# Simulation of Ventilator Allocation in Critically Ill Patients with COVID-19

*To the Editor*:

Crisis Standards of Care are defined as a "substantial change in health care operations" made necessary by an overwhelming public health emergency (1). The coronavirus disease (COVID-19) pandemic has created such a crisis in many countries around the world, forcing the rationing of life-saving care. Although published triage systems share some common procedures, the driving ethical principles and resulting rationing algorithms vary widely across the world and within the United States (2). Italian ICUs used age-based cutoffs (3), but most U.S. protocols do not include age as a primary criterion, instead ranking patients based on objective outcome predictors like the Sequential Organ Failure Assessment (SOFA) score or the presence of comorbidities (2, 4, 5).

Although there is an active theoretical debate over these protocols, there have been few empirical assessments of their performance (6, 7). We performed a Monte Carlo simulation of a severe ventilator shortage in a diverse, multicenter population of critically ill patients with COVID-19 receiving mechanical ventilation. The study objective was to assess the impact of four triage strategies on ventilator allocation and survival to hospital discharge across racial and ethnic groups and age.

## Methods

The study included all critically ill adult patients with laboratory-confirmed COVID-19 who received mechanical ventilation at three healthcare settings in the greater Chicagoland area between March 2020 and February 2021. We extracted age, sex, self-identified racial and ethnic identity, International Classification of Diseases version 10 (ICD-10) codes for preexisting comorbidities, and SOFA score components from the electronic health record. We calculated each patient's 24-hour maximum SOFA and used ICD-10 codes to identify a "severe" comorbidity Elixhauser threshold corresponding to a 90% predicted 1-year mortality (8).

We evaluated four ventilator allocation protocols: *1*) lottery; *2*) youngest first; *3*) SOFA only; and *4*) multiprinciple (Table 1). The SOFA-only protocol assigns priority tiers by SOFA score, with ties broken through a lottery (4). The multiprinciple protocol calculates priority scores based on categorical tiers of SOFA and the presence of severe comorbidities, with ties broken by age group (5).

The primary outcome was survival to hospital discharge estimated with a Monte Carlo simulation model. For each protocol, the model simulates a 50% ventilator shortage by *1*) randomly subsampling two patients, *2*) comparing their priority scores based on the protocol, *3*) assigning the ventilator to the higher-priority patient, and *4*) repeating this process until all study patients are sampled. We calculated the lives saved in each simulation by observing the actual survival to hospital discharge of patients assigned ventilators, assuming that patients who were not allocated a ventilator did not survive. We repeated the simulation 1,000 times for each protocol and compared the mean survival to hospital discharge between protocols overall and by age, race, and ethnicity using $t$ tests. Significance tests were two sided with a $P$ value threshold of $<0.05$.

## Results

During the study period, there were 998 patients with laboratory-confirmed COVID-19 who received mechanical ventilation. The median age was 64 years (interquartile range, 53–73 yr) and mortality rate was 37.8%. The cohort was 32.2% non-Hispanic Black, 32.4% non-Hispanic White, 26.9% Hispanic, and 8.5% other. Hispanic patients (mean 56.0 yr) were significantly younger than Black patients (61.7 yr), and both groups were significantly younger than White patients (66.5 yr). Using maximum SOFA score in the first 24 hours of ICU admission, Black patients had a significantly higher score (mean 9.2) compared with Hispanic (7.5) and White patients (7.5). Black patients had higher rates of severe comorbidities (20.9%), compared with Hispanic (9.3%) and White patients (9.3%) ($P < 0.001$ for all comparisons above).

Under the SOFA-only protocol (score range 1–3), the mean score for Black patients was 1.95 compared with 1.67 for Hispanic patients and 1.64 for White patients. SOFA-only used a lottery tiebreaker for 18% of simulated patient pairs. Under the multiprinciple protocol (score range 1–7), the mean score was 2.59 for Black patients compared with 1.91 for Hispanic patients and 1.87 for White patients. This protocol used an age tiebreaker 15% of the time and the lottery tiebreaker 5% of the time.

