Targeting transcriptional regulation of SARS-CoV-2 entry factors ACE2 and TMPRSS2

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Contributed by Arul M. Chinnaiyan, November 18, 2020 (sent for review October 16, 2020; reviewed by William L. Dahut and Nicholas Nichols)

Severe acute respiratory syndrome coronavirus 2 (SARS-CoV-2), the virus responsible for COVID-19, employ two key host proteins to gain entry and replicate within cells, angiotensin-converting enzyme 2 (ACE2) and the cell surface transmembrane protease serine 2 (TMPRSS2). TMPRSS2 was first characterized as an androgen-regulated gene in the prostate. Supporting a role for sex hormones, males relative to females are disproportionately affected by COVID-19 in terms of mortality and morbidity. Several studies, including one employing a large epidemiological cohort, suggested that blocking androgen signaling is protective against COVID-19. Here, we demonstrate that androgens regulate the expression of ACE2, TMPRSS2, and androgen receptor (AR) in subsets of lung epithelial cells. AR levels are markedly elevated in males relative to females greater than 70 y of age. In males greater than 70 y old, smoking was associated with elevated levels of AR and ACE2 in lung epithelial cells. Transcriptional repression of the AR enhancerosome with AR or bromodomain and extraterminal domain (BET) antagonists inhibited SARS-CoV-2 infection in vitro. Taken together, these studies support further investigation of transcriptional inhibition of critical host factors in the treatment or prevention of COVID-19.

SARS-CoV-2 | TMPRSS2 | androgen receptor | BET inhibitors | ACE2

The COVID-19 pandemic has become one of the greatest public health challenges in modern times, leading to an unprecedented surge in research efforts to develop vaccines and treatments (1). The genome of severe acute respiratory syndrome coronavirus 2 (SARS-CoV-2), the coronavirus responsible for COVID-19, is a positive, single-stranded RNA that encodes nonstructural and structural proteins required for the viral life cycle. Among these are its four main structural proteins: N, Nucleocapsid; E, Envelope; M, Membrane; and S, Spike (2). The Spike glycoprotein plays a pivotal role in SARS-CoV-2 infection by recognizing and attaching to the angiotensin-converting enzyme 2 (ACE2) transmembrane protein on host cells (3). The Spike protein is also cleaved and activated by cell surface transmembrane protease serine 2 (TMPRSS2) to facilitate membrane fusion and entry (4).

Targeting the expression or activity of these host receptors has confirmed their critical role in the pathogenicity of coronavirus infections (4–6). Studies with TMPRSS2 transgenic knockout mice have shown that loss of TMPRSS2 can reduce coronavirus replication in lungs, eliciting a weaker proinflammatory response, and result in a milder lung pathology (5). SARS-CoV-2 entry into cells is also decreased upon TMPRSS2 functional inhibition by the serine protease inhibitor camostat (4). Likewise, ACE2 antibodies or soluble recombinant ACE2 can attenuate viral entry and infection by SARS-CoV-2 (4, 6). Thus, a better understanding of regulatory mechanisms that control expression levels of ACE2 and TMPRSS2 could be key to developing effective novel treatments for SARS-CoV-2 infections. Interestingly, TMPRSS2 has been widely studied in the context of prostate cancer, where it is highly expressed, and TMPRSS2 expression is increased in response to androgens through direct transcriptional regulation by the androgen receptor (AR) (7). Oncogenic androgen-regulated TMPRSS2-ETS gene fusions are also found in upward of 50% of prostate cancers (8, 9).

Since the earliest demographics data were emerging from the COVID-19 pandemic, it became clear that there is a gender disparity in severity of disease course which persists across nations, with males having higher hospitalization and mortality rates in COVID-19 than females, with androgen receptor expression found to be greater in males than females (10). It was subsequently noted that males greater than 70 y of age and cigarette smokers are disproportionately affected by COVID-19. We report here that androgens are upregulated in males relative to females in lung epithelial cells greater than 70 y of age (Fig. 1). Importantly, AR levels are markedly elevated in males relative to females greater than 70 y of age (Fig. 1). Smoking was associated with elevated levels of AR and ACE2 in lung epithelial cells. (Fig. 1).

Author contributions: Y.Q., X.-M.W., R. Mannan, R. Mehra, J.Z.S., and A.M.C. designed research; Y.Q., X.-M.W., R. Mannan, S.P., Y.Z., J.W.W., L.X., D.R.R., Y.-M.W., J.C.-Y.T., X.C., S.A.S., I.I.A., P.B., S.K., S.P.N., S.Z.-W., I.M., F.S., R.W., Y.C., A.D.D., Z.M., C.D.P., and R. Mehra performed research; S.W. contributed new reagents/analytic tools; Y.Q., X.-M.W., R. Mannan, S.P., Y.Z., J.W.W., L.X., D.R.R., Y.-M.W., G.R., A.P., S.Z.-W., C.D.P., R. Mehra, J.Z.S., and A.M.C. analyzed data; and Y.Q., X.-M.W., R. Mannan, S.J.E., R. Mehra, J.Z.S., and A.M.C. wrote the paper.

Reviewers: W.L.D., National Cancer Institute; and N.N., University of California, Los Angeles.

The authors declare no competing interest.

