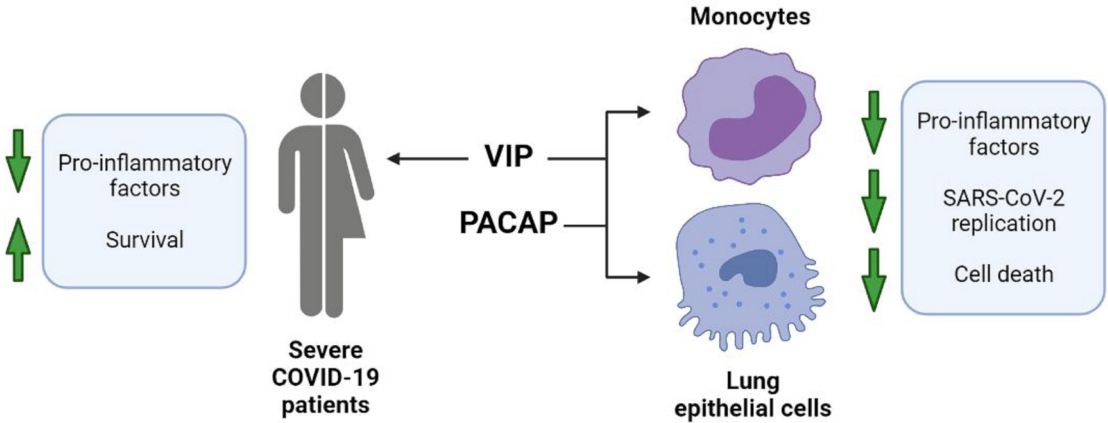

D
Monocytes
IL-6 (n-fold change over uninfected control)
15
10
5
0
*
*
**
**
**
*
***
**
#
#
#
#
Nil
AM580
Bay 11-7082
Nil
AM580
Bay 11-7082
Nil
AM580
Bay 11-7082
VIP [5 nM]
PACAP [5 nM]

Figure 7


Monocytes
Pro-inflammatory factors
Survival
VIP
PACAP
Pro-inflammatory factors
SARS-CoV-2 replication
Cell death
Severe COVID-19 patients
Lung epithelial cells