When simulating a 50% ventilator shortage, the youngest-first protocol was associated with a significantly higher survival rate (34.7%) compared with all other protocols (Table 1). The multiprinciple protocol (33.5%) and the SOFA-only protocol (32.9%) had significantly higher survival than random ventilator allocation with a lottery (31.1%).

When ventilators were randomly assigned, there were no significant differences in survival in Black, White, or Hispanic patients compared with average survival (Figure 1). Black patients

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**Table 1.** Ventilator Allocation Protocols and Lives Saved under a 50% Ventilator Shortage

| Protocol | Rules | Average Survival (%) | Survival by Race (%) | | | Allocation by Race (%) | | |
|---|---|---|---|---|---|---|---|---|
| | | | Black | White | Hispanic | Black | White | Hispanic |
| Lottery | Random assignment | 31 (30–33) | 31 (27–35) | 31 (27–34) | 32 (27–36) | 50 (45–54) | 50 (46–54) | 50 (44–55) |
| Youngest first | Rank by age | 35 (34–36) | 35 (32–38) | 28* (25–31) | 42† (38–45) | 50 (47–54) | 41* (37–44) | 61† (57–65) |
| SOFA only | Three SOFA tiers:<br>Red: ⩽7<br>Yellow: 8–11<br>Blue: >11<br>Lottery tiebreaker | 33 (32–34) | 29* (26–32) | 36 (32–39) | 35 (31–38) | 44* (40–48) | 54† (50–58) | 53 (49–58) |
| Multiprinciple | SOFA category points:<br>1: ⩽8<br>2: 9–11<br>3: 12–14<br>4: >14<br>Chronic conditions:<br>+3 points if “severe”<br>Age tiebreaker‡ | 34 (32–35) | 29* (26–32) | 34 (31–37) | 38† (35–42) | 42* (39–46) | 51 (48–55) | 58† (54–62) |

*Definition of abbreviation*: SOFA = Sequential Organ Failure Assessment.

Ventilator allocation protocols, average survival, survival by race/ethnicity, and allocation by race/ethnicity are presented. Allocation protocols were adapted from published state protocols, and SOFA categories used reflect the categories as defined in these blueprint protocols. Data are presented as mean and 95% confidence intervals. The survival is measured by percentage of patients who survived to hospital discharge under a 50% ventilator shortage. Shortage of 50% indicates that only one ventilator is available for every two patients requiring mechanical ventilation. We assumed all patients who were not allocated a ventilator died.

*Statistically significant *lower* survival or allocation in the racial/ethnic group than the average for the protocol ($P < 0.05$)

†Statistically significant *higher* survival or allocation in the racial/ethnic group than the average for the protocol ($P < 0.05$)

‡Tiebreaker with age categories adapted from published protocols: 0–49, 50–69, 70–84, and ⩾85. If a simulated patient pair remained tied after applying the age tiebreaker, a lottery tiebreaker was applied.

were less likely to receive a ventilator and had lower survival in both the SOFA-only (29% vs. 33%, $P = 0.03$) and multiprinciple protocols (29% vs. 34%, $P = 0.008$) but had average allocation and survival in the youngest-first protocol. Hispanic patients were more likely to receive a ventilator and had higher survival in the youngest-first (42% vs. 35%, $P < 0.001$) and multiprinciple protocol (38% vs. 34%, $P = 0.007$). White patients were more likely to be allocated ventilators in the SOFA-only protocol, but this did not lead to significantly higher survival.

In a sensitivity analysis, we found that the results were robust when assuming 10% survival without ventilator allocation (compared with 0% in the primary analysis).

## Discussion

In this Monte Carlo simulation of a severe ventilator shortage in a Chicagoland population of patients with COVID-19, a youngest-first allocation system saved the most lives but led to significantly lower allocation and survival in the oldest patients. A lottery system of random ventilator allocation saved the fewest lives but had equal survival by race/ethnicity. Black patients had equivalent survival when given equal access to ventilators in a lottery system but lower survival in triage systems that used SOFA scores. Finally, critically ill Black and Hispanic patients requiring mechanical ventilation were younger than White patients and were most likely to be allocated ventilators in the youngest-first system.