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This article contains supporting information online at https://www.pnas.org/lookup/suppl/doi:10.1073/pnas.2021450118/-/DCSupplemental.

www.pnas.org/cgi/doi/10.1073/pnas.2021450118

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rates than females (10, 11). The reasons for these gender disparities may be multifactorial, but one possible explanation could be differences in levels of sex hormones, such as androgens, and the transcriptional signaling networks that subsequently occur in males versus females, including up-regulation of the TMPRSS2 host entry factor in males. This has raised the hypothesis that inhibition of AR activity and down-regulation of TMPRSS2 may prevent SARS-CoV-2 infection (12). In support of this theory, a retrospective study in Italy analyzing rates of SARS-CoV-2 infectivity among prostate cancer patients found a significantly reduced incidence in patients receiving androgen deprivation therapy (ADT) (13). Similarly, a small prospective study of patients hospitalized due to COVID-19 observed a decreased rate of intensive care unit admissions among men that had been taking androgenics for at least 6 mo prior to hospitalization (14). Conversely, another large prospective study reported no difference in risk of SARS-CoV-2 infection with ADT in prostate cancer patients, suggesting the need for further research into the role of androgens in regulating viral entry factors and disease course (15). Additionally, the interplay of androgens with other variables, such as comorbid health conditions, age, and smoking, remains to be fully elucidated, with initial evidence suggesting a correlation between current smoking status, ACE2/TMPRSS2 expression, and AR signaling (10, 16).

Given these knowledge gaps, the goals of the current study were to determine which cells of the upper airway tract express ACE2 and TMPRSS2 and test whether their expressions could be therapeutically targeted by AR inhibitors used in prostate cancer treatment. Coexpression of SARS-CoV-2 host entry factors and AR was observed in alveolar and bronchial epithelial cells, with significantly higher levels of ACE2 and AR in the lungs of aged male smokers. Importantly, TMPRSS2 and ACE2 expressions were decreased with therapies that directly target AR, as well as inhibitors of bromodomain and extraterminal domain (BET) proteins, known epigenetic regulators of AR transcriptional activity (17). Critically, these therapies led to decreased SARS-CoV-2 infection in cellular models, and, thus, these findings support further studies into AR and BET inhibitors as candidate treatment modalities for COVID-19.

Results

Single-Cell Sequencing Analysis of AR, ACE2, and TMPRSS2 Expression in Lungs and Their Responses to Androgen.

To determine whether androgen signaling regulates the expression of SARS-CoV-2 entry factors ACE2 and TMPRSS2, we used several human cell lines that are reported to be permissive to infection with either pseudotyped virus expressing SARS-CoV-2 Spike protein or isolated SARS-CoV-2 (4, 18). Despite being well characterized as suitable cell lines for antiviral drug screens with SARS-CoV-2, lung adenocarcinoma Calu-3 and colon adenocarcinoma Caco-2 cell lines both lack robust endogenous AR expression, rendering screening results uninterpretable for AR-targeting drugs. Here, we confirmed that neither androgen stimulation nor AR antagonists altered the levels of TMPRSS2 and ACE2 in Calu-3 and Caco-2 cells (SI Appendix, Fig. S1 A and B). On the other hand, we discovered that the BET inhibitor JQ1 and degrader ZBC260 consistently down-regulated ACE2 in Calu-3 (SI Appendix, Fig. S1A) and TMPRSS2 and ACE2 in Caco-2 cells (SI Appendix, Fig. S1F), suggesting that BET proteins may play a role in regulating SARS-CoV-2 entry factor expression. Additionally, in other cell lines originating from the lung lineage with high endogenous expression of AR, TMPRSS2, and ACE2, we found that both androgen and AR antagonists also did not change TMPRSS2 and ACE2 messenger RNA (mRNA) levels in bulk gene expression analysis (SI Appendix, Fig. S1 C–F). The varying endogenous expressions of AR, TMPRSS2, and ACE2 in lung cell lines limit their use in SARS-CoV-2 research; thus, there is a need for understanding their expression patterns in the lung at the single-cell level.

Given the complexity of the lungs, which comprise more than 25 distinct cell types including bronchial and alveolar cells (19–23), identification of specific cells that express AR, TMPRSS2, and ACE2 genes will be critical to understanding the biology of SARS-CoV-2 infection. Thus, we performed bioinformatics analysis of published single-cell RNA sequencing (scRNAseq) data of human and murine lungs (19–23). The results demonstrated that AR was expressed with TMPRSS2 and ACE2 in several types of human (Fig. 1A) and murine (Fig. 1B and C and SI Appendix, Fig. S2) lung epithelial cells, including alveolar (AT1 and AT2) epithelial cells, with maximal expression in ciliated and secretory epithelial cells (bronchial cells). This suggested that pulmonary TMPRSS2 and ACE2 in alveolar and bronchial cells had the potential to be regulated by AR.

To test this hypothesis by single-cell sequencing, we castrated adult immune-competent C57BL/6 male mice to create an androgen-deprived condition to compare lung tissue from intact and castrated mice. However, scRNAseq approaches require the dissociation of viable cells from the tissue milieu, and this method yielded suboptimal levels of lung epithelial cells. As an alternative strategy not affected by dissociation-induced artifacts (24), we performed single-nucleus RNA sequencing (snRNAseq) from frozen samples and found significant enrichment of lung epithelia (Fig. 1B). In fact, snRNAseq identified more cell types, including two additional epithelial cell types (basal and rare neuroendocrine/NE cells), and retained similar expression patterns of Ar, Ace2, and Tmprss2 as compared to scRNAseq (Fig. 1C). Using this approach, we performed snRNAseq of lungs from intact and castrated mice and found no change in cellular composition between conditions (Fig. 1D and E). Importantly, a global reduction of Ace2, Tmprss2, and Ar expression in lungs from the castrated sample was observed (Fig. 1F). Analysis of publicly available scRNAseq data of intact and castrated prostates exhibited similar regulation (Fig. 1F). Together, these data demonstrate that an androgen-deprived environment leads to decreased Tmprss2 and Ace2 expression in lung epithelial cells.

