Association of a Novel Index of Hospital Capacity Strain with Admission to Intensive Care Units

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Appendix 1. Conceptual model of capacity strain

In contrast to prior studies centered on capacity strain at a specific level of care, we took a holistic, hospital-level view of capacity strain. Strain metrics fell into three categories: patient occupancy, patient turnover, and patient acuity and associated clinical burden. We pooled together all units within a single level of care (e.g., all medical wards) by hospital. We excluded hospital locations that took care of exclusively non-medical patients (e.g., surgical or neurological) or pediatric patients with the view that capacity strain greatly respects barriers between entirely unrelated bed capacity pools (e.g., a general medicine ward and a neurology-dedicated ward).

Appendix 2. Strain metrics

Occupancy. Occupancy is a widely studied strain metric.[1-12] It is easily visible to clinicians both in the unit of interest as well as viewed from elsewhere, such as ED or ward clinicians considering making an ICU referral. It is also easily interpretable: any clinician will know without difficulty what it means to have 0, 1, or 2 open ICU beds. We extended our measures of occupancy outside of the ICU to include the occupancies of the ED, wards, and step-down units, with the rationale that an interpretation of ICU beds availability may be done in the context of ED congestion and hospital-wide bed availability. We measured occupancy on an hourly level to reflect its dynamic nature and that fact that an interpretation of bed availability would be based more on an at-present assessment than on recent but potentially different, outdated occupancy data. For example, a full ICU that discharges 2-3 patients in quick succession within one hour has a very different strain status at the top and bottom of that hour. When patients spent time in transient locations (e.g., procedural settings, dialysis units, radiology), even if between two different hospital units, we considered them still on the census of their prior location, as in most circumstances, the original care team would not relinquish full clinical responsibility until the patient arrived in their new care destination.

Turnover. ICU turnover as a strain metric is a recognition that significantly greater work—in terms of cognitive load, bedside diagnostics and therapeutics, and documentation—is required in the first day of an ICU admission than on most successive days. We defined ICU turnover as the number of ICU patients newly admitted during the prior 24 hours and likewise calculated the ICU turnover metric on a rolling hourly basis throughout the study period. Because this strain metric is based on the workload of new ICU admissions, a single ICU bed could conceivably contribute more than once to ICU turnover if more than one patient were admitted to it over a 24-hour period (necessitating transfer out of any prior admissions). We restricted our assessment of turnover to the ICU alone, as new admissions in other locations, while important for local assessments of strain, would be less likely to significantly influence an ICU-centric disposition decision. We did not consider routine ICU-to-ward transfers of recovering patients to be a potential source of ICU capacity strain, but we did create a separate metric of ICU discharges that included patients for whom the ICU team was responsible for all aspects of a hospital discharge, such as discharge directly home, to another hospital, or to any rehab location. This was likewise calculated hourly based on the prior 24-hours of ICU discharges and limited to calculation in ICU locations.

Acuity. Our approach to acuity was two-fold: (1) a granular assessment of ICU census acuity and (2) a more limited assessment of outside-of-ICU acuity to capture patients that might be competing for ICU bed capacity and/or requiring significant bedside resources. We calculated rolling LAPS2 scores daily at 7:00am based on the preceding 24-hours of physiological data, regardless of where those data were collected, for all patients who spent time in the ICU. We then took the mean LAPS2 score of all patients in the ICU at 7:00am on a daily basis throughout the study period. The choice of a once-daily assessment at 7:00am was based on the notion that morning rounds in the ICU is when the overall physiological state of the census, based on fresh diagnostic data and an assessment of the prior day's and overnight clinical events, is internalized by the ICU team.

For non-ICU locations, we decided against a similar granular physiologic approach, as it was unlikely that an ICU-centric disposition decision would be heavily influenced by granular acuity changes in other hospital locations. Instead, we sought to capture patients potentially competing for ICU bed availability and measured counts of patients requiring potentially ICU-indicated therapies including: vasopressors, mechanical ventilation, BiPAP, and other respiratory support (a composite of nonrebreather mask, high-flow nasal cannula, or $FiO2 \geq 60\%$). Counts in each category were measured in rolling 8-hour windows for EDs, wards, and step-down units, in addition to ICUs, with patients contributing only to the count of the highest therapy level (i.e., mechanical ventilation, if not then BiPAP, if not then other respiratory support). A patient could contribute once per 8-hour window for each therapy category at a given level of care, but could contribute multiple times per 8-hour window if they moved between levels of care (e.g., from the ED to the wards) and re-triggered the criteria in the new location. CPAP was not counted to avoid including patients with stable obstructive sleep apnea; we could not distinguish home from acute BiPAP, so all instances were included. The other respiratory support composite was not counted in the ED to avoid including patients placed on high supplemental oxygen empirically on arrival and quickly weaned down without a true requirement of that magnitude. Patients contributed to strain metrics based on their physical location independent of any “boarder” status or upcoming transfer, with the rationale that patients who will be soon or are meant to be cared for elsewhere, at a given time are still largely utilizing the resources of the physical unit in which they are located, including physical bed, nursing staff, respiratory therapists, social workers, and often physician teams.

Appendix 3. Strain metric standardization

We applied two levels of standardization to our raw strain metrics. First, all count-based measures (i.e., all measures except for mean ICU census LAPS2) were standardized to the bed capacity of the unit(s) in which they were measured and expressed as a percentage of bed capacity. This allowed for the comparison of counts measured in units with different bed capacities (e.g., distinguishing 10 patients in a 10-bed ICU versus 10 patients in a 20-bed ICU) or in a single unit with a bed capacity that changed during the study period such as due to a bed expansion or contraction.