Recent studies of general ICU patients without COVID-19 and a mixed population of ICU patients with and without COVID-19 in a single healthcare system found minimal or no association between race/ethnicity and priority tier (6, 7). The inequities in survival found in our study are likely attributable to differences in study population and the simulation methodology. Our study population was restricted to patients with COVID-19 who received mechanical ventilation but constituted a broadly representative sample from multiple healthcare systems across Chicago. In addition, our methodology simulates the triage process and may have exposed inefficiencies and disparities missed with traditional regression analysis.

“Color-blind” allocation protocols can unintentionally exacerbate health inequities. For example, Black patients in our cohort had higher SOFA scores and higher prevalence of comorbidities leading to lower priority for ventilators and lower survival. If applied to populations similar to our cohort, many U.S. ventilator allocation protocols would amplify existing healthcare disparities, layering inequitable resource allocation onto the current disproportionate health impact of the pandemic on disadvantaged communities (9).

Although youngest-first saved the most lives, U.S. state protocols either ignore age or use it as a secondary criterion (2). Proponents of prioritizing younger critically ill patients for treatment argue that they are worse off because they have not lived through all life’s stages

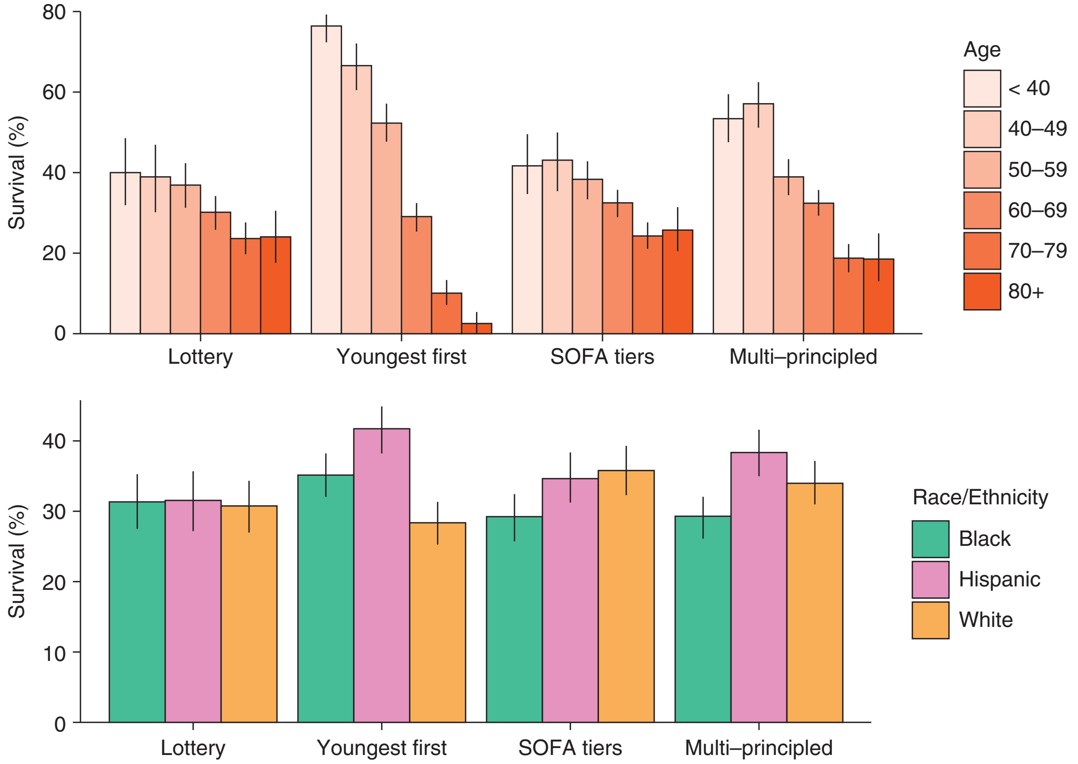

**Figure 1.** Survival to hospital discharge by age, race, and ethnicity by allocation protocol in a Monte Carlo simulation of a 50% ventilator shortage. Black refers to non-Hispanic Black patients and White refers to non-Hispanic White patients. In lottery allocation, survival was 40% in patients younger than 40 years compared with 24% in patients 80 years or older. In youngest-first, survival was 76% in patients younger than 40 years compared with 2.6% in patients 80 years or older. In the multiprinciple protocol with an age tiebreaker, survival was 53% in patients younger than 40 years compared with 19% in patients 80 years or older. In lottery allocation, survival was not significantly different between racial and ethnic groups (average survival 31%). In the SOFA-only protocol, survival to discharge was 29% for Black patients compared with 35% for Hispanic patients and 36% for White patients. In the multiprinciple protocol, survival was 29% for Black patients compared with 38% for Hispanic patients and 34% for White patients. SOFA = Sequential Organ Failure Assessment.

(10–12). In our population, youngest-first resulted in higher survival in Black and Hispanic patients, reflecting the relatively younger age of Black and Hispanic patients developing severe COVID-19 disease.

Our study is limited by *1*) only including patients with COVID-19 infection, *2*) a lack of standard intubation criteria across hospital systems, and *3*) a static simulation model. We cannot generalize these findings to all patients who would need mechanical ventilation in other crisis scenarios. Future work is required to develop dynamic simulation models that reevaluate patients during their hospital course.