To compare expression levels of AR, TMPRSS2, and ACE2 between lung and prostate, we analyzed publicly available datasets and calculated relative expressions by normalizing to a set of genes which were stably expressed across tissue lineages (20–23, 25, 26). In cells with detectable Tmprss2, the expression levels were generally lower in human lung epithelial than prostate epithelial cells (SI Appendix, Fig. S3 A and B); however, in mice, Tmprss2 was expressed at comparable levels in AT1 (alveolar) and ciliated cells (bronchial) of lung tissues with prostate luminal cells (SI Appendix, Fig. S3 C and D). ACE2 detection was sparse in both lungs and prostates from humans and mice, but, noticeably, outlier expression of this gene was higher in lung AT2 cells compared to other cells in the lung and epithelial cells in the prostate of both humans and mice. AR detection was low in both human lung and prostate, whereas it was higher in mouse prostate epithelial cells compared to mouse lung epithelial cells. This analysis indicates that TMPRSS2 and ACE2 are expressed in both lung and prostate tissues in humans and mice, with higher relative TMPRSS2 expression in human prostate epithelial cells.

Androgen Positively Regulates Expression of AR and SARS-CoV-2 Entry Factors Tmprss2 and Ace2 in Murine Lungs.

To evaluate the effect of systemic androgen levels on murine lungs, we castrated adult immune-competent C57BL/6 male mice, and a group of castrated male mice were restimulated with testosterone for 5 d. To also test whether lungs from female mice are responsive to androgen stimulation, we treated intact female mice with testosterone (SI Appendix, Fig. S4A). Systemic testosterone levels from mouse serum confirmed down-regulation of testosterone upon castration in male mice and significant up-regulation by

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Fig. 1. Single-cell analysis of host SARS-CoV-2 entry factors and AR in human and mouse lungs. (A) Bubble plots of ACE2, TMPRSS2, and AR expression from publicly available scRNAseq datasets of human lung. Color bar represents mean expression (mean_expr) of each gene in specific cell types, and bubble size represents the percentage of cells in each cell type that expresses that gene (here and in C). Each plot is labeled below with an identifier, reflecting the name of the first author of the appropriate manuscript (same with C) (20–23). AT1, alveolar type 1; AT2, alveolar type 2; SMC, smooth muscle cell; Alv., alveolar. (B) Stacked bar plot representing the fraction of appropriate, color-coded cell types obtained by scRNAseq (public dataset) and snRNAseq (this study) of mouse lung. (C) Bubble plot of Ace2, Tmprss2, and AR expression from publicly available scRNAseq dataset and snRNAseq dataset from this study of mouse lung. NE, neuroendocrine; Endo. Cap., endothelial capillary; Endo. Vas., endothelial vasculature. (D) The t-distributed stochastic neighbor embedding (tSNE) plots of scRNAseq data from mouse lungs collected from intact or castrated (cast) mice. Each dot represents a cell, and each cell type identified by our analysis is distinctly color coded. Fibro, fibroblast. (E) Stacked bar plot representing the fraction of appropriate, color-coded cell types obtained by snRNAseq of lungs from intact and castrated (cast) mice. (F) Combined violin and scatter plots representing the expression of Ace2, Tmprss2, and AR in lungs from intact and castrated mice from publicly available datasets of mouse prostate and this study of mouse lung. Each dot is an individual cell (only nonzero values are indicated), and all cell types from each sample have been included here to perform a pseudobulk gene expression analysis.
Fig. 2. Expression levels of AR, Tmprss2, and Ace2 in murine lungs are regulated by androgen. (A) Representative images of AR IHC in murine lungs from intact and castrated male mice. (B) Quantitative analysis of AR IHC score of murine lungs from male (intact, castrated, castrated + testosterone) and female (intact, intact + testosterone); n = 6 in each group, and P values were calculated by unpaired t test (here and in D and F). (C) Representative images of Tmprss2 ISH and (E) Ace2 ISH in murine bronchial cells from intact and castrated male mice. (D) Quantitative analysis of Tmprss2 ISH and (F) Ace2 ISH H-score in murine bronchial cells from male and female. (G) Representative image showing coexpression of Ar and Tmprss2 ISH in murine bronchial cells. Arrows indicate cells expressing both Ar and Tmprss2. A magnified area (1) is shown on the right for this and panel H. (H) Representative image showing coexpression of Ace2 and Tmprss2 ISH in murine bronchial cells.
testosterone treatment in both castrated male and intact female mice (SI Appendix, Fig. S4B).

Levels of Ar, Tmprss2, and Ace2 were examined using bulk lung tissue harvested from individual mice. The results showed no significant differences for Ar levels in treatment groups of male mice but a significant up-regulation in female mice treated with testosterone; however, Tmprss2 and Ace2 were not significantly altered between treatment groups in this bulk pooled tissue analysis (SI Appendix, Fig. S4C). Similar to mRNA levels, protein expression of ACE2 was not different among groups of pooled samples (SI Appendix, Fig. S4D). We further tested ACE2 protein expression from individual lung samples obtained from intact and castrated severe combined immunodeficiency male mice but again observed no difference (SI Appendix, Fig. S4E).