Second, all measures were then further standardized to historical norms to take into account that an absolute measure of a strain metric might mean something different close to versus significantly different than the norm for a given unit. To do this, we calculated the median of each strain metric by unit, hospital, and calendar year (e.g., ED at Hospital X in Year Y), and then calculated the absolute difference between the measured metric and the historical median. As an example, 8 patients in a 10-bed ICU with a unit-/hospital-/year-specific median of 90% ICU occupancy would standardize to: (8/10*100%) – 90% median = ¯10% change in ICU occupancy.

A valid alternative approach considered but ultimately rejected was calculation of a fold difference by dividing the measured metric by the historical median. Compared to absolute difference, fold difference had the advantage of distinguishing, for example, a 10% increase in occupancy between 10 and 20% and between 90 and 100%, which are valued as equivalent in the absolute difference approach. However, low counts in various locations lead to very low calculated historical norms and therefore exceedingly high fold differences when counts were transiently elevated (for example, two mechanical ventilators on a ward that has a median of zero). We intentionally did not adjust for seasonal changes or other semi-predictable variation over time in strain metrics, as these variations, in addition to unpredictable changes in strain, are part of what we aimed to capture.

Appendix 4. Assignment of strain metrics to clinical cohorts

We considered using the time of an admission order or inpatient bed request but ultimately rejected this approach as we felt their timing was susceptible to influence by bed availability (e.g., an artificially early bed request placed to "get in line" during busy periods) or hospital-specific performance metrics (e.g., time from presentation to bed request). Instead, we chose to anchor on a clinical time point relatively consistent across facilities: the time of first routine labs drawn in the ED, including complete blood count, basic or complete metabolic panel, venous or arterial blood gas, or serum lactate.

Appendix 5. Development of the composite strain index

Coefficient creation model:

ridge logit Pr [$ICU\ admission$ | $strain\ metrics, patient\ covariates$] $by\ facility, diagnosis$

$$Strain\ Index\ (SI) = \sum \beta_{m,h,d} * strain_m$$

where $\beta_{m,h,d}$ = the β-coefficient from the coefficient creation model for metric *m* at hospital *h* among diagnosis *d*, and $strain_m$ = the standardized value of strain metric *m* assigned to the patient based on their anchor time and hospital.

TABLES

Table E1. Primary clinical cohort inclusion criteria

Cohort	Inclusion criteria	
Sepsis	**Suspected infection in the ED**	At least one antimicrobial order *and* at least one microbiologic culture order
	and	
	At least 1 physiologic criterion in the ED	SOFA ≥ 2
		qSOFA ≥ 2
		Lactate ≥ 4, at any time
		Single SpO2 ≤ 85% while receiving any supplemental O_2
		NRB *or* FiO2 ≥ 60% for at least 2 measurements at least 2 hours apart, at any time
		Any BiPAP, CPAP, *or* HFNC, at any time
Acute respiratory failure	**At least 1 physiologic criterion in the ED**	Single SpO2 ≤ 85% while receiving any supplemental O_2
		FiO2 ≥ 6L *or* 40% for at least 2 measurements at least 2 hours apart, at any time
		PaCO2 > 45 mmHg *or* PvCO2 > 50 *and* RR ≥ 22, at any time/in any order
		PaCO2 > 60 mmHg *or* PvCO2 > 65 *and* pH ≤ 7.3, on same blood gas, at any time
		Any BiPAP *or* CPAP, at any time

Notes: Inclusion criteria use all data available during the ED stay. For SOFA and qSOFA scores: Total scores are calculated using the worst value for each subscore during the ED stay. Patients requiring mechanical ventilation are excluded by design. BiPAP and CPAP are considered respiratory support. PaO2 and FiO2 value are required for a respiratory subscore > 0. Patients requiring vasopressors are excluded by design (maximum cardiovascular subscore = 1). Renal subscore relied on serum creatinine alone, as urine output is not recorded with fidelity during short ED stays. CPAP, continuous positive airway pressure; BiPAP, bi-level positive airway pressure; ED, emergency department; HFNC, high-flow nasal cannula; O2, oxygen; NRB, non-rebreather mask; SOFA, Sequential Organ Failure Assessment score; qSOFA, Quick Sequential Organ Failure Assessment score.

Table E2. Example set of strain metric β-coefficients for one hospital

Strain metric	β-coefficients	
	Sepsis	ARF
ICU census acuity	0.002	-0.011
ED occupancy	0.000	0.000
Ward occupancy	0.009	-0.009
SDU occupancy	-0.005	-0.014
ICU occupancy	-0.018	-0.019
ICU discharges	0.033	0.018
ICU turnover	-0.006	0.000
ED vasopressors	-0.169	-0.015
ED mechanical ventilation	-0.093	-0.064
ED BiPAP	-0.027	0.300
Ward vasopressors	-0.297	-0.123
Ward mechanical ventilation	0.070	-0.099
Ward BIPAP	-0.260	-0.004
Ward other respiratory support[a]	-0.021	-0.015
SDU vasopressors	-0.020	0.012
SDU mechanical ventilation	0.006	-0.032
SDU BIPAP	0.020	-0.038
SDU other respiratory support[a]	-0.020	-0.003
ICU vasopressors	-0.003	-0.002
ICU mechanical ventilation	-0.015	-0.007
ICU BIPAP	-0.045	-0.026
ICU other respiratory support[a]	0.004	-0.006

