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MAJOR ARTICLE

Risk Factors for SARS-CoV-2 Infection and Severe Outcomes Among People With Human Immunodeficiency Virus: Cohort Study

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Background. Studies on COVID-19 in people with HIV (PWH) have had limitations. Further investigations on risk factors and outcomes of SARS-CoV-2 infection among PWH are needed.

Methods. This retrospective cohort study leveraged the national OPTUM COVID-19 data set to investigate factors associated with SARS-CoV-2 positivity among PWH and risk factors for severe outcomes, including hospitalization, intensive care unit stays, and death. A subset analysis was conducted to examine HIV-specific variables. Multiple variable logistic regression was used to adjust for covariates.

Results. Of 43 173 PWH included in this study, 6472 had a positive SARS-CoV-2 result based on a polymerase chain reaction test or antigen test. For PWH with SARS-CoV-2 positivity, higher odds were found for those who were younger (18–49 years), Hispanic White, African American, from the US South, uninsured, and a noncurrent smoker and had a higher body mass index and higher Charlson Comorbidity Index. For PWH with severe outcomes, higher odds were identified for those who were SARS-CoV-2 positive, older, from the US South, receiving Medicaid/Medicare or uninsured, a current smoker, and underweight and had a higher Charlson Comorbidity Index. In a subset analysis including PWH with HIV care variables (n = 5098), those with unsuppressed HIV viral load, a low CD4 count, and no antiretroviral therapy had higher odds of severe outcomes.

Conclusions. This large US study found significant ethnic, racial, and geographic differences in SARS-CoV-2 infection among PWH. Chronic comorbidities, older age, lower body mass index, and smoking were associated with severe outcomes among PWH during the COVID-19 pandemic. SARS-CoV-2 infection was associated with severe outcomes, but once we adjusted for HIV care variables, SARS-CoV-2 was no longer significant; however, low CD4 count, high viral load, and lack of antiretroviral therapy had higher odds of severe outcomes.

Keywords. COVID-19; electronic health records; human immunodeficiency virus; risk factors; SARS-CoV-2.

Research on the effects of concurrent HIV on SARS-CoV-2 infection has provided compelling insights, yet some aspects continue to warrant further investigation. While people with HIV (PWH) were tested for SARS-CoV-2 more frequently than patients without HIV [1], SARS-CoV-2 test positivity rates among PWH were similar to the general population's [1, 2]. The risk factors for acquiring SARS-CoV-2 infection and the outcomes among PWH, when compared with people without HIV, have been consistent across large studies. Two analyses highlight the relationship between HIV status and COVID-19 outcomes: one included >18 million patients diagnosed with SARS-CoV-2 infection and found that the unadjusted death rate was 1.25-fold higher among PWH [3]; the second examined >38 million patients with SARS-CoV-2 infection and reported that after adjusting for age and sex, HIV was associated with an increased risk of death [4].

In previous reports where worse outcomes for SARS-CoV-2 infection were observed in PWH, findings were attributed to different methodological approaches or to a combination of underlying immunodeficiency, social determinants of health, and higher prevalence of chronic comorbid conditions among PWH [5–12]. In the United States, racial inequities beyond medical comorbidities and lower CD4 counts increased the

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risk of SARS-CoV-2 infection among a cohort of PWH [13]. Thus, further large-scale investigations are needed in the United States on infection risk factors and outcomes of SARS-CoV-2 infection in PWH as compared with PWH who are SARS-CoV-2 negative.

To investigate these trends, we utilized a large US longitudinal COVID-19 data set derived from electronic health records (EHRs) to examine the risk factors for SARS-CoV-2 infection and severe outcomes among PWH. Specifically, we compared them with PWH who were SARS-CoV-2 negative to explore the role of unique epidemiologic factors among PWH in the United States, including age, gender, race, ethnicity, US region, smoking, insurance status, comorbidities, HIV viral load (VL), CD4 count, and antiretroviral therapy (ART).

METHODS

Data Source

We used the OPTUM COVID-19–specific relational data set, a subset from the deidentified national OPTUM longitudinal EHR repository that includes data from >700 hospitals and >7000 clinics in the United States.

Patient Consent Statement

The study data were sourced from the expert-certified deidentified OPTUM COVID-19 data set, thus negating the need for individual patient consent or Institutional Review Board approval while maintaining adherence to applicable ethical standards.