However, given the coexpression patterns of Ar, Tmprss2, and Ace2 at the single-cell level in lung and their regulation by castration (Fig. 1), we developed in situ analysis methods to analyze AR, Tmprss2, and Ace2 at the cellular level in lung sections generated from C57BL/6 male (intact, castrated, castrated + testosterone) and female mice (intact, intact + testosterone). In murine lungs, AR was detected by immunohistochemistry (IHC) in nuclei, with localization in both bronchial and nonbronchial epithelial cells (Fig. 2A and SI Appendix, Fig. S5A). AR protein levels were calculated as an AR IHC score by factoring in IHC staining intensity and subcellular localization of AR protein. The AR IHC score was significantly lower in lungs of castrated male mice compared to intact male mice without changing subcellular localization of AR protein (Fig. 2A and B). Baseline AR expression in lungs of females was notably lower than intact males. When mice were challenged with testosterone, AR IHC scores increased in lungs of castrated male mice and intact female mice (Fig. 2A and B and SI Appendix, Fig. S5A), suggesting that pulmonary AR expression in bronchial and nonbronchial cells is positively regulated by androgen.

Tmprss2 and Ace2 were analyzed using lung sections of the same cohort. Consistent with single-cell sequencing analysis, Tmprss2 RNA visualized by Tmprss2 in situ hybridization (ISH) localized in both bronchial and nonbronchial cells (Fig. 2C and SI Appendix, Fig. S5A and B) of murine lungs. Similar to AR protein, Tmprss2 decreased in male bronchial cells upon castration and reactivated with testosterone treatment (Fig. 2C and D). Similarly, localization of Tmprss2 ISH was also observed in intact female bronchial cells after testosterone treatment (Fig. 2D and SI Appendix, Fig. S5A). Tmprss2 RNA in nonbronchial cells was shown to have the same regulation by androgen as in bronchial cells (SI Appendix, Fig. S5B and C). However, Ace2 RNA was only detectable in bronchial cells of murine lung. Bronchial expression of Ace2 was down-regulated upon castration in male mice and significantly reactivated with testosterone stimulation in castrated male and intact female mice (Fig. 2E and F and SI Appendix, Fig. S5A). To investigate ACE2 protein expression in lungs, we optimized ACE2 IHC to compare with Ace2 ISH staining; lack of a suitable antibody for TMPRSS2 precluded its use. Consistent with being a known transmembrane protein, ACE2 IHC showed strong positive membrane staining in both bronchial and nonbronchial cells. This suggests that Ace2 RNA may have a short half-life, or the Ace2 ISH signal is too low to be detected in nonbronchial cells. Since almost all bronchial cells showed positive ACE2 IHC staining, quantitative analysis of ACE2 positive cells in nonbronchial cells was calculated and presented here. ACE2 protein levels significantly decreased upon castration in male lungs and increased with testosterone stimulation in lungs of both castrated male and intact female mice (SI Appendix, Fig. S5D and E). Together, our data indicate that pulmonary Tmprss2 and Ace2 expression in bronchial and nonbronchial cells are positively regulated by androgen.

Additionally, we performed co-staining experiments with Ar and the SARS-CoV-2 entry factors. ISH analysis showed that Ar and Tmprss2 were coexpressed at the cellular level in bronchial cells, and Ace2 and Tmprss2 were also coexpressed in bronchial cells (Fig. 2G and H). In nonbronchial cells, including alveolar cells, Tmprss2 and Ar were also coexpressed (SI Appendix, Fig. S5F). Tmprss2 is partially coexpressed with lung epithelial marker Sftpb in both bronchial and alveolar cells (SI Appendix, Fig. S5G and H). This evidence indicates that SARS-CoV-2 entry factors TMPRSS2 and ACE2 are coexpressed with AR in subsets of pulmonary epithelia, including bronchial and alveolar cells.

Expression Analysis of Ar, Tmprss2, and Ace2 in Human Lungs Shows Higher AR Levels in Males than Females. We extended the in situ analysis to human lung tissues using normal lung sections from male, female, and metastatic castration-resistant prostate cancer (mCRPC) patients. AR protein had clear nuclear localization in bronchial and alveolar cells of human lungs. The intensity and quantity of AR protein, represented by AR IHC score, in lungs indicated that males had significantly higher levels of AR than female, whereas mCRPC (of which patients are typically on therapies that systemically suppress testosterone levels) had the lowest AR levels (Fig. 3A and B). RNA expression of Tmprss2 was examined by ISH on the same cohort and showed bronchial and nonbronchial expression of Tmprss2 in human lungs (SI Appendix, Fig. S6A). However, quantitative analysis of Tmprss2 ISH did not show significant differences between males and females in either bronchial or nonbronchial cells (Fig. 3C). Additionally, ACE2 protein was expressed in nonbronchial cells of human lungs (SI Appendix, Fig. S6B), but there was no differential expression in males and females (Fig. 3D). These results are similar to those observed above in our murine models. Although manipulation of androgen levels with either castration in male mice or replacement with testosterone in both male and female mice led to significant alterations in Tmprss2 and Ace2 (and ACE2 protein) levels, intact male and female mice had similar expression levels of these factors (Fig. 2D and F and SI Appendix, Fig. S5C and E).

