Columbia University

reliable Artificial Intelligence for Health and Medicine (reAIM) Lab

Neural Information Processing Systems

Path-specific effects for pulse-oximetry guided decisions in critical care

NeurIPS 2025

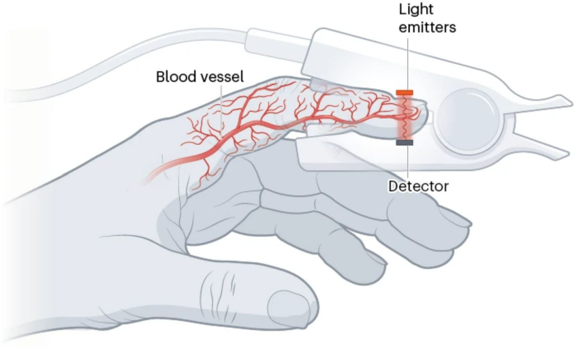
Kevin Zhang, Yonghan Jung, Divyat Mahajan, Karthikeyan Shanmugam, Shalmali Joshi

Evidence of racial bias in pulse oximeter device measurements

nature

NEWS & VIEWS FORUM | 19 October 2022

Skin colour affects the accuracy of medical oxygen sensors



npr

COVID-19 made pulse oximeters ubiquitous. Engineers are fixing their racial bias

Original Investigation | Pulmonary Medicine

Analysis of Discrepancies Between Pulse Oximetry and Arterial Oxygen Saturation Measurements by Race and Ethnicity and Association With Organ Dysfunction and Mortality

An-Kwok Ian Wong, MD, PhD[1,2]; Marie Charpignon, MS[3]; Han Kim, MSE[4] ; et al

Original Investigation

Assessment of Racial and Ethnic Differences in Oxygen Supplementation Among Patients in the Intensive Care Unit

Eric Raphael Gottlieb, MD, MS[1,2,3]; Jennifer Ziegler, MD, MSc[4]; Katharine Morley, MD, MPH[2,5] ; et al

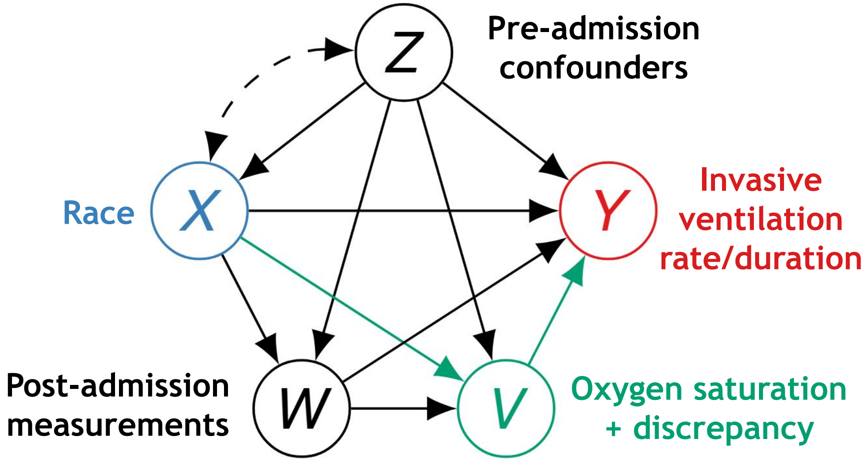
Original Investigation

Racial and Ethnic Discrepancy in Pulse Oximetry and Delayed Identification of Treatment Eligibility Among Patients With COVID-19

Ashraf Fawzy, MD, MPH[1]; Tianshi David Wu, MD, MHS[2,3]; Kunbo Wang, MS[4] ; et al

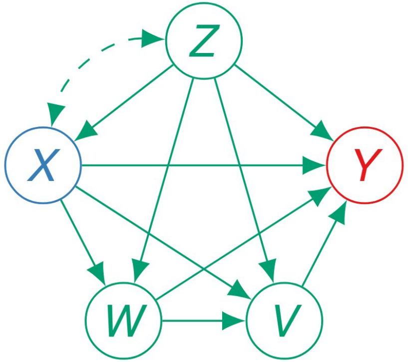
Quantifying *path-specific causal effect* of *pulse-oximeter discrepancies* on clinical decision-making in the ICU