Notes: A negative sign can be interpreted to mean that an increase in a given strain metric would be expected to yield a decrease in the probability of ICU admission. P-values are intentionally not reported; most β-coefficients do not reach independent statistical significance and all were included in the composite strain index regardless. [a] *Composite of non-rebreather mask, high-flow nasal cannula, or FiO2 ≥ 60%. ARF, acute respiratory failure; BiPAP, bi-level positive airway pressure; ED, emergency department; ICU, intensive care unit; SDU, step-down unit.*

Table E3. Association of the strain index with ICU admission among patients with sepsis and ARF

Strain index decile	OR (95% CI)	p-value	Adjusted predicted probability of ICU admission (95% CI)[a]
Sepsis			
1	Ref.	Ref.	0.290 (0.280-0.300)
2	0.72 (0.67-0.77)	<0.001*	0.227 (0.218-0.236)
3	0.60 (0.56-0.65)	<0.001*	0.198 (0.189-0.206)
4	0.52 (0.48-0.56)	<0.001*	0.176 (0.168-0.184)
5	0.48 (0.44-0.51)	<0.001*	0.163 (0.155-0.171)
6	0.44 (0.41-0.48)	<0.001*	0.153 (0.145-0.160)
7	0.42 (0.39-0.46)	<0.001*	0.147 (0.140-0.155)
8	0.40 (0.37-0.43)	<0.001*	0.140 (0.133-0.147)
9	0.34 (0.31-0.36)	<0.001*	0.121 (0.114-0.128)
10	0.25 (0.23-0.27)	<0.001*	0.093 (0.087-0.099)
ARF			
1	Ref.	Ref.	0.472 (0.456-0.489)
2	0.62 (0.57-0.68)	<0.001*	0.358 (0.343-0.373)
3	0.51 (0.46-0.56)	<0.001*	0.312 (0.298-0.326)
4	0.45 (0.41-0.49)	<0.001*	0.286 (0.272-0.300)
5	0.39 (0.35-0.43)	<0.001*	0.257 (0.244-0.271)
6	0.35 (0.32-0.39)	<0.001*	0.241 (0.228-0.254)
7	0.30 (0.27-0.33)	<0.001*	0.213 (0.201-0.225)
8	0.28 (0.25-0.31)	<0.001*	0.201 (0.189-0.213)
9	0.23 (0.21-0.26)	<0.001*	0.172 (0.161-0.184)
10	0.15 (0.14-0.17)	<0.001*	0.121 (0.110-0.132)

*Notes: * $p < 0.001$. [a] Models adjusted for patient-level covariates age, gender, ethnicity, race, insurance, LAPS2, COPS2, hospital. Keeping all other variables fixed at the mean. ARF, acute respiratory failure; CI, confidence interval; ICU, intensive care unit; OR, odds ratio.*

Table E4. Association of ICU occupancy with ICU admission among patients with sepsis and ARF

ICU occupancy decile	Adjusted predicted probability of ICU admission (95% CI)[a]	
	Sepsis	ARF
1	0.200 (0.191-0.209)	0.303 (0.289-0.318)
2	0.182 (0.174-0.191)	0.273 (0.259-0.287)
3	0.174 (0.166-0.182)	0.275 (0.261-0.289)
4	0.175 (0.167-0.183)	0.291 (0.276-0.306)
5	0.170 (0.162-0.178)	0.258 (0.244-0.272)
6	0.173 (0.164-0.183)	0.264 (0.248-0.279)
7	0.160 (0.152-0.168)	0.261 (0.247-0.275)
8	0.168 (0.160-0.176)	0.258 (0.244-0.271)
9	0.158 (0.151-0.166)	0.239 (0.226-0.252)
10	0.143 (0.136-0.151)	0.201 (0.189-0.213)

Notes: [a] Models adjusted for patient-level covariates age, gender, ethnicity, race, insurance, LAPS2, COPS2, hospital. Keeping all other variables fixed at the mean. CI, confidence interval; ICU, intensive care unit.

Table E5. Association of the strain index with hospital mortality in "usually ward" and "usually ICU" subgroups

Acuity	Cohort	Odds Ratio (95% CI)	p-value
Usually ward[a]	Sepsis (n = 6,523)	0.87 (0.63-1.21)	0.40
	ARF (n = 3,522)	0.97 (0.53-1.80)	0.93
Usually ICU[b]	Sepsis (n = 2,133)	1.14 (0.84-1.54)	0.40
	ARF (n = 3,117)	1.07 (0.88-1.30)	0.51

Notes: Patients with missing mortality status due to rare transfers to another acute care hospital were excluded. [a] Sepsis patients with SOFA = 0 and no mechanical ventilation or vasopressors in the ED. ARF patients with LAPS2 ≤ 50 and no mechanical ventilation or vasopressors in the ED. [b] Mechanical ventilation and vasopressors in the ED. All models adjusted for patient-level covariates age, gender, ethnicity, race, insurance, LAPS2, COPS2, hospital. ARF, acute respiratory failure; CI, confidence interval; COPS2, COmorbidity Point Score v2; ED, emergency department; ICU, intensive care unit; LAPS2, Laboratory-based Acute Physiology Score v2; SOFA, Sequential (Sepsis-related) Organ Failure Assessment.

