Since January 2020 Elsevier has created a COVID-19 resource centre with free information in English and Mandarin on the novel coronavirus COVID-19. The COVID-19 resource centre is hosted on Elsevier Connect, the company's public news and information website.

Elsevier hereby grants permission to make all its COVID-19-related research that is available on the COVID-19 resource centre - including this research content - immediately available in PubMed Central and other publicly funded repositories, such as the WHO COVID database with rights for unrestricted research re-use and analyses in any form or by any means with acknowledgement of the original source. These permissions are granted for free by Elsevier for as long as the COVID-19 resource centre remains active.
The FDA-approved gold drug aurano
sensitive cell death pathways (Diaz et al., 2019; Chirullo et al., 2013). A preclinical study showed that aurano
zymes leads to cellular oxidative stress and intrinsic apoptosis (Lugea et al., 2017; Thangamani et al., 2016). Inhibition of these redox en-
zymes results in a 95% reduction in the viral RNA at 48 h after infection. Aurano treatment dra-
matically reduced the expression of SARS-COV-2-induced cytokines in human cells. These data indicate that aurano could be a useful drug to limit SARS-COV-2 infection and associated lung injury due to its antiviral, anti-inflammatory and anti-reactive oxygen species (ROS) properties. Further animal studies are warranted to evaluate the safety and efficacy of aurano for the management of SARS-COV-2 associated disease.

SARS-COV-2 has recently emerged as a new public health threat. Herein, we report that the FDA-approved drug, aurano, inhibits SARS-COV-2 replication in human cells at low micro molar concentration. Treatment of cells with aurano resulted in a 95% reduction in the viral RNA at 48 h after infection. Aurano treatment dra-
matically reduced the expression of SARS-COV-2-induced cytokines in human cells. These data indicate that aurano could be a useful drug to limit SARS-COV-2 infection and associated lung injury due to its antiviral, anti-inflammatory and anti-reactive oxygen species (ROS) properties. Further animal studies are warranted to evaluate the safety and efficacy of aurano for the management of SARS-COV-2 associated disease.

Gold-based compounds have shown promising activity against a wide range of clinical conditions and microorganism infections. Aurano, a gold-containing triethyl phosphine, is an FDA-approved drug for the treatment of rheumatoid arthritis since 1985 (Roder and Thomson, 2015). It has been investigated for potential therapeutic application in a number of other diseases including cancer, neurodegenerative disorders, HIV/AIDS, parasitic infections and bacterial infections (Roder and Thomson, 2015; Harbut et al., 2015). Aurano was approved by FDA for phase II clinical trials for cancer therapy (Hou et al., 2018; Oh et al., 2017; Rigobello et al., 2009). Oral aurano was effective in rodent models of various parasitic infections (Leitsch, 2017; Capparelli et al., 2017). A preclinical study showed that aurano significantly reduces HIV load in combination with antiretroviral therapy (Lewis et al., 2011). A clinical trial is ongoing to develop aurano as a drug candidate to reduce the latent viral reservoir in patients with HIV infection utilizing the role of aurano in redox-sensitive cell death pathways (Diaz et al., 2019; Cirillo et al., 2013).

The mechanism of action of aurano involves the inhibition of redox enzymes such as thioredoxin reductase, induction of endoplasmic reticulum (ER) stress and subsequent activation of the unfolded protein response (UPR) (Harbut et al., 2015; May et al., 2018; Wiederhold et al., 2017; Thangamani et al., 2016). Inhibition of these redox enzymes leads to cellular oxidative stress and intrinsic apoptosis (Lugea et al., 2017; Hetz, 2012). In addition, aurano is an anti-inflammatory drug that reduces cytokines production and stimulate cell-mediated immunity (Walz et al., 1983). It has been reported that aurano interferes with the Interleukin 6 (IL-6) signaling by inhibiting phos-
phorylation of JAK1 and STAT3 (Han et al., 2008; Kim et al., 2007). The dual inhibition of inflammatory pathways and thiol redox enzymes by aurano makes it an attractive candidate for cancer therapy and treating microbial infections.

Coronaviruses are a family of enveloped viruses with positive sense, single-stranded RNA genomes (Rothan and Byrareddy, 2020). SARS-CoV-2, the causative agent of COVID-19, is closely related to severe acute respiratory syndrome coronavirus (SARS-CoV-1) (Rothan and Byrareddy, 2020; Mehta et al., 2020). It is known that ER stress and UPR activation contribute significantly to the viral replication and pa-
thogenesis during a coronavirus infection (Fung and Liu, 2014). Infection with SARS-CoV-1 increases the expression of the ER protein folding chaperons GRP78, GRP94 and other ER stress related genes to maintain protein folding (Tang et al., 2005). Cells overexpressing the SARS-CoV spike protein and other viral proteins exhibit high levels of UPR activation (Siu et al., 2014; Sung et al., 2009). Thus, inhibition of redox enzymes such as thioredoxin reductase and induction of ER stress by aurano could significantly affect SARS-COV-2 protein synthesis (Rothan and Kumar, 2019).