In conclusion, in a Monte Carlo simulation model of ventilator allocation, systematic triage protocols saved more lives than a lottery. Youngest-first saved the most lives and did not exacerbate racial disparities. SOFA-only and multiprinciple protocols saved fewer lives than youngest-first and reduced ventilator allocation and survival in Black patients. Through simulation modeling, we found the ethical trade-offs between existing allocation protocols. ■

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**Author disclosures** are available with the text of this letter at www.atsjournals.org.

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# Machine Learning–based Sleep Staging in Patients with Sleep Apnea Using a Single Mandibular Movement Signal

*To the Editor*:

We all sleep, and sleep patterns and architecture influence our health and wellbeing. At present, the gold standard method for recording detailed sleep patterns to detect and monitor sleep disorders is in-laboratory overnight polysomnography (PSG), requiring specialized equipment and trained staff. This is no longer feasible in view of the size of the population with suspected sleep disorders, and especially in the coronavirus disease (COVID-19) era (1).

Mandibular movements reveal the changes in trigeminal motor nucleus activity driven by brainstem centers involved in sleep and wake transitions (2, 3). The activity of upper airway muscles anchored on the mandibular jaw is the net result of the activation of brainstem respiratory and sleep centers and their respective interactions. This produces specific mandibular movement patterns reflecting the interactions between sleep stages and respiratory control. We previously demonstrated that sleep mandibular movements represent a powerful tool for characterizing respiratory disturbances in obstructive sleep apnea (OSA) (4–6).

Figure 1 gives examples of how the different sleep stages each have typical mandibular movement signal patterns.

Recordings of mandibular movements throughout the night provide hundreds of temporal–spatial signals for modeling and

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Author Contributions: N.-N.L.-D. conceived and designed the project, analyzed the data, drafted the initial manuscript, and reviewed and revised the manuscript; J.-B.M. conceived and designed the study, performed the research, analyzed the data, drafted the initial manuscript, and reviewed and revised the manuscript; N.C. and V.C. performed the research and participated in data acquisition; R.T. reviewed and revised the manuscript; S.B. analyzed the data and reviewed and revised the manuscript; J.-L.P. conceived and designed the study, analyzed the data, and reviewed and revised the manuscript. All authors helped revise the manuscript and approved it for submission.

Data sharing statement: The deidentified data used in this study are not publicly available at present. Parties interested in data access should contact N.-N.L.-D. (nam@hellosunrise.com) for queries related to the Extreme Gradient Boosting (XGB) classifier and J.-B.M. (martinot.j@respisom.be) for queries related to the sleep laboratory data set. The data sets generated and/or analyzed during the current study are available from the corresponding author on reasonable request. Applications will need to undergo ethical and legal approvals by the respective institutions. Those interested in research collaborations should contact J.-B.M. (martinot.j@respisom.be).

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