Dual staining experiments showed that, in alveolar cells, AR and ACE2 protein were coexpressed (Fig. 3E) in individual cells. AR and Tmprss2 RNA were also coexpressed in both bronchial and nonbronchial cells (Fig. 3F) shown by dual RNA ISH staining. ACE2 and Tmprss2 RNA were further coexpressed in bronchial and nonbronchial cells (Fig. 3G). These data suggest that bronchial and alveolar cells express AR, Tmprss2, and ACE2 simultaneously; thus, the cellular regulation of Tmprss2 and ACE2 by AR becomes feasible in human lungs.

Smoking Elevates AR and ACE2 Expressions in Aged Male Lungs. SARS-CoV-2 has been reported as having higher detrimental impacts in elderly populations, especially men with a smoking history (10). Here, we evaluated the expression of AR and ACE2 in lung tissues from a group of younger (<30 y old) and older (>70 y old) males and females. AR protein had significantly higher expression in males than females in the age group over 70 y old (Fig. 4A and B and SI Appendix, Fig. S7A), whereas similar (relatively lower) expression levels were observed in the under 30-y-old group (Fig. 4C and D and SI Appendix, Fig. S7B).

Smoking is a known risk factor for lung disease and a more severe COVID-19 disease course (10); therefore, we examined whether smoking status could alter the expression level of AR and ACE2 in male and female lungs. In an analysis with all age and genders combined, both AR and ACE2 protein had slightly higher expression in smokers than nonsmokers (SI Appendix, Fig. S7C–F). Importantly, elderly male smokers had significantly higher AR and ACE2 protein expression than nonsmokers in lungs of males over 70 y of age (Fig. 4E–H and SI Appendix, Fig. S7G and H). These data demonstrate that aged males have increased AR and SARS-CoV-2 host entry factor ACE2 protein expression.

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Fig. 3. Expression patterns of AR, TMPRSS2, and ACE2 in human lungs. (A) Quantitative analysis of AR IHC score of human lungs in male (n = 21), female (n = 18), and mCRPC (n = 5). P values were calculated by unpaired t test. (B) Representative images of (C) Quantitative analysis of TMPRSS2 ISH in bronchial and nonbronchial cells and (D) ACE2 IHC in nonbronchial cells of male (n = 17) and female (n = 11). P values were calculated by unpaired t test and showed no significance (ns). (E) Representative IHC images showing coexpression of ACE2 and AR in human lungs. Arrows indicate cells expressing both ACE2 and AR. (F) Representative ISH images showing coexpression of AR and TMPRSS2 and (G) ACE2 and TMPRSS2 in human bronchial and nonbronchial cells. Arrows indicate cells expressing both (F) AR and TMPRSS2 and (G) ACE2 and TMPRSS2.
expression in lungs, and their expression is enhanced by smoking. This suggests that older smoking men have a higher vulnerability to SARS-CoV-2 infection due to elevated entry factor levels.

AR and BET Antagonists Diminish SARS-CoV-2 Infection and Replication. In the prostate lineage, our previous chromatin immunoprecipitation sequencing data in LNCaP demonstrated that TMPRSS2 is

Fig. 4. Smoking elevates AR and ACE2 expression in aged male lungs. (A) Representative images and (B) quantitative analysis of AR IHC score of human lungs in males (n = 17) and females (n = 9) over 70 y of age. P values were calculated by unpaired t test in all panels. (C) Representative images and (D) quantitative analysis of AR IHC score of human lungs in males (n = 8) and females (n = 9) under 30 y old. (E) Representative images and (F) quantitative analysis of AR IHC score of aged male (>70 y old) lungs in nonsmokers (n = 6) and smokers (n = 11). (G) Representative images and (H) quantitative analysis of ACE2 IHC of aged male (>70 y old) lungs in nonsmokers (n = 6) and smokers (n = 11).
AR antagonists diminish SARS-CoV-2 infection in LNCaP cells. (Fig. 5). SARS-CoV-2 virus was detected and quantified by high-content immunofluorescence imaging of its nucleocapsid protein, whereas nuclei were counterstained with Hoechst-33342 (Fig. 5B). Using this SARS-CoV-2 bioassay platform, we demonstrated that AR antagonists FDA-approved for prostate cancer treatment (apalutamide, darolutamide, enzalutamide) inhibited SARS-CoV-2 infection in LNCaP cells in a dose-dependent manner, with concentration that inhibits response by 50% (IC\textsubscript{50}) values of 79, 768, and 90 nM, respectively. Our experimental small-molecule AR protein degrader ARD-61 (28) also exhibited a dose-dependent reduction in SARS-CoV-2 infectivity, with an IC\textsubscript{50} of 20 nM (Fig. 5C), further demonstrating that AR is indispensable for SARS-CoV-2 infection. In concordance with our data above, TMPRSS2 and ACE2 were downregulated in a dose-dependent manner by AR inhibitors (Fig. 5D).