1. Extend existing causal mediation analysis for multiple mediators
2. Develop robust estimators with theoretical guarantees and better performance in small-sample regimes (e.g. ICU data)



Study	Causal Analysis	Path-Spec. Analysis	Multi-Med.	ICU Data	Finite Guar.
Sjoding, 2020	Assoc.	×	×	✓	×
Wong, 2021	Assoc.	×	×	✓	×
Gottlieb, 2022	Part.	Part.	×	✓	×
Miles, 2017	✓	✓	✓	×	×
Tchetgen, 2012	✓	✓	×	×	×
VanderWeele, 2014	✓	✓	×	×	×
Ours	✓	✓	✓	✓	✓

Causal fairness model with two mediators

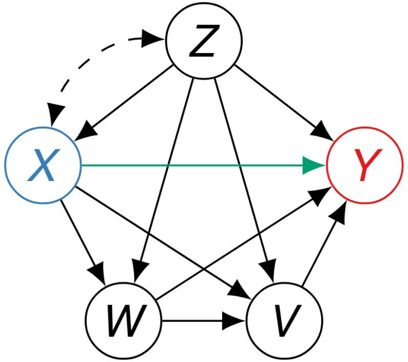


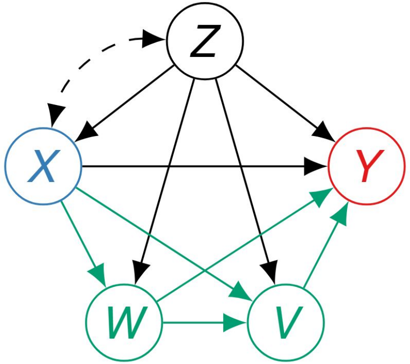
Total Effect (TE)

$$\mathbb{E}[Y_{x_1}] - \mathbb{E}[Y_{x_0}]$$

$$\mathbb{E}[Y_{x_1, W_{x_0}, V_{x_0}}] - \mathbb{E}[Y_{x_0}]$$

Natural Direct Effect (NDE)



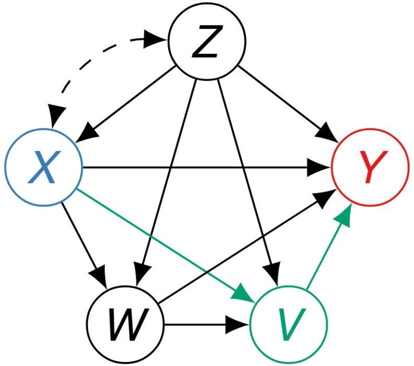


Natural Indirect Effect (NIE)

$$\mathbb{E}[Y_{x_1}] - \mathbb{E}[Y_{x_1, W_{x_0}, V_{x_0}}]$$

$$\mathbb{E}[Y_{x_1}] - \mathbb{E}[Y_{x_1, V_{x_0}, W_{x_1}}]$$

V-specific Direct Effect (VDE)



Pearl, *UAI*, 2001

Pulse oximetry application

VDE doubly robust estimator

The VDE is identifiable using the back-door adjustment and given by

$$\mathbb{E}[Y_{x_1, V_{x_0}, W_{x_1}}] = \sum_{w,v,z} \mathbb{E}[Y \mid x_1, w, v, z] P(v \mid x_0, w, z) P(w \mid x_1, z) P(z). \quad (1)$$

We use the doubly robust estimator,

$$\begin{aligned} \varphi((Y, V, W, X, Z); \boldsymbol{\mu}_0, \boldsymbol{\pi}_0) \triangleq\ & \pi_0^3(V, W, X, Z)\{Y - \mu_0^3(V, W, X, Z)\} \\ & + \pi_0^2(W, X, Z)\{\mu_0^3(V, W, x_1, Z) - \mu_0^2(W, X, Z)\} \\ & + \pi_0^1(X, Z)\{\mu_0^2(W, x_0, Z) - \mu_0^1(X, Z)\} + \mu_0^1(x_1, Z). \end{aligned}$$

$$\mathbb{E}[\varphi((Y, V, W, X, Z); \boldsymbol{\mu}_0, \boldsymbol{\pi}_0)] = \text{Eq. (1)}$$