Study Population

The study included adults (≥18 years old) who had a SARS-CoV-2 polymerase chain reaction (PCR) or antigen test performed between 20 January 2020 and 19 December 2021. The study group included patients who met any of the following criteria:

- Positive HIV antigen/antibody test result or detectable HIV VL (≥20 copies/mL)
- HIV-specific *ICD-9/10* codes (042, V08, B20, Z21)
- ART drug prescription or self-reported medication, other than medications that are commonly used for pre-exposure prophylaxis (emtricitabine/tenofovir disoproxil fumarate and emtricitabine/tenofovir alafenamide)

Study Design

The primary outcome for this retrospective cohort of PWH was SARS-CoV-2 infection, defined as testing positive on a SARS-CoV-2 PCR or antigen test. Secondary outcomes included 30-day hospitalization, intensive care unit (ICU) stay, and death. Factors included patient demographics (age, gender, race/ethnicity, and geographic region where care was received), smoking status, body mass index (BMI), and insurance type (captured in the 12 months prior to the SARS-CoV-2 test). We calculated an adjusted Charlson Comorbidity Index (CCI) [14] based on *ICD* codes. While CCI is a widely used tool to assess the burden of comorbid conditions in medical research, the original CCI was created prior to ART availability, and our goal was to assess the incremental contributions of non–HIV-related comorbidities. To avoid overestimation of the mortality associated with AIDS in the current era of widespread ART availability, we excluded the score's 6 points for AIDS, since all PWH in our data set would have been awarded these points based on HIV *ICD* codes [15]. For the secondary outcomes, we added SARS-CoV-2 infection as an additional covariate to adjust for its independent contribution to these outcomes.

As our data set included only the year of birth, we calculated age by subtracting it from the year of the last data set update (2022). We categorized PWH into 3 age categories (18–49, 50–64, and ≥65 years). We combined race and ethnicity into 1 variable with 5 categories (African American, non-Hispanic White, Hispanic White, Asian, or other). We combined 6 smoking statuses into 2 categories (currently smoking and not currently smoking). We stratified BMI into 6 categories according to standard definitions (underweight, normal weight, overweight, obesity class 1, obesity class 2, and obesity class 3) [16]. We classified insurance into 5 categories (commercial, uninsured, Medicaid, Medicare, and other payor types). Imputation was used for 10%–19% missingness in the smoking status, BMI, and insurance categories, assuming missing at random. Sensitivity analysis postimputation was performed to evaluate if imputation introduced a systematic bias.

For PWH who had available CD4 counts and HIV VL in the 12 months preceding SARS-CoV-2 infection, we performed a subset analysis based on the following: CD4 count stratified into low (absolute <200, percentage <14%), medium (200–499, 14%–28%), and high (≥500, ≥29%); HIV VL by suppressed (<200 copies/mL) and unsuppressed (≥200) status; and active ART treatment or not (any prescription for ART in the prior 12 months that is not solely emtricitabine/tenofovir disoproxil fumarate or emtricitabine/tenofovir alafenamide).

As PWH may have been tested for SARS-CoV-2 on multiple occasions, the date of the first positive SARS-CoV-2 test result was used to identify SARS-CoV-2 infection index cases and track outcomes. Among individuals with multiple SARS-CoV-2 tests that were all negative, 1 test was selected randomly to track their outcomes. This was done to achieve a similar index distribution over time between the groups.

Secondary outcomes were 30-day hospitalization, ICU stay, and death. Hospitalizations were defined as any inpatient or observation encounter in the first 30 days after the SARS-CoV-2 test date. We defined ICU stays as any ICU or critical care unit encounter in the first 30 days after the SARS-CoV-2 test date. Since the death date was provided as only the month of death in the deidentified data set, we