In addition, SARS-COV-2 infection causes acute inflammation and neutrophilia that leads to a cytokine storm with over expression of IL-6, TNF-alpha, monocyte chemoattractant protein (MCP-1) and reactive oxygen species (ROS) (Mehta et al., 2020). The severe COVID-19 illness
represents a devastating inflammatory lung disorder due to cytokines storm that is associated with multiple organ dysfunction leading to high mortality (Mehta et al., 2020; Sarzi-Puttini et al., 2020). Taken together, these studies suggest that auranoﬁn could mitigate SARS-COV-2 infection and associated lung damage due to its anti-viral, anti-inﬂammatory and anti-ROS properties.

We investigated the anti-viral activity of auranoﬁn against SARS-CoV-2 and its effect on virus-induced inﬂammation in human cells. We infected Huh7 cells with SARS-CoV-2 (USA-WA1/2020) at a multiplicity of infection (MOI) of 1 for 2 h and treated with 4 μM of auranoﬁn or with 0.1% DMSO. Cell pellets and culture supernatants were collected at 24 and 48 h after infection and viral RNA levels were measured by RT-PCR using primers and probe targeting the SARS-COV-2 N1 region and the SARS-COV-2 N2 region. The cellular RNA extracted from infected cells was quantiﬁed, normalized and viral RNA levels per ug of total cellular RNA were calculated. The results were identical for both set of primers showing dramatic reduction in viral RNA at both 24 and 48 h. SARS-COV-2 infectivity titers were measured in cell culture supernatants at 48 h after infection by plaque assay. Data represent the mean ± SEM, representing two independent experiments conducted in duplicate, t-test p < 0.001.

Fig. 1. Auranoﬁn inhibits replication of SARS-COV-2 in human cells. Huh7 cells were infected with SARS-COV-2 at a multiplicity of infection (MOI) of 1 for 2 h and treated with 4 μM of auranoﬁn or with 0.1% DMSO. Cell pellets and culture supernatants were collected at 24 and 48 h after infection and viral RNA levels were measured by RT-PCR using primers and probe targeting the SARS-COV-2 N1 region and the SARS-COV-2 N2 region. The cellular RNA extracted from infected cells was quantiﬁed, normalized and viral RNA levels per ug of total cellular RNA were calculated. The results were identical for both set of primers showing dramatic reduction in viral RNA at both 24 and 48 h. SARS-COV-2 infectivity titers were measured in cell culture supernatants at 48 h after infection by plaque assay. Data represent the mean ± SEM, representing two independent experiments conducted in duplicate, t-test p < 0.001.
model (GraphPad software). At 48 h, there was a dose-dependent reduction in viral RNA levels in the auranoﬁn-treated cells. Fig. 2 represents the EC_{50} values of auranoﬁn treatment against SARS-CoV-2 infected Huh7 cells. Auranoﬁn inhibited virus replication in the infected cells at EC_{50} of approximately 1.4 μM. It is important to note that in this study, we used 20 to 100-times more virus dose (MOI of 1) to infect the cells compared to the recently published reports on anti-viral activities of chloroquine, hydroxychloroquine and remdesvir against SARS-CoV-2 in vitro (Wang et al., 2020; Liu et al., 2020).

To assess the effect of auranoﬁn on inﬂammatory response during SARS-CoV-2 infection, we measured the levels of key cytokines in auranoﬁn and DMSO-treated cells at 24 and 48 h after infection (Natekar et al., 2019). SARS-CoV-2 infection induces a strong up-regulation of IL-6, IL-1β, TNFα and NF-kB in Huh7 cells (Fig. 3). Treatment with auranoﬁn dramatically reduced the expression of SARS-CoV-2-induced cytokines in Huh7 cells. SARS-CoV-2 infection resulted in a 200-fold increase in the mRNA expression of IL-6 at 48 h after infection compared to corresponding mock-infected cells. In contrast, there was only a 2-fold increase in expression of IL-6 in auranoﬁn-treated cells. TNF-α levels increased by 90-fold in the DMSO-treated cells at 48 h after infection, but this increase was absent in the auranoﬁn-treated cells. Similarly, no increase in the expression of IL-1β and NF-kB was observed in the auranoﬁn-treated cells.