Furthermore, we previously reported that androgen signaling in prostate cancer requires BET protein activity (17) and identified a BRD4 binding site in the TMPRSS2 and ACE2 genes (SI Appendix, Fig. S8); thus, we examined whether pulmonary AR, TMPRSS2, and Ace2 levels were responsive to systemic treatment with BET inhibitor JQ1 in male mice. After 5 d, individual lungs were collected from intact C57BL/6 male mice treated with either vehicle or 50 mg/kg JQ1 (SI Appendix, Fig. S9A). Levels of TMPRSS2 and Ace2 were then examined using bulk lung tissue harvested from individual mice. The results showed significant transcriptional repression of TMPRSS2 and Ace2 by JQ1 in this bulk lung tissue analysis (SI Appendix, Fig. S9B), which we did not observe using bulk lung tissue in intact and castrated male mice (SI Appendix, Fig. S4C). RNA ISH of the same cohort confirmed that TMPRSS2 and ACE2 levels were significantly lower in mice treated with JQ1 compared to vehicle in bronchial cells (Fig. 6A and B and SI Appendix, Fig. S9C). Furthermore, ACE2 IHC in lungs demonstrated that ACE2 protein levels were reduced by JQ1 in nonbronchial cells (Fig. 6A and B and SI Appendix, Fig. S9D). Protein levels of AR measured by AR IHC...
Fig. 6. BET antagonists down-regulate AR, ACE2, and Tmprss2 in murine lung and decrease SARS-CoV-2 infection in human cells. (A) Representative images of AR IHC, Tmprss2 and Ace2 ISH in bronchial cells, and ACE2 IHC in nonbronchial cells in murine lungs, from vehicle and JQ1-treated male mice. (B) Quantitative analysis of AR IHC score, Tmprss2 and Ace2 ISH H score, and percentage of ACE2 positive cells in 500 nonbronchial cells of murine lung from vehicle (n = 6) and JQ1 (n = 9) treated male mice. P values were calculated by unpaired t test. (C) Representative images of immunofluorescent staining of nuclei and SARS-CoV-2 nucleocapsid protein in various treatment groups of BET inhibitors in the SARS-CoV-2 bioassay in LNCaP cells. (D) Dose–response curves of SARS-CoV-2 virus percent infection and cell viability of LNCaP cells treated with various BET antagonists. (E) Relative levels of TMPRSS2 and ACE2 in LNCaP cells with indicated treatment for 72 h. P values were calculated by unpaired t test. *: P < 0.05; **: P < 0.01. (F) As in C, but in H1437 cells. (G) As in D, but in H1437 cells. (H) Protein levels of ACE2 with control (Ctrl), 1 μM JQ1, or 1 μM OTX015 treatment for 72 h in H1437 cells. (I) Relative levels of ACE2 in H1437 cells with indicated treatment for 72 h. JQ1 (1 μM), OTX015 (1 μM). ***: P < 0.001. P values were calculated by unpaired t test.
score were lower in lungs of JQ1-treated mice (Fig. 6 A and B and SI Appendix, Fig. S9D).

Together, these data suggested that, like AR-targeting compounds, BET inhibitors may possess therapeutic potential for mitigating SARS-CoV-2 infection. We thus used the SARS-CoV-2 bioassay platform to evaluate the antiviral effects of BET inhibitors (JQ1, OTX015) and a BET protein degrader (ZBC260) (29). JQ1, OTX015, and ZBC260 all decreased the infectivity of SARS-CoV-2 in LNCaP cells, with IC50 values of 10, 8, and 3.5 nM, respectively (Fig. 6 C and D), and BET inhibitor or degrader treatment led to associated decreases in TMPRSS2 and ACE2 (Fig. 6E). Similarly, in H1437 cells originating from the lung lineage, JQ1 and OTX015 decreased the infectivity of SARS-CoV-2, with IC50 values of 10 nM for both compounds (Fig. 6 F and G), and resulted in associated decreases in ACE2 protein and mRNA levels (Fig. 6 H and I). These data suggest that BET proteins may play a role in regulating SARS-CoV-2 entry factor ACE2 expression independent of AR regulation, thus supporting the notion that BET inhibition may have a broad therapeutic range in mitigating SARS-CoV-2 infection.

**Discussion**

ACE2 and TMPRSS2 were shown to be the key mediators of SARS-CoV-2 viral entry early in the COVID-19 pandemic, but which cells of the upper airway tract express them and mechanisms governing their expression in the lung were not defined (3, 4). Here, through snRNAsseq, ISH, and IHC methodologies, TMPRSS2 and ACE2 expression was identified in specific alveolar and bronchial epithelial cell types, as well as coexpression with AR. Similar to the prostate, TMPRSS2 expression was found to be regulated by androgens in certain cells in the lungs, and we also identified ACE2 as an AR-regulated target; these findings support an early hypothesis that differences in androgen levels may be one reason for gender disparities in COVID-19 outcomes (12). Analysis of other variables here also showed that ACE2 and AR levels were elevated in older male smokers, providing a possible link between smoking and age risk factors with a more severe COVID-19 disease course (10).

Importantly, we find that targeting the transcriptional regulation of ACE2 and TMPRSS2 may be an attractive treatment approach for COVID-19 (Fig. 7). Our data show that strategies that decrease AR signaling, either through AR antagonists already FDA-approved for prostate cancer treatment [enzalutamide, apalutamide, darolutamide (30)], AR degraders [ARD-61 (28)], or castration, can lead to dose-dependent decreases in TMPRSS2 and ACE2 expression and attenuate SARS-CoV-2 infectivity. As an important caveat, we relied upon LNCaP prostate cancer cells for the SARS-CoV-2 bioassay with AR inhibitors, since we were unable to identify a lung epithelial cell line susceptible to SARS-CoV-2 infection that also had adequate AR signaling. LNCaP cells are dependent on AR and express the protein at high levels, so it is possible that AR signaling and subsequent targeting efficacy may be different in the lung epithelial cells of COVID-19 patients.