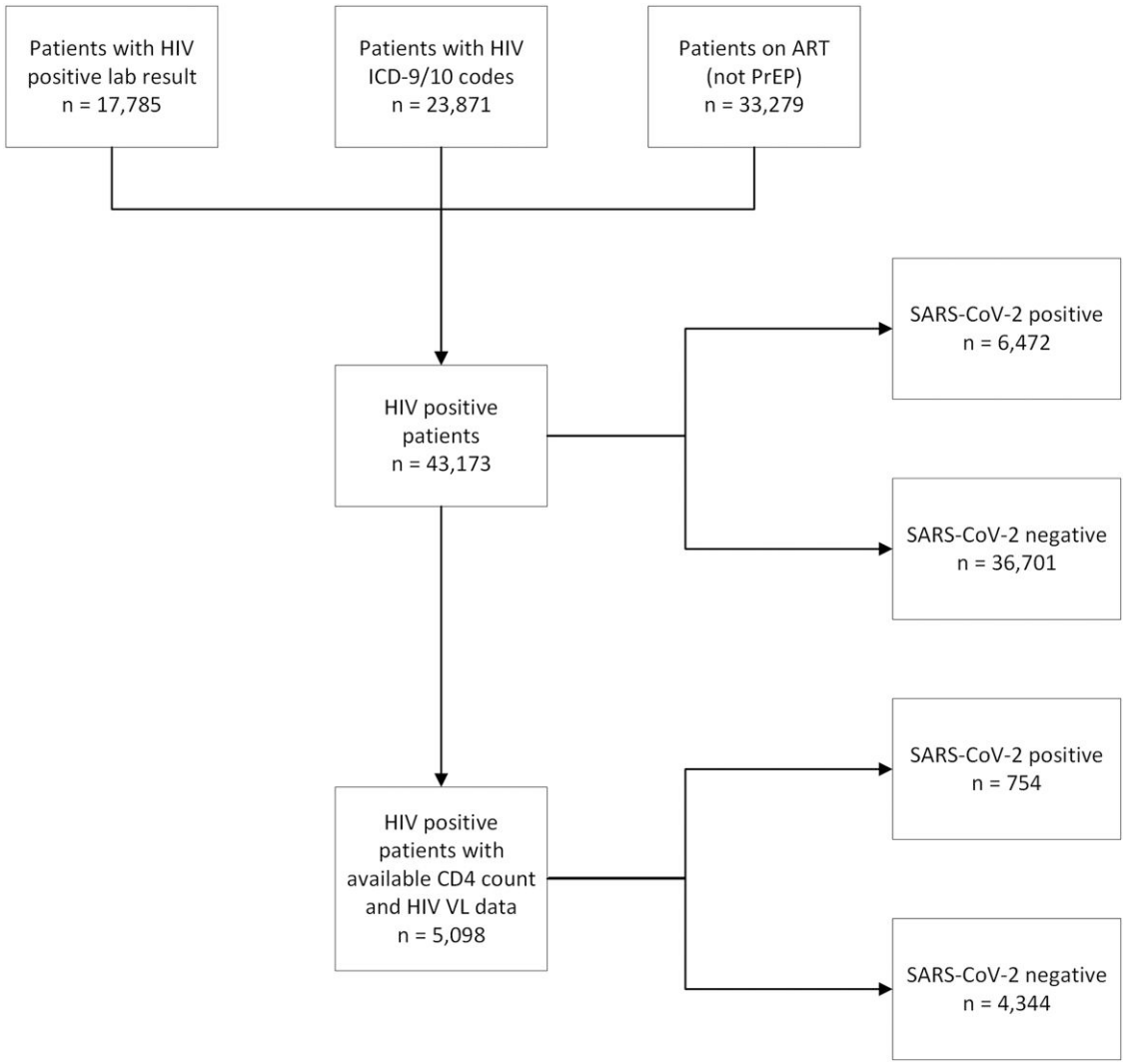

Figure 1. The study's cohort selection process for the primary and subset analyses. ART, antiretroviral therapy; PrEP, pre-exposure prophylaxis; VL, viral load.

captured death in the same month or the following month to the SARS-CoV-2 test date. The last test date for inclusion was 19 December 2021.

Statistical Analysis

Data were analyzed with RStudio (version 2021.09.0) [17]. Logistic regression models were built with the RMS package in R [18]. For the study analysis and subset analysis, we used multiple variable logistic regression to describe the proportional odds of outcomes for the risk factors. Statistical significance ($\alpha < .05$) between groups with 95% CI was calculated. As a continuous variable, CCI was modeled through restricted cubic splines with 3 or 4 knots when nonlinear distribution was observed with the outcome. Adjusted odds ratios (ORs) were used to quantify associations in all reported models. We visualized the models using forest plots.

Additionally, in a post hoc analysis to compare the outcomes between PWH who were SARS-CoV-2 positive and negative before and after the introduction of SARS-CoV-2 vaccines at the population level, we used unadjusted ORs from logistic regression to compare hospitalizations, ICU stays, and death in both groups before and after 1 January 2021.

RESULTS

Analysis included 43 173 PWH who were tested for SARS-CoV-2 during the 2-year study period. In this cohort, 6472 PWH had a positive SARS-CoV-2 result from a PCR or antigen test (Figure 1).

The baseline characteristics of the cohort are summarized in Table 1. PWH with SARS-CoV-2 infection were more likely to be younger, female, or Hispanic. A greater proportion of PWH with SARS-CoV-2 infection (27%) received care in the US South as compared with PWH without SARS-CoV-2 (10%). Current smokers represented 27% of PWH but only 21% of