Table E6. Association of the strain index with hospital discharge disposition in "usually ward" and "usually ICU" subgroups

Acuity	Cohort	Odds ratio (95% CI) of discharge not to home	p-value
Usually ward[a]	Sepsis (n = 6,554)	0.96 (0.78-1.19)	0.73
	ARF (n = 3,530)	0.88 (0.69-1.13)	0.33
Usually ICU[b]	Sepsis (n = 2,168)	1.12 (0.80-1.58)	0.51
	ARF (n = 3,149)	1.20 (0.95-1.51)	0.13

Notes: Deaths considered to be discharges not to home. [a] Sepsis patients with SOFA = 0 and no mechanical ventilation or vasopressors in the ED. ARF patients with LAPS2 ≤ 50 and no mechanical ventilation or vasopressors in the ED. [b] Mechanical ventilation and vasopressors in the ED. All models adjusted for patient-level covariates age, gender, ethnicity, race, insurance, LAPS2, COPS2, hospital. ARF, acute respiratory failure; CI, confidence interval; COPS2, COmorbidity Point Score v2; ED, emergency department; ICU, intensive care unit; LAPS2, Laboratory-based Acute Physiology Score v2; SOFA, Sequential (Sepsis-related) Organ Failure Assessment.

Table E7. Association of the strain index with patient-level characteristics

	Sum of squares	Degrees of freedom	F-value	Pr(>F)	R (p-value)
Sepsis					
Age	1.06	1	11.47	<0.001*	-0.011 (0.001)
Race	14.76	3	53.51	<0.001*	categorical
Ethnicity	0.24	1	2.66	0.10	n/a
Gender	0.10	1	1.04	0.31	n/a
LAPS2	10.03	1	109.00	<0.001*	-0.026 (<0.001)
COPS2	1.21	1	13.14	<0.001*	0.012 (<0.001)
Insurance	206.27	2	1121.38	<0.001*	categorical
ARF					
Age	0.24	1	1.41	0.23	n/a
Race	34.57	3	68.30	<0.001*	categorical
Ethnicity	0.27	1	1.61	0.20	n/a
Gender	0.46	1	2.74	0.10	n/a
LAPS2	1.53	1	9.08	<0.001*	-0.0065 (0.16)
COPS2	1.42	1	8.43	<0.001*	0.015 (0.001)
Insurance	394.07	2	1168.03	<0.001*	categorical

*Notes: * p < 0.001. ARF, acute respiratory failure; COPS2, COmorbidity Point Score v2; LAPS2, Laboratory-based Acute Physiology Score v2.*

SUPPLEMENTAL FIGURES

Figure E1. Strain index weekly variability among- and within-hospital over time among patients with sepsis