Nuisance parameters defined following Jung, *NeurIPS*, 2024

Theoretical guarantees of the VDE estimator

Algorithm

1. (***Sample-Splitting***)
   Take any L-fold partition of the data $\mathcal{D} = \cup_{\ell=1}^{L} \mathcal{D}_\ell$.

2. (***Learning by Partitions***)
   Learn $\hat{\mu}_\ell^i, \hat{\pi}_\ell^i$ *using* $\mathcal{D} \setminus \mathcal{D}_\ell$ *and compute* $\hat{\psi}_\ell \triangleq \mathbb{E}_{\mathcal{D}_\ell}[\varphi(Y, V, W, X, Z); \hat{\boldsymbol{\mu}}, \hat{\boldsymbol{\pi}}]$.

3. (***Aggregation***)
   Construct $\hat{\psi} \triangleq \frac{1}{L}(\hat{\psi}_1 + \cdots, \hat{\psi}_L)$.

Theorem 2 (informal)

Suppose the second and third moments of φ *exist.*

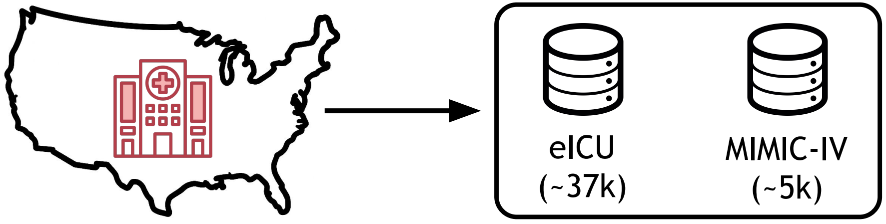
Let $R_1 \triangleq \frac{1}{L}\sum_{\ell=1}^{L}(\mathbb{E}_{\mathcal{D}_\ell}[\hat{\varphi}_\ell] - \mathbb{E}_P[\varphi_0])$. *Then,*

$$\hat{\psi} - \psi_0 = R_1 + \frac{1}{L}\sum_{\ell=1}^{L}\sum_{i=1}^{3}\mathbb{E}[\{\hat{\mu}_\ell^i - \mu_0^i\}\{\pi_0^i - \hat{\pi}_\ell^i\}].$$

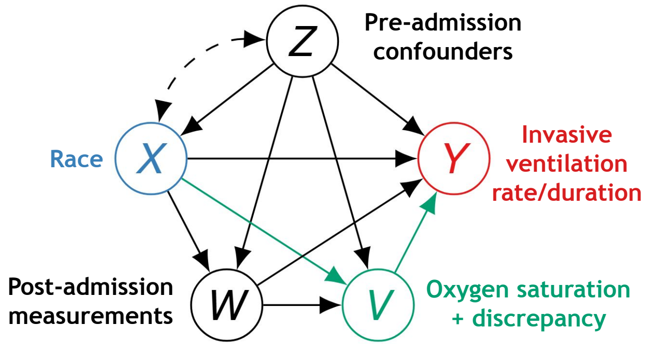
Moreover, $R_1 \xrightarrow{p} 0$ *and* R_1 *is asymptotically normal.*