Table 1. Characteristics of People With HIV by SARS-CoV-2 Status

Characteristic	Overall (N = 43 173)	SARS-CoV-2 Status, No. (%)	
		Negative (n = 36 701)	Positive (n = 6472)
Age, y			
18–49	22 478 (52)	18 889 (51)	3589 (55)
50–64	14 401 (33)	12 373 (34)	2028 (31)
≥65	6294 (15)	5439 (15)	855 (13)
Gender			
Female	15 086 (35)	12 694 (35)	2392 (37)
Male	28 087 (65)	24 007 (65)	4080 (63)
Race/ethnicity			
African American	11 379 (26)	9600 (26)	1779 (27)
Asian	1298 (3.0)	1114 (3.0)	184 (2.8)
Hispanic White	1587 (3.7)	1038 (2.8)	549 (8.5)
Non-Hispanic White	21 157 (49)	18 323 (50)	2834 (44)
Other	7752 (18)	6626 (18)	1126 (17)
Region			
Midwest	13 626 (32)	11 869 (32)	1757 (27)
Northeast	15 554 (36)	13 484 (37)	2070 (32)
Other/unknown	4529 (10)	3963 (11)	566 (8.7)
South	5580 (13)	3853 (10)	1727 (27)
West	3884 (9.0)	3532 (9.6)	352 (5.4)
HIV Care-Specific Characteristics	Overall (n = 5098)	Negative (n = 4344)	Positive (n = 754)
HIV viral load, copies/mL			
<200	4079 (80)	3465 (80)	614 (81)
≥200	1019 (20)	879 (20)	140 (19)
CD4 count: absolute (%)			
<200 (<14)	1271 (25)	1053 (24)	218 (29)
200–499 (14–28)	2049 (40)	1763 (41)	286 (38)
≥500 (≥29)	1778 (35)	1528 (35)	250 (33)
Antiretroviral therapy			
Yes	4592 (90)	3910 (90)	682 (90)
No	506 (9.9)	434 (10.0)	72 (9.5)

the SARS-CoV-2 infection group. The average BMI was comparable between those with and without SARS-CoV-2 (29.56 and 28.66 kg/m^2, respectively). In this cohort, 54% of PWH had commercial insurance and 4% were uninsured. Among those who were SARS-CoV-2 positive, 54% had commercial insurance and 7.9% were uninsured. Patients with SARS-CoV-2 infection were more likely to have congestive heart failure, diabetes mellitus, and chronic kidney disease. Patients who were SARS-COV-2 negative were more likely to have malignancies (Table 2). The average adjusted CCI was 2.06 for the SARS-CoV-2 infection group, as compared with 1.96 in the negative group, which is not clinically significant. Thirty-day hospitalizations, ICU stays, and deaths happened more frequently in the SARS-CoV-2 infection group at 21%, 4.0%, and 2.3% vs 19%, 3.3%, and 1.5% in the SARS-CoV-2 negative group, respectively.

Prior to accounting for HIV care variables, the primary analysis (Figure 2*A*) revealed higher adjusted odds of SARS-CoV-2 infection among PWH who were younger (18–49 years), Hispanic White or African American, living in the US South, uninsured, and a noncurrent smoker and had a higher BMI and CCI. Higher adjusted odds of hospitalization were observed among PWH who were SARS-CoV-2 positive, older, female, African American or Hispanic White, living in the US South, receiving Medicaid/Medicare or uninsured, a current smoker, and underweight and had a higher CCI (Figure 2*B*). ICU stays were observed more frequently among PWH who were SARS-CoV-2 positive, older, male, African American, living in the US South, receiving Medicaid/Medicare or uninsured, a current smoker, and underweight and had a higher CCI. Adjusted odds of death were higher among PWH who were SARS-CoV-2 positive, older, living in the South or Midwest, uninsured or receiving Medicaid/Medicare, and underweight and had a higher CCI. Sensitivity analysis determined that imputation did not introduce systemic bias.

In the subset analysis among a subgroup of PWH (n = 5098) who had available CD4 count and HIV VL in the 12 months prior to their SARS-CoV-2 tests, the distribution of baseline characteristics and comorbidities was similar to the initial analysis (Supplementary Appendix 1, Tables 1 and 2). Eighty percent had undetectable HIV VL (<200), 90% were receiving ART, and 75% had a CD4 count ≥200 (≥14%). In this subset

Table 2. Charlson Comorbidities Among People With HIV by SARS-CoV-2 Status

	SARS-CoV-2 Status, No. (%)	
Comorbidities	Negative (n = 36 701)	Positive (n = 6472)
No known comorbidities	16 307 (44)	2761 (43)
Congestive heart failure	3257 (8.9)	712 (11)
Coronary artery disease	3045 (8.3)	568 (8.8)
Peripheral vascular disease	2810 (7.7)	482 (7.4)
Cerebrovascular disease	3253 (8.9)	601 (9.3)
Chronic obstructive pulmonary disease	11 024 (30)	1984 (31)
Diabetes mellitus		
Uncomplicated	5614 (15)	1287 (20)
Complicated	2991 (8.1)	694 (11)
Chronic kidney disease	4486 (12)	929 (14)
Liver disease		
Mild	6145 (17)	1147 (18)
Severe	832 (2.3)	167 (2.6)
Metastatic solid tumor	1059 (2.9)	124 (1.9)
Malignancy	4136 (11)	587 (9.1)
Peptic ulcer disease	1290 (3.5)	244 (3.8)
Rheumatic disease	1062 (2.9)	202 (3.1)
Dementia	666 (1.8)	151 (2.3)
Hemiplegia/paraplegia	771 (2.1)	150 (2.3)