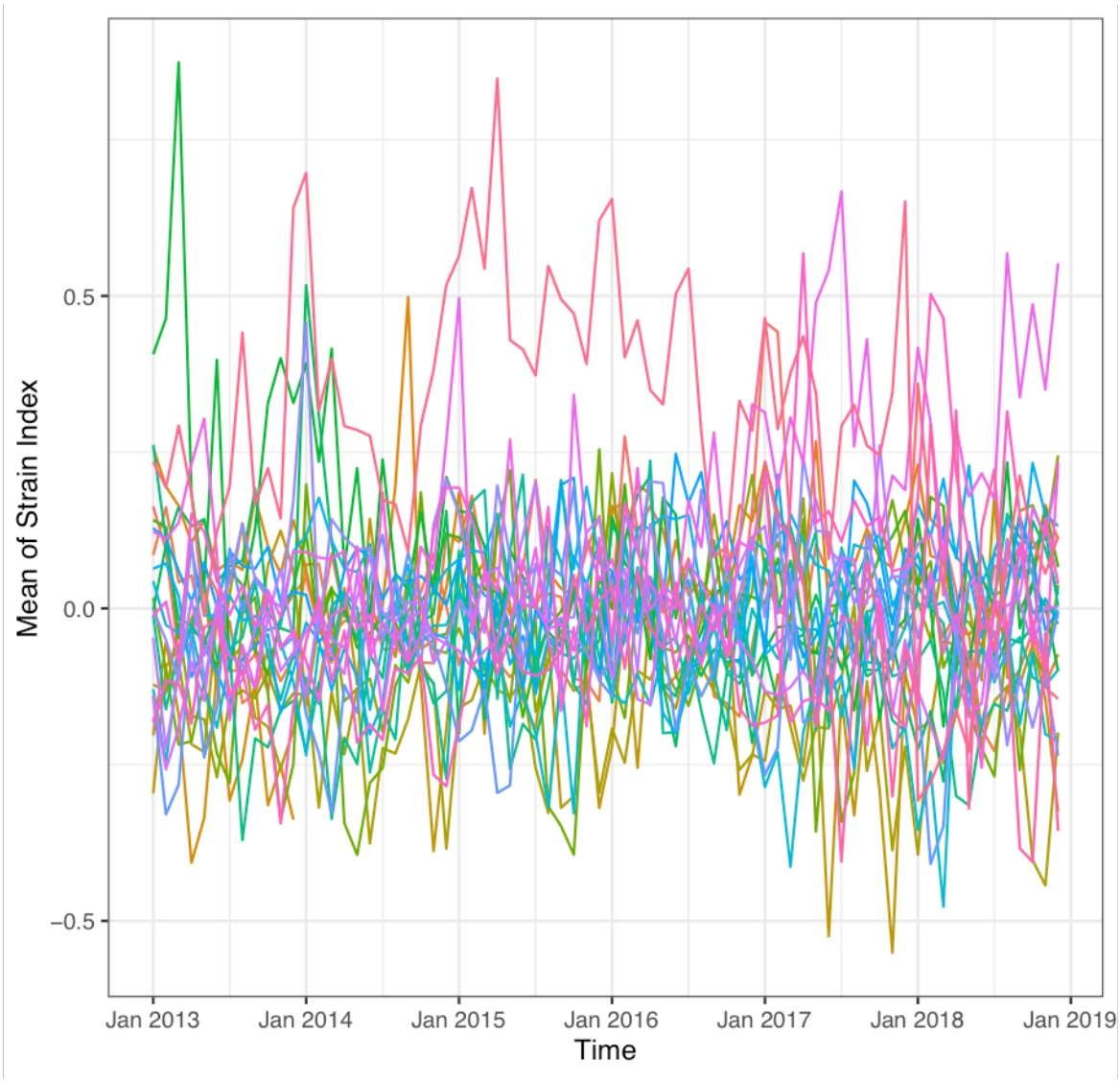
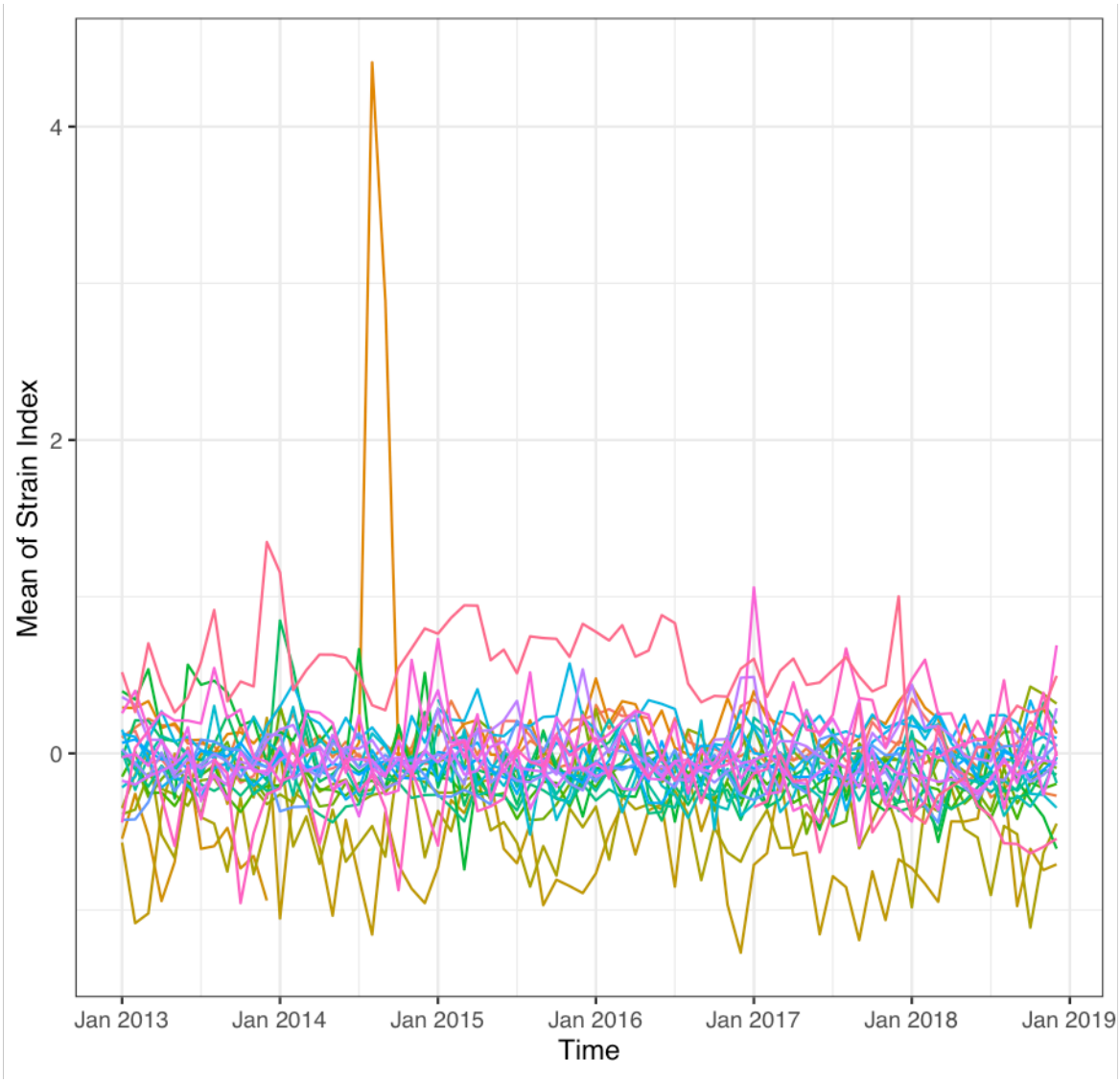


Figure E2. Strain index weekly variability among- and within-hospital over time among patients with ARF



Note: Outlier peak in Q3-2015 due to a small number of patients (n = 6) with high values contributing to that weekly mean at that single hospital.