Liganded BET protein small-molecule inhibitors [JQ1, OTX015— which has been studied clinically in the context of cancers (31)] or degraders [ZBC260 (29)] also decrease expression of viral host entry factors and prevent SARS-CoV-2 infection. This could result from the known coactivator role that BET proteins play in mediating AR activity (17) or through the AR-independent roles of BET proteins in transcriptional regulation (31). It is also important to note that, while we demonstrate androgen regulation of ACE2, TMPRSS2, and AR in subsets of lung epithelial cells, our data do not suggest that all cells in the lung control these factors through AR signaling. For instance, JQ1 and OTX015 decrease SARS-CoV-2 infectivity and ACE2 levels in H1437 lung adenocarcinoma cells (Fig. 6 F–I), but androgens and AR antagonists did not decrease ACE2 in this cell line (SI Appendix, Fig. S1D). Thus, in cell types where AR regulation of ACE2 and TMPRSS2 does not exist, the broader transcriptional repression by BET inhibitors may block expression of these key host factors, and agents targeting BET proteins may have a different therapeutic efficacy in COVID-19 than direct AR inhibitors. BET inhibitors can also affect innate and adaptive immune responses, through processes such as repression of IFNG (IFN gamma) (32), which could potentially attenuate the cytokine storm associated with COVID-19.

Several clinical trials are already underway to evaluate targeting of androgen signaling for treatment of COVID-19 (10). Some of these studies are examining the efficacy of the AR antagonists enzalutamide, apalutamide, and apabetalone, which was recently tested in a phase 3 study for cardiovascular disease (33). A plethora of clinical trials are also underway to examine compounds that inhibit the function of TMPRSS2 or ACE2 (10, 34). For example, numerous studies are evaluating the utility of protease inhibitors of TMPRSS2, alone or in combination with other agents, in COVID-19 patients; these include camostat (11 clinical trials initiated at time of publication, such as...
NCT04353284, NCT04524663, NCT04470544), nafamostat (NCT04352400, NCT04418128, NCT04390594, NCT04373053), and bromhexine (NCT04424134, NCT04355026, NCT04273763, NCT04340349, NCT04405999). Notably, TMPRSS2 has also been shown to cleave the hemagglutinin protein of influenza viruses, a step necessary for influenza infectivity. Similar to coronavirus models, TMPRSS2 knockout mice exhibit reduced lung pathogenesis and decreased viral spread after infection with different strains of influenza virus, including H1N1, the virus responsible for the 2009 swine flu pandemic (35, 36). Therapeutics targeting TMPRSS2 expression or activity may, therefore, be beneficial not only for coronavirus-infected patients but also those infected with influenza.

Although our findings show a significant role of androgens in mediating expression of TMPRSS2 and ACE2, the full array of mechanisms responsible for the gender disparities observed in COVID-19 outcomes is likely multifactorial. For instance, males and females have differences in innate immune responses and susceptibility to viral infections in general (10, 11). Estrogen signaling, via the estrogen receptor, controls a complex network of immune response genes, and it has been postulated that estrogens play a protective role in preventing the cytokine storm that can occur in the later stages of COVID-19 (37). Androgens also control genes involved in the immune response but generally support a more immune-suppressive state (38). Our study also finds that AR levels are higher in older males (greater than 70 y of age) compared to females, and smoking increases AR and ACE2 expression in males over 70 y old. Behavioral factors, such as smoking, and comorbid conditions that are more prevalent in males (e.g., hypertension, chronic obstructive pulmonary disease, diabetes) may be contributing factors to the increased mortality and hospitalization rates observed in men through mechanisms in addition to those highlighted in our study (10, 11, 39, 40).

Finally, apart from bronchial epithelium and lung which were investigated in our cohort, cells lining the nasopharyngeal airway also might play a role in virus infection and sustenance. TMPRSS2-ERG has long been studied by the prostate cancer field as an oncogenic gene fusion under the control of the androgen-regulated TMPRSS2 promoter expressed in the majority of prostate cancers (Fig. 7). Due to the COVID-19 pandemic, TMPRSS2 has gained notability in a different realm as the priming factor for SARS-CoV-2 Spike protein following attachment to ACE2. Our studies presented herein provide a strong rationale for the use of AR or BET inhibitors in COVID-19 treatment to decrease TMPRSS2 and ACE2 expression, and the results of the many clinical studies mentioned above are eagerly awaited.

Methods

Cell Culture. H1437, HCC4006, Caco-2, Calu-3, and LNCaP cells were obtained from American Type Culture Collection (ATCC) and maintained under 5% CO₂ at 37 °C in medium according to ATCC. HPAEpiC (human pulmonary alveolar epithelial cells) were purchased from ScienCell Research Laboratories. All cell lines were tested negative for mycoplasma and authenticated by genotyping.

Compounds. Apalutamide, darolutamide, dexamethasone, enzalutamide, mifepristone, DTX015, and JQ1 were purchased from Selleckchem. R1881, dihydrotestosterone (DHT), and beta-estradiol were purchased from Sigma-Aldrich. BET protein degrader ZBC260 and AR protein degrader ARD-61 were described previously (28, 29).

IHC. IHC was performed on 4-μm-thick formalin-fixed, paraffin-embedded (FFPE) tissue sections using anti-AR rabbit monoclonal primary antibody (prediluted, pH 9, catalog no. 760-4605, Roche-Ventana) and anti-ACTB rabbit monoclonal primary antibody (1:100, pH 9, catalog no. GTX301160, GeneTex). IHC was carried out on the Benchmark XT automated slide staining system (Roche-VENTANA Medical Systems) using the UltraView Universal diaminobenzidine (DAB) detection kit (catalog no. 760-500, Roche-Ventana) and Hematoxylin II (catalog no. 790-2208, Roche-Ventana) for counterstain. Dual IHC was performed consecutively, and signals were developed using the Universal DAB detection kit and the Discovery purple kit (catalog no. 760-229, Roche-Ventana). Staining was evaluated under 100x and 200x magnification using a bright-field microscope. See SI Appendix for scoring details.