analysis (Figure 3), higher adjusted odds of SARS-CoV-2 infection among PWH were observed in those who lived in the South, had a race/ethnicity other than non-Hispanic White, were uninsured, and had class 3 obesity and a low CD4 count. Nonsmokers had lower adjusted odds of SARS-CoV-2 infection. Higher odds of hospitalization were observed among PWH who were African American, had a higher CCI, received Medicaid/Medicare, were underweight, and had unsuppressed HIV VL. Lower adjusted odds of hospitalization were observed among uninsured PWH. Higher odds of ICU stay were observed among PWH who were male and receiving Medicaid; had a higher CCI, unsuppressed HIV VL, and low CD4 count; and were not undergoing ART. Higher adjusted odds of death among PWH were observed for those with the following factors: higher CCI, receipt of Medicaid/Medicare, underweight status, detectable HIV VL, lower CD4 count, and no ART. Lower odds of death were observed among African Americans and those in the US West.

When we used 1 January 2021 as a cutoff to split our cohort temporally and compare outcomes in 2 periods that reflect COVID-19 vaccination availability and treatment advancement, the unadjusted ORs before 1 January 2021 were significantly higher for hospitalizations (OR, 1.22; 95% CI, 1.12–1.33), ICU stays (OR, 1.38; 95% CI, 1.15–164), and death (OR, 1.69; 95% CI, 1.34–2.12) in PWH who were SARS-CoV-2 positive vs negative. However, after 1 January 2021, the unadjusted OR was not statistically significant for hospitalizations (OR, 1.08; 95% CI, .98–1.19), ICU stays (OR, 1.05; 95% CI, .84–1.30), or death (OR, 1.37; 95% CI, .99–1.84) in PWH who were SARS-CoV-2 positive vs negative.

DISCUSSION

Using EHR data in the national COVID-19 OPTUM data set, we were able to examine the intersection between the HIV epidemic and the COVID-19 pandemic on a national scale. Our study findings confirmed many previous studies' signals and discovered several new ones. These findings highlight the significant ethnic, racial, and geographic differences in SARS-CoV-2 infection among PWH that added to the preexisting disproportionate burden of HIV among these groups in the United States. Our primary analysis indicated a significant association between living in the US South and increased odds of SARS-CoV-2 infection, hospitalization, ICU stays, and death among PWH, congruent with our earlier findings in pediatric patients with COVID-19 [19]. The racial and ethnic burden of the COVID-19 pandemic also paralleled the HIV epidemic in the United States. When compared with non-Hispanic White PWH, Hispanic White and African American PWH had higher odds of SARS-CoV-2 infection and hospitalizations.

The determinants influencing the outcomes of severe SARS-CoV-2 infections exhibited temporal changes during the course of this study. These determinants encompassed shifts in the immunologic landscape that were attributed to (1) varying rates of individuals with a degree of protection from prior infection or vaccination, (2) fluctuations in the virulence of viral variants, and (3) advancements in SARS-CoV-2 treatment. Prior to 1 January 2021, PWH in our cohort who tested positive for SARS-CoV-2 experienced significantly higher odds of hospitalization, ICU stays, and death. However, after 1 January 2021, this was no longer the case. This suggests that with access to vaccines and evidence-based therapies, the morbidity and mortality of SARS-CoV-2 infection on PWH can be mitigated. Even though several social determinants of health were associated with SARS-CoV-2 infection among PWH, more equitable access to health care could improve patient outcomes in this population.

Similar to previous studies [7, 11, 12, 20–25], our study found that a higher burden of comorbidities was the primary variable associated with ICU stays and death. SARS-CoV-2 infection was also associated with higher odds of hospitalization, ICU stays, and death in our primary analysis. However, regardless of SARS-CoV-2 status, after we accounted for HIV care–specific variables, lower CD4 count, having a detectable HIV VL, and not receiving ART were associated with higher odds of ICU stays and death. Additionally, a lower CD4 count was associated with higher odds of SARS-CoV-2 test positivity, and having a detectable HIV VL was associated with higher odds of hospitalization.