Taken together these results demonstrate that auranoﬁn inhibits replication of SARS-CoV-2 in human cells at low micro molar concentration. We also demonstrate that auranoﬁn treatment resulted in signiﬁcant reduction in the expression of cytokines induced by virus infection. These data indicate that auranoﬁn could be a useful drug to limit SARS-CoV-2 infection and associated lung injury. Further animal studies are warranted to evaluate the safety and efﬁcacy of auranoﬁn for the management of SARS-CoV-2 associated disease.

1. Methods

1.1. SARS-CoV-2 infection and drug treatment

In this study, we used a novel SARS-CoV-2 (USA-WA1/2020) isolated from an oropharyngeal swab from a patient in Washington, USA (BEI NR-52281). Virus strain was ampliﬁed once in Vero E6 cells and had titers of 5 × 10^{6} plaque-forming units (PFU)/mL. Huh7 cells (human liver cell line) were grown in DMEM (Gibco) supplemented with 5% heat-inactivated fetal bovine serum. Cells were infected with SARS-CoV-2 or PBS (Mock) at a multiplicity of infection (MOI) of 1 for 2 h (Natekar et al., 2019; Azouz et al., 2019; Kim et al., 2018; Krause et al., 2019). Cell were washed twice with PBS and media containing different concentrations of auranoﬁn (0.1–10 μM, Sigma) or DMSO (0.1%, Sigma) was added to cells. Supernatants and cell lysates were harvested at 24 and 48 h after infection. The cytotoxicity of auranoﬁn in Huh7 cells was measured using trypan blue method as described previously (Varghese and Busselberg, 2014). Brieﬂy, Huh7 cells were treated with different concentrations of auranoﬁn (0.1–10 μM) for 48 h and percentage cell numbers were quantiﬁed using trypan blue.

1.2. Virus quantiﬁcation

Virus infectivity titers were measured in cell culture supernatants by plaque formation assay using Vero cells as we described previously (Natekar et al., 2019). Virus RNA levels were analyzed in the supernatant and cell lysates by quantitative reverse transcription-polymerase chain reaction (qRT-PCR). RNA from cell culture supernatants was extracted using a Viral RNA Mini Kit (Qiagen) and RNA from cell lysates was extracted using a RNeasy Mini Kit (Qiagen) as described previously (Natekar et al., 2019). The cellular RNA extracted from infected cells was quantiﬁed, normalized and viral RNA levels per ug of total cellular RNA were calculated. qRT-PCR was used to measure viral RNA levels using previously published primers and probes speciﬁc for the SARS-CoV-2. Forward (5′-GACCCCAAAATCAGCGAAAT-3′), reverse (5′-CTCTGTTACTGCCAATCCTG-3′), probe, (5′-FAM-ACCC CCGATTACGTTTTGGGTGCC-BHQ1-3′) targeting the SARS-CoV-2 N1 region and Forward (5′-TACACAAATGGCGCGAAT-3′), reverse (5′-GGCGGACATTCGAGAAAGA3′), probe, (5′-FAM-ACAATTTGGCCTCCA GCCTTAC-BHQ1-3′) targeting the SARS-CoV-2 N2 region (Integrated DNA Technologies). Viral RNA copies were determined after comparison with a standard curve produced using serial 10-fold dilutions of SARS-CoV-2 RNA (Kumar et al., 2017; Kim et al., 2018).
1.3. Cytokine analysis

For mRNA analysis of IL-6, IL-1β, TNFα and NF-κB, cDNA was prepared from RNA isolated from the cell lysates using a iScript™ cDNA Synthesis Kit (Bio-Rad, Hercules, CA, USA), and qRT-PCR was conducted as described previously (Natekar et al., 2019). The fold change in infected cells compared to corresponding controls was calculated after normalizing to the GAPDH gene. The primer sequences used for qRT-PCR are listed in Table 1.

CRediT authorship contribution statement

Hussin A. Rothan: Conceptualization, Methodology, Validation, Formal analysis, Writing - original draft. Shannon Stone: Methodology, Validation, Formal analysis. Janhavi Natekar: Methodology, Validation, Formal analysis. Pratima Kumari: Methodology, Validation, Formal analysis. Komal Arora: Formal analysis, Writing - original draft. Mukesh Kumar: Investigation, Conceptualization, Formal analysis, Writing - original draft, Writing - review & editing, Resources, Supervision, Funding acquisition.

Declaration of competing interest

Authors declare no conflict of Interest.

Acknowledgements

This work was supported by a grant (R21NS099838) from National Institute of Neurological Disorders and Stroke, grant (R21OD024896) from the Office of the Director, National Institutes of Health, and Institutional funds.

References


Han, S., Kim, K., Kim, H., Kwon, J., Lee, Y.H., Lee, C.K., Song, Y., Lee, S.J., Ha, N., Kim, K.,