Figure E3. Association of ICU occupancy with ICU admission among patients with sepsis and ARF

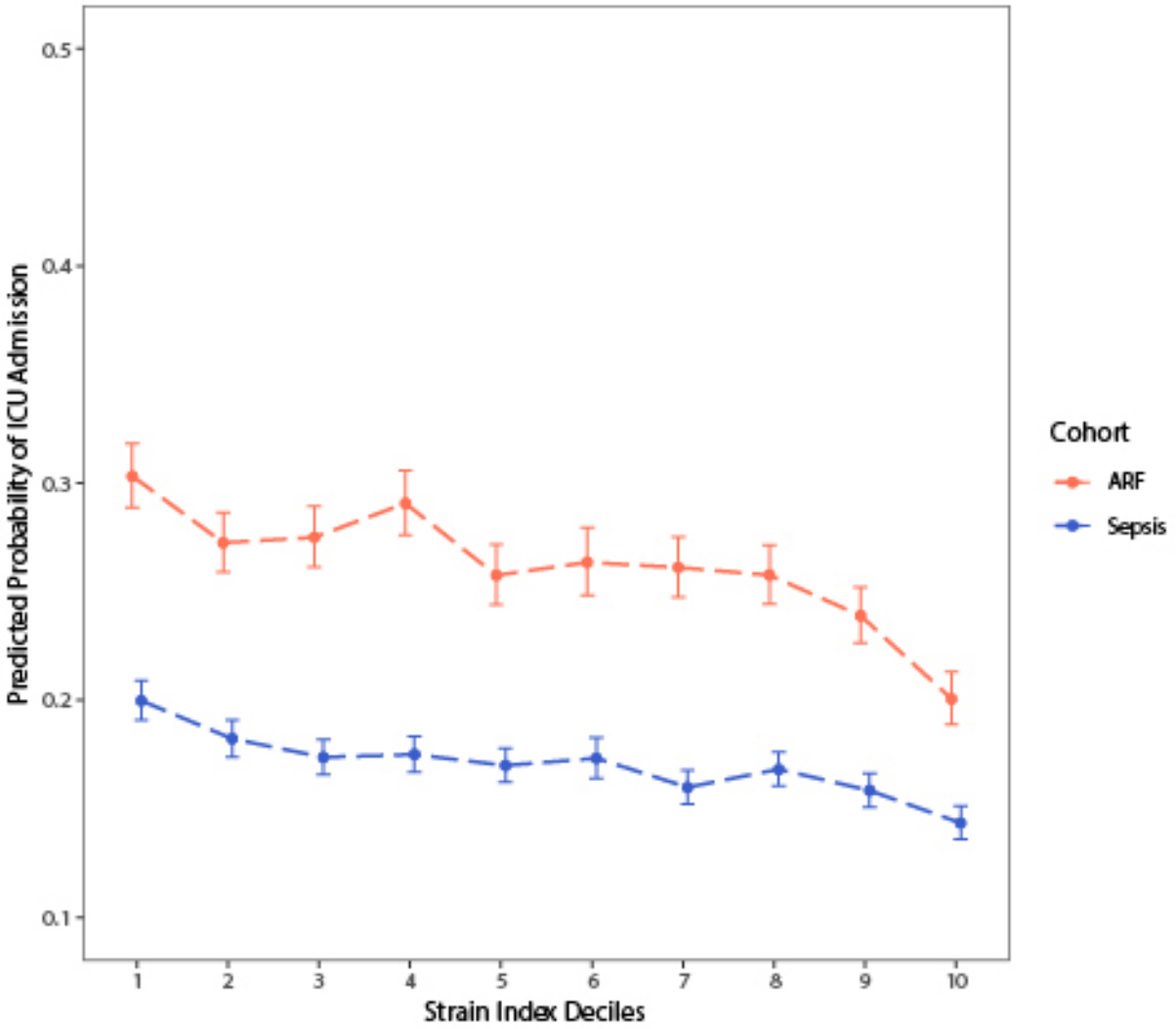


Figure E4. Association of the strain index and age among patients with sepsis (box plot)

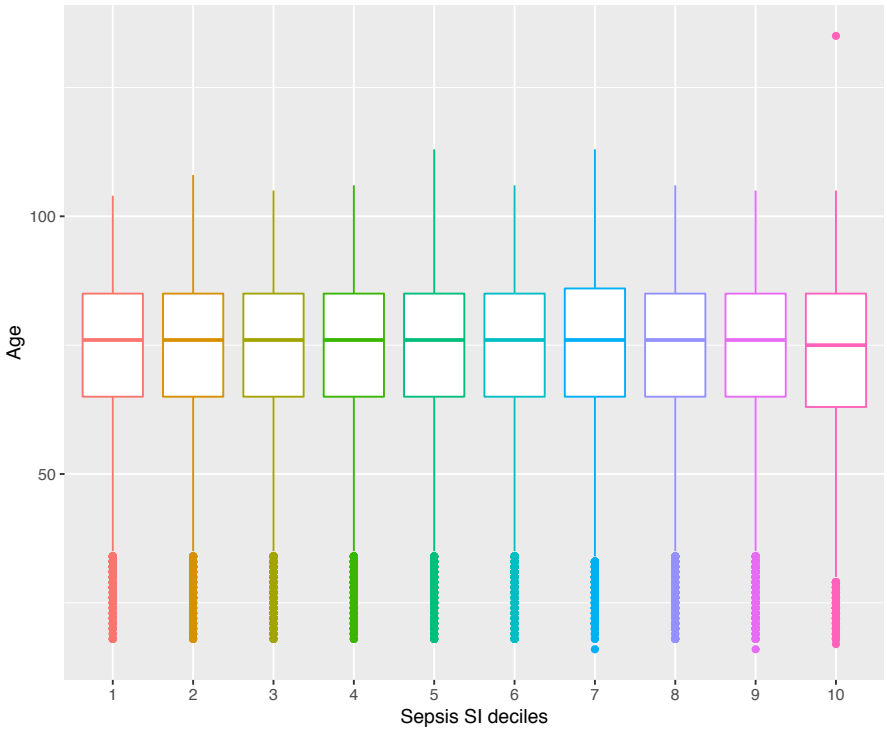


Figure E5. Association of the strain index and age among patients with sepsis (scatter plot)