Accounting for BMI among PWH in the United States while examining SARS-CoV-2 infection and severe outcomes

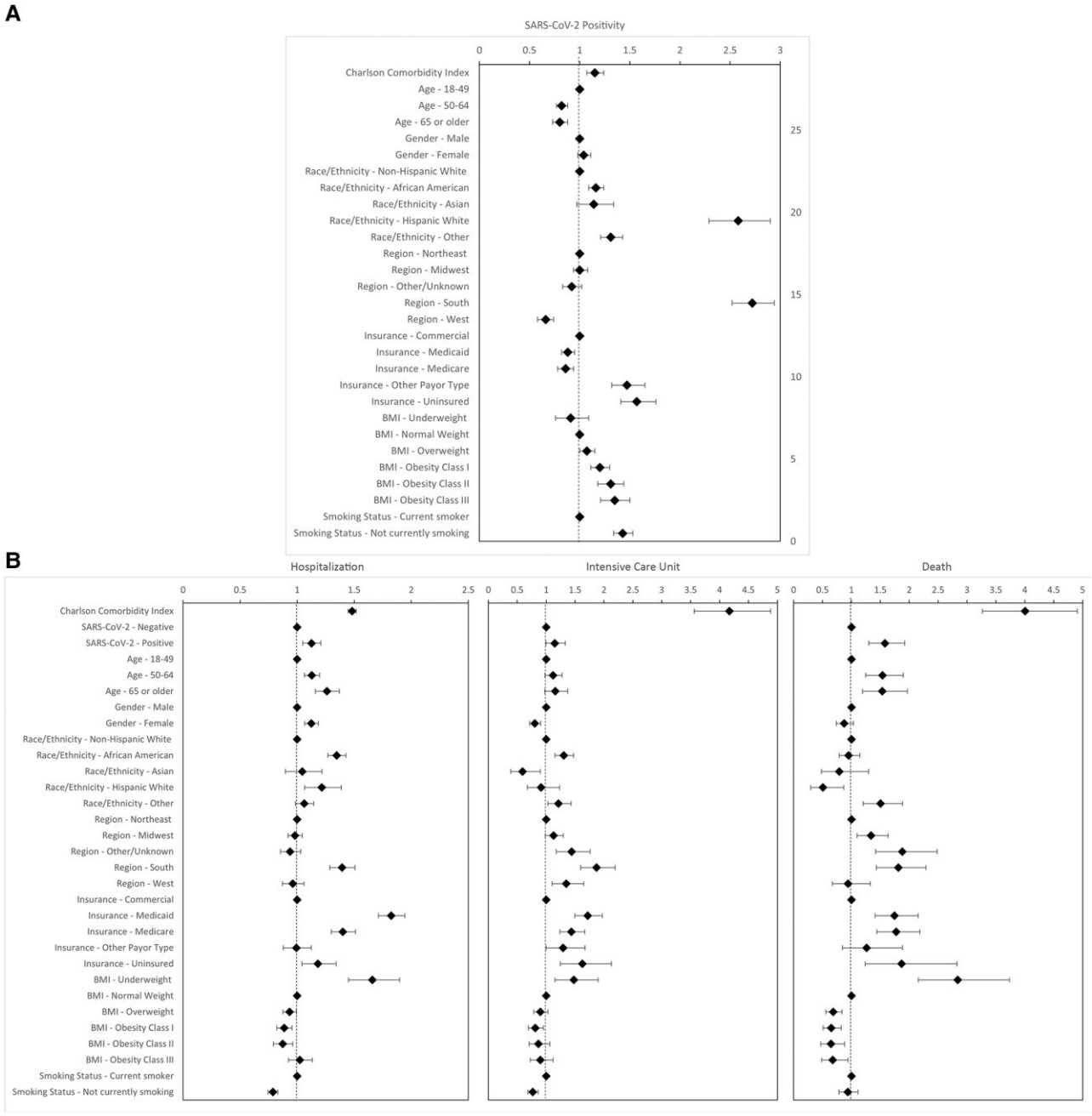

Figure 2. Adjusted odds ratios and 95% CIs from the multivariable logistic regression models in the primary analysis. *A,* Risk factors for SARS-CoV-2 test positivity among people with HIV in the United States. *B,* Risk factors for severe outcomes within 30 days of SARS-CoV-2 testing (positive and negative) among people with HIV. BMI, body mass index.

unveiled noteworthy findings. Higher BMI was a significant risk factor for SARS-CoV-2 infection. However, being underweight was associated with higher odds of hospitalization and death among PWH, even after adjusting for HIV-specific variables. As weight gain can be an effect of ART and a lower BMI is one of the identifying signs of AIDS—which independently may contribute to a higher risk of comorbidities, severe outcomes, and death—we hypothesize that weight, as a possible reflection of HIV stage, probably contributed to these findings.