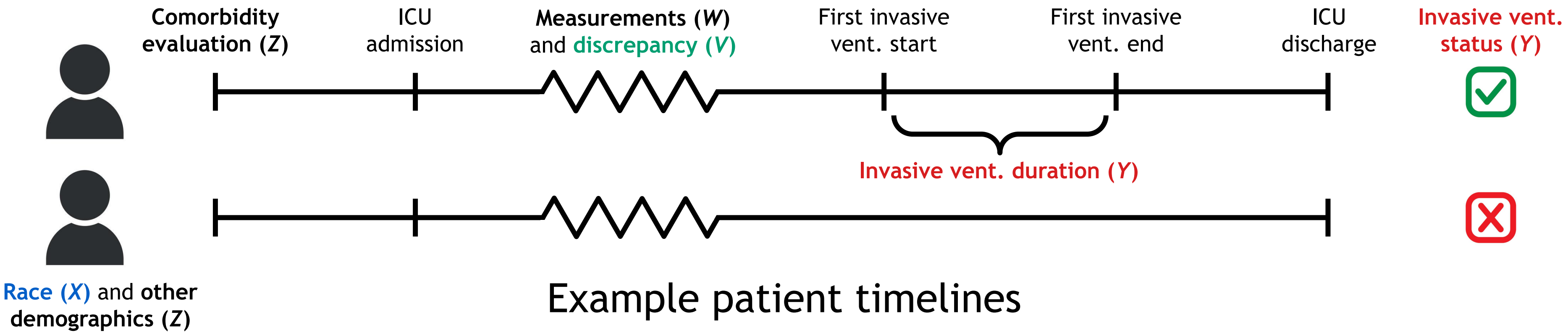
Since $\mathbb{E}[\pi_0^i] = 1$, we use the self-normalized (SN) estimator, $\hat{\pi}_{\text{SN}}^i \leftarrow \hat{\pi}^i / \mathbb{E}_{\mathcal{D}}[\hat{\pi}^i]$, as this improves the estimation stability in practice.

Critical care data on invasive ventilation-related outcomes



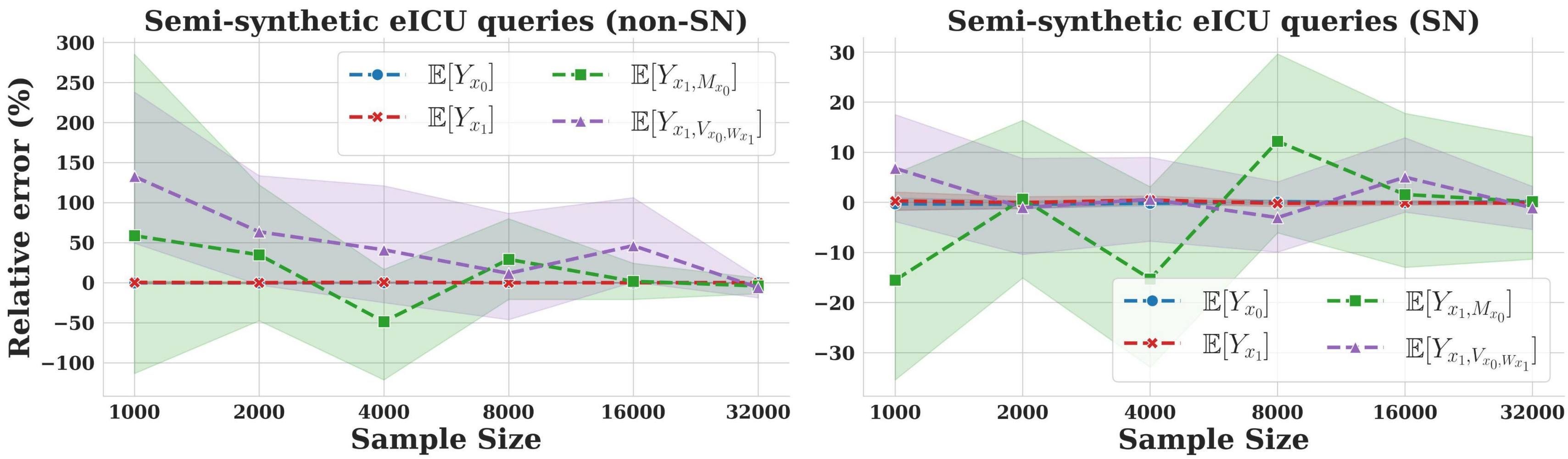
EWA to summarize measurement trajectories