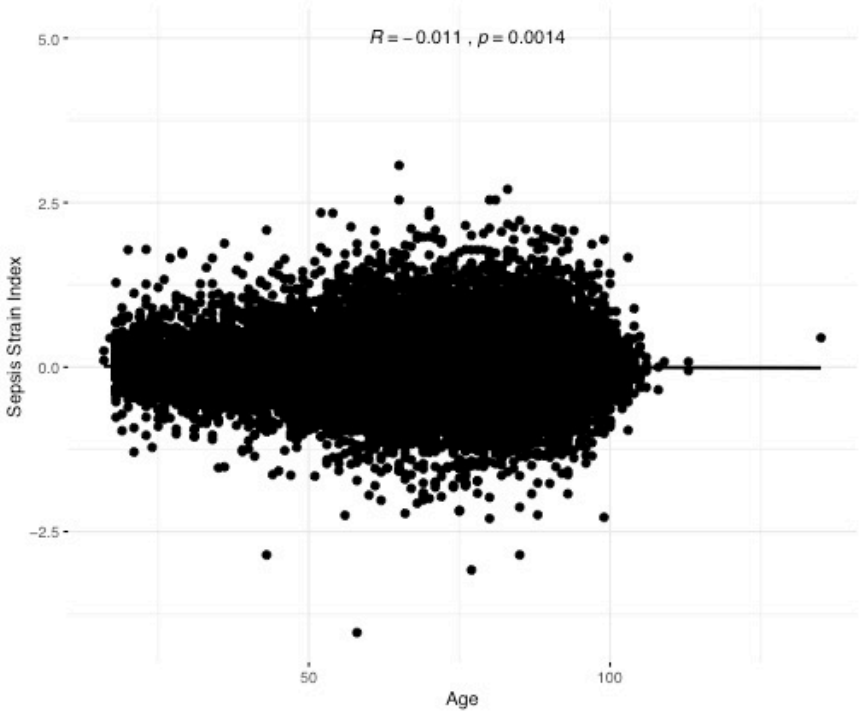


Figure E6. Association of the strain index and LAPS2 among patients with sepsis (box plot)

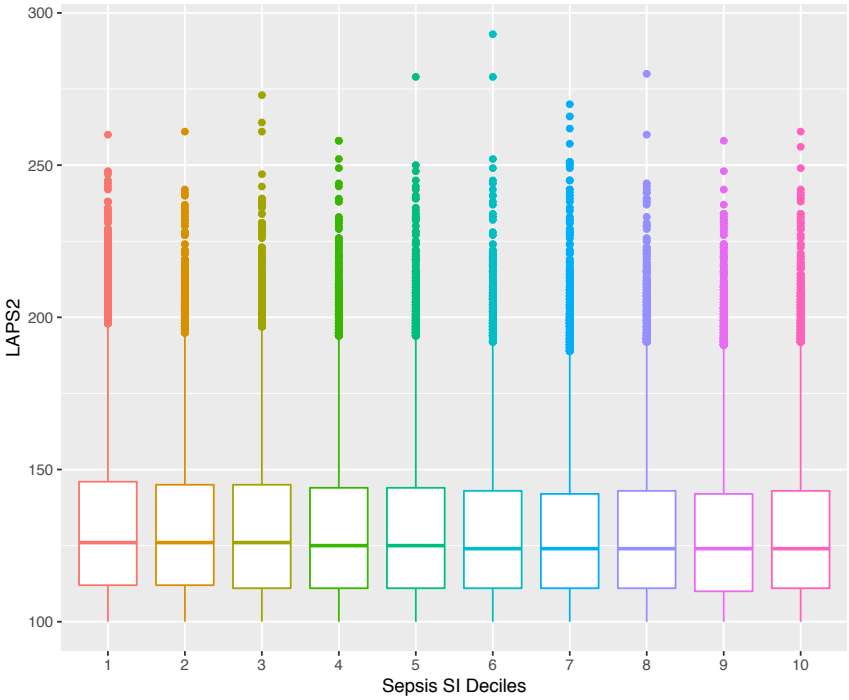


Figure E7. Association of the strain index and LAPS2 among patients with sepsis (scatter plot)