When compared with PWH who had commercial insurance, uninsured PWH had significantly higher odds of SARS-CoV-2 infection, hospitalization, ICU stays, and death. With the caveat that there is an overlap between older age (a known risk factor for SARS-CoV-2 infection severity) and being on Medicare, PWH receiving Medicare/Medicaid had higher odds of

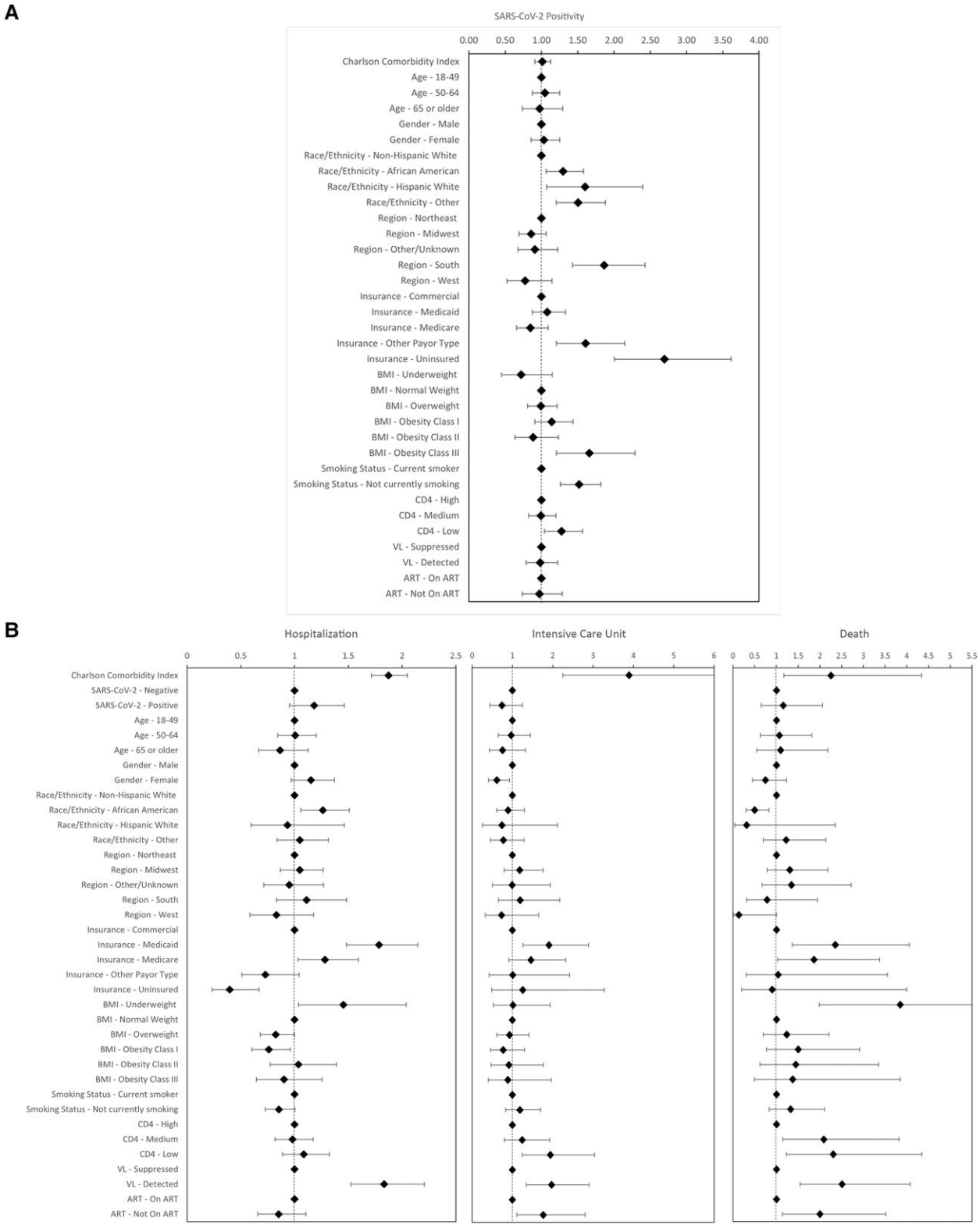

Figure 3. Adjusted odds ratios and 95% CIs from the multivariable logistic regression models in a subset of PWH who had available CD4 count, HIV VL, and ART data in the 12 months preceding their SARS-CoV-2 test in the electronic health record repository. *A*, Risk factors for SARS-CoV-2 test positivity among PWH in the United States, accounting for CD4 count, HIV VL, and ART. *B*, Risk factors for severe outcomes within 30 days of SARS-CoV-2 testing (positive and negative) among PWH in the United States, accounting for CD4 count, HIV VL, and ART. ART, antiretroviral therapy; BMI, body mass index; PWH, people with HIV; VL, viral load.

hospitalization, ICU stays, and death. After accounting for HIV care–specific variables, our analysis had similar findings regarding insurance. Uninsured PWH were less likely to be hospitalized irrespective of their SARS-CoV-2 status. It is important to note that our study included only hospitalizations available in the study data set and might not have captured hospitalizations outside the OPTUM COVID-19–specific data set.