RNA ISH. RNA ISH was performed on 4-μm-thick FFPE tissue sections using RNAscope 2.5 high definition (HD) Brown kit (Advanced Cell Diagnostics) for single target and RNAscope 2.5 HD Duplex kit (322430) for dual targets. RNA quality was evaluated using a positive control probe against human PPIB. Assay background was monitored using a negative control probe against bacterial gene DapB. RNA ISH was performed as previously described (41, 42). FFPE tissue sections were baked, deparaffinized in xylene, and dehydrated in 100% ethanol. After hydrogen peroxide pretreatment and heat-induced target retrieval, tissue samples were permeabilized using protease and hybridized with target probe followed by a series of signal amplification steps. Chromogenic detection was performed using DAB for single target or a consecutive combination of horseradish peroxidase-based Green and alkaline phosphatase-based Fast Red chromogens, followed by 50% Gill’s Hematoxylin I (Fisher Scientific) counterstain. Staining was evaluated under 100x and 200x magnification using a bright-field microscope. See SI Appendix for probes and scoring information.

SARS-CoV-2 Infection Bioassay. LNCaP and H1437 cells were grown in Roswell Park Memorial Institute (RPMI) 1640 supplemented with 10% fetal bovine serum and seeded at 8,000 cells per well in poly-D-lysine–coated 384-well plates (Perkin-Elmer, 6057300), or 10,000 cells per well in 96-well plates (Corning, 3602), respectively. Cells were allowed to attach and recover for 12 h to 18 h. BET and AR antagonists were solubilized in dimethyl sulfoxide (DMSO) and dispersed (0.1 nM to 10 μM, 1∶10 dilution series; n = 3) using an HPD300e digital compound dispenser and allowed to incubate 24 h prior to infection, with a final DMSO vehicle concentration of 0.1%. SARS-CoV-2 WA1/2020 strain (BEI resources catalog no. NR-52281) was added in BSL3 containment at a final working dilution equivalent to a multiplicity of infection of 10 and was allowed to incubate for 48 h at 37 °C. Wells were then fixed with 4% paraformaldehyde, permeabilized with 0.3% Triton X-100, and blocked with antibody buffer (1.5% bovine serum albumin [BSA], 1% goat serum, 0.0025% Tween-20). Following blocking, plates were sealed, surface decontaminated, and transferred to a BSL2 laboratory for staining. Cells were stained overnight with SARS-CoV-2 nucleoprotein primary antibody (ProSci catalog no. 35-579, 1∶2,000) and then stained with anti-mouse IgG Alexa Fluor 647 secondary (Invitrogen catalog no. A21235, 1∶1,000) and Hoechst 33342 (Invitrogen catalog no. H3570, 1∶2,000).

High-Content Imaging and Analysis of SARS-CoV-2–Infected Cells. Plates were imaged on a Thermo-Fisher CX5 high-content microscope with a UPlanFLN 10×/0.3NA objective. Nine fields were acquired per well for each of the two fluorescent channels (Hoechst-33823 nm, N-protein-650/13 nm). Images were analyzed using CellProfiler to quantify the percentage of infected cells at the well level (43). Infected cell areas were first identified by Otsu segmentation in the N-protein image. Nuclei were then identified in a similar manner and were related to infected cell areas using the relate objects module. Infected cells were identified if a nucleus was residing within an infected cell area, and percentages per well were calculated from the infected celltotal cell count. Dose-response curves were fit and IC₅₀ values tabulated using the four-parameter logistic model in Graphpad Prism. Plate-based normalization was performed using 32 infected (0% effect) and 32 uninfected (100% effect) control wells (mean LNCaP infectivity range: 18 to 25%). Viability was assessed by comparing cell counts in treated wells to the average cell count in the 32 uninfected control wells (100% viability).

Analysis of Published Human and Mouse Single-Cell Sequencing Datasets. To evaluate ACE2/TMPRSS2/AR expression in lung tissues at the cell level, we searched for publicly available scRNAseq datasets based on the following criteria: 1) profiled healthy human and/or mouse lung tissues; 2) generated with 10x Chromium platform; and 3) libraries prepared from single cells. Four human datasets and three mouse datasets were selected (19–23, 25, 44–46). Raw unique molecular index (UMI) counts were downloaded from Gene Expression Omnibus (GEO). For datasets that included samples from patients, only cells from healthy controls were extracted. Data processing (including normalization and identification of highly variable genes) and integration were performed with Seurat v3 (46). To standardize cell annotation across datasets, label transfering was applied using annotations from one dataset as reference (Habermann study for human, Raredon study for
mouse). Only cells with high-confidence label prediction (max prediction score of \(\geq 0.9\)) were used to evaluate cell type-specific expression of ACE2/ TMPRSS2/AR. Log-normalized expression value by Seurat was used to generate the violin plots. See SI Appendix for data analysis of the lung and prostate comparisons.

### Statistical Analysis

Sample sizes are listed on the figures or in figure legends. \(P\) values were calculated by GraphPad Prism 8 using two-tailed unpaired \(t\) test, and exact \(P\) values are provided.

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