Example patient timelines

Semi-synthetic experiments

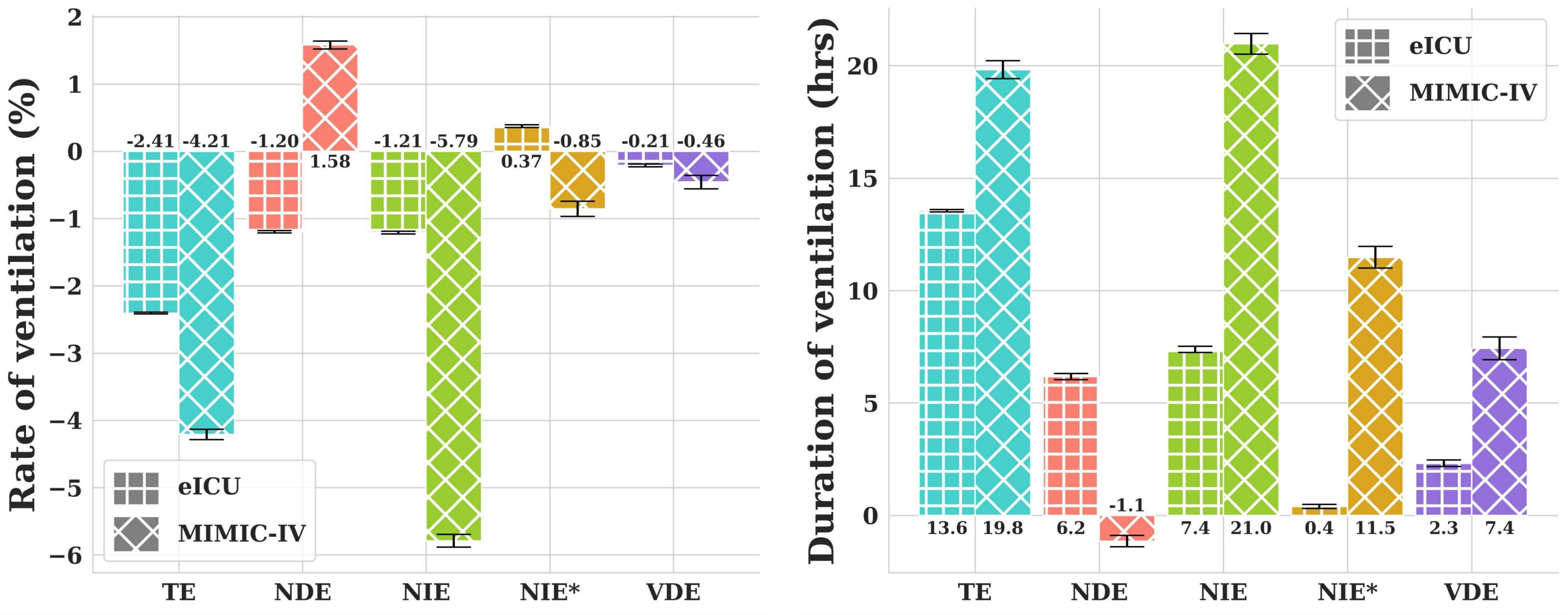


Bands show 95% CIs

The self-normalized estimator (right) has smaller variance compared to the canonical doubly robust estimator (left)

Real-world experiments

Positive effect = more frequent or longer treatment for Black patients vs. White patients



Error bars show 95% CIs

Ventilation rate VDE is negligible (95% CI **eICU [-0.23, -0.19]**, **MIMIC-IV [-0.56, -0.36]**), but more pronounced for ventilation duration (95% CI **eICU [2.2, 2.5]**, **MIMIC-IV [6.9, 7.9]**)

Conclusions and future work

- We examine heterogeneity by race in a clinically actionable healthcare process using path-specific causal analysis with theoretical guarantees

- Bias primarily manifests in ventilation duration, not in treatment initiation

- Future work could model temporality explicitly

In-person poster session @ San Diego

Thu 4 Dec, 11am-2pm PST, Exhibit Hall C/D/E

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