In accordance with previous studies [5, 6, 9–12, 22, 25], we found that older age and smoking among PWH were associated with higher odds of severe outcomes, including hospitalization, ICU, and death. Yet, younger PWH and nonsmokers undergoing SARS-CoV-2 testing had higher odds of SARS-CoV-2 test positivity, consistent with indications from other studies [13, 21, 26]. We hypothesize that this may be partially related to testing bias: younger PWH were more likely to seek testing for SARS-CoV-2 when symptomatic, and older PWH with comorbidities were more likely to seek health care for non–SARS-CoV-2 concerns and become subject to asymptomatic testing due to routine screening protocols implemented during the COVID-19 pandemic. Alternatively, older PWH might have exercised more caution due to a perceived higher risk of worse outcomes should they contract SARS-CoV-2 infection. In the same vein, as compared with smokers, nonsmokers were less likely to have chronic cough that may have been confused with COVID-19 symptoms and thus may have sought out testing more frequently. Interestingly, with a cautious interpretation due to the low number of events in our subset analysis, these age and smoking effects were no longer significant after adjusting for HIV care–specific variables.

As PWH have unique epidemiologic characteristics and a higher number of comorbidities than the general population, by comparing PWH who were SARS-CoV-2 positive and negative in the United States, we partially overcame the inherent biases contained in the comparison of PWH vs people without HIV. This became more evident in our subset analysis, where SARS-CoV-2 infection, region, and race/ethnicity were no longer significant risk factors for severe outcomes, while HIV care–specific variables were major contributors to hospitalization, ICU stays, and death. However, this finding should also be interpreted with caution considering the low number of secondary outcome events in our subset analysis.

While some limitations are inherent in cohort studies from real-world data repositories, using a national EHR repository in the United States allowed for a large sample size for our cohort of PWH. However, several limitations should be taken into consideration while interpreting our results. First, EHR data repositories may not be as inclusive as data sets that include entire health systems [27]. For this reason, some risk factors that may affect outcomes, such as vaccination, could not be included, and only a small proportion of our study population had CD4 and VL data available for the subset analysis. Second, age and 30-day mortality rates were approximated by birth year and death month, respectively, as the OPTUM repository is a certified deidentified database and does not host date of birth or date of death but, alternatively, month of birth and month of death. Third, given the low number of events among severe outcomes in our subset analysis, which was subject to the availability of HIV care–specific data in the data set, the results of our secondary analysis should be interpreted with caution. Fourth, considering the study design from an EHR repository, the contribution of SARS-CoV-2 infection to the secondary outcomes, including 30-day hospitalization, ICU stays, and death, is unknown. Fifth, while there is a difference between gender and sex at birth, gender as a study variable was captured from the categorized data for gender in the deidentified EHR repository, which might be subject to the criteria that each participating entity mapped onto its own variables. Last, there is potential for misclassification bias due to the reliance on *ICD* codes for disease categorization and the use of laboratory testing data for HIV disease markers.

CONCLUSION

In a large US national cohort of PWH, our study affirmed and strengthened the validity of the findings that chronic comorbidities, older age, smoking, low CD4 count, lack of HIV viral suppression, and not receiving ART were associated with severe outcomes among PWH during the COVID-19 pandemic. Our observations also offer supportive evidence for the disproportionate burden of SARS-CoV-2 infection among PWH from certain ethnicities, racial groups, and geographic regions and introduce new insights regarding the effects of BMI and insurance status in this population. While SARS-CoV-2 infection was associated with more severe outcomes, once we adjusted for demographics, comorbidities, and HIV-specific variables, it was no longer significant; in fact, the HIV-specific variables CD4 count, VL, and ART usage held a significant association with higher odds of death. Additionally, once vaccines and evidence-based therapies became available, there was no increase in morbidity or mortality associated with SARAS-CoV-2 infection in PWH. These findings underscore the importance of strengthening access to continuous HIV care amid the challenges posed by the COVID-19 pandemic. Our findings additionally may be beneficial in helping to identify opportunities for affecting the incidence of SARS-CoV-2 infection in PWH by targeting testing and vaccination strategies.

Supplementary Data

Supplementary materials are available at *Open Forum Infectious Diseases* online. Consisting of data provided by the authors to benefit the reader, the posted materials are not copyedited and are the sole responsibility of the authors, so questions or comments should be addressed to the corresponding author.

Notes

Author contributions. All authors contributed equally to the work.

Data availability. Project codes are available at https://github.com/MedfordLab upon request.

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