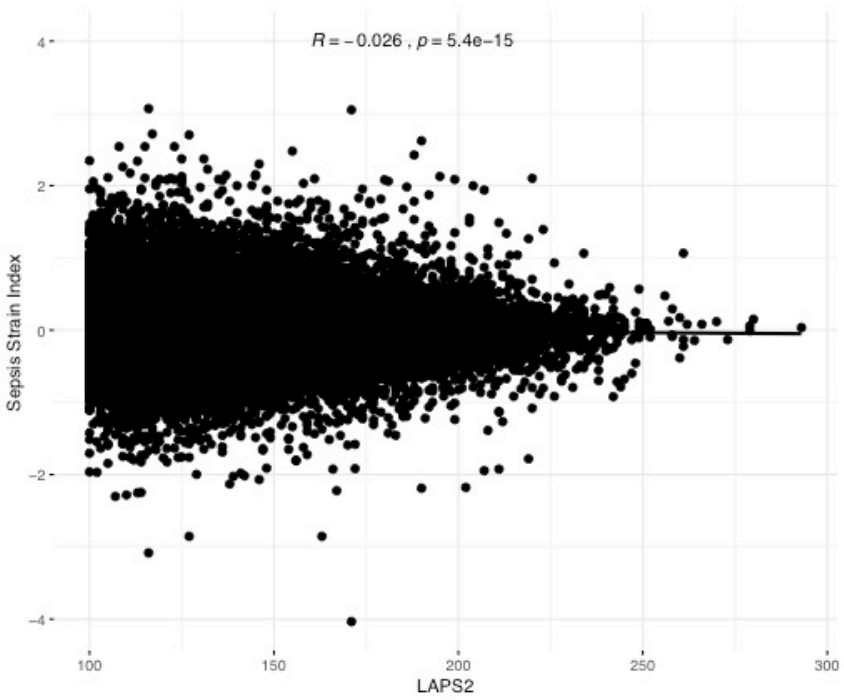


Figure E8. Association of the strain index and COPS2 among patients with sepsis (box plot)

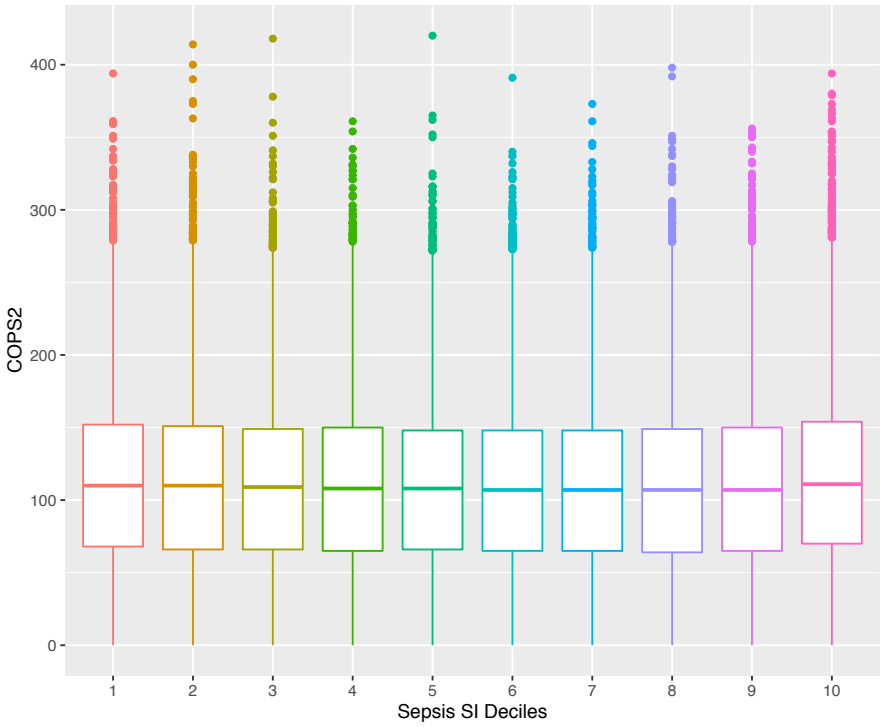


Figure E9. Association of the strain index and COPS2 among patients with sepsis (scatter plot)

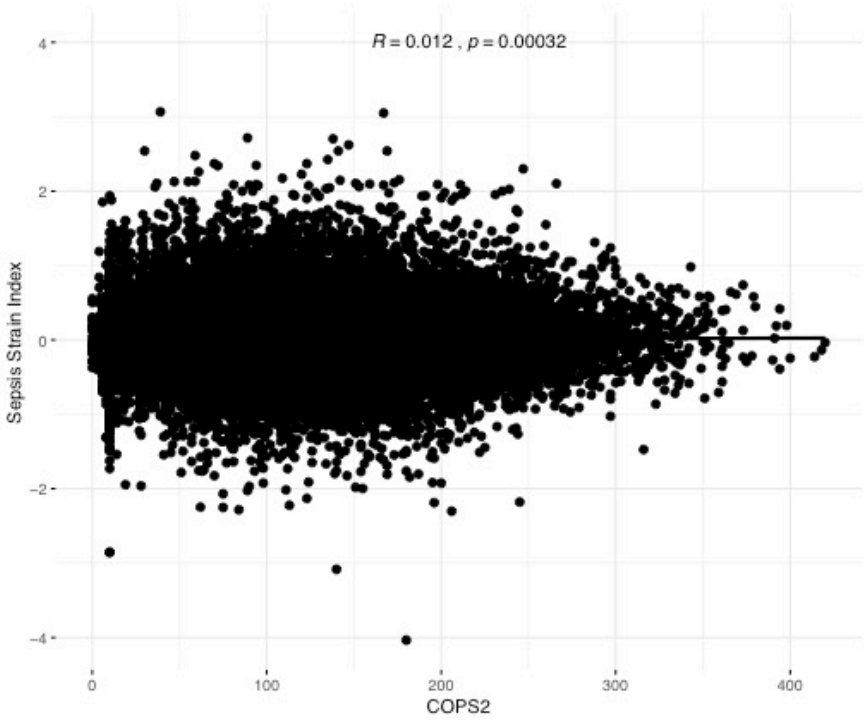


Figure E10. Association of the strain index and race among patients with sepsis (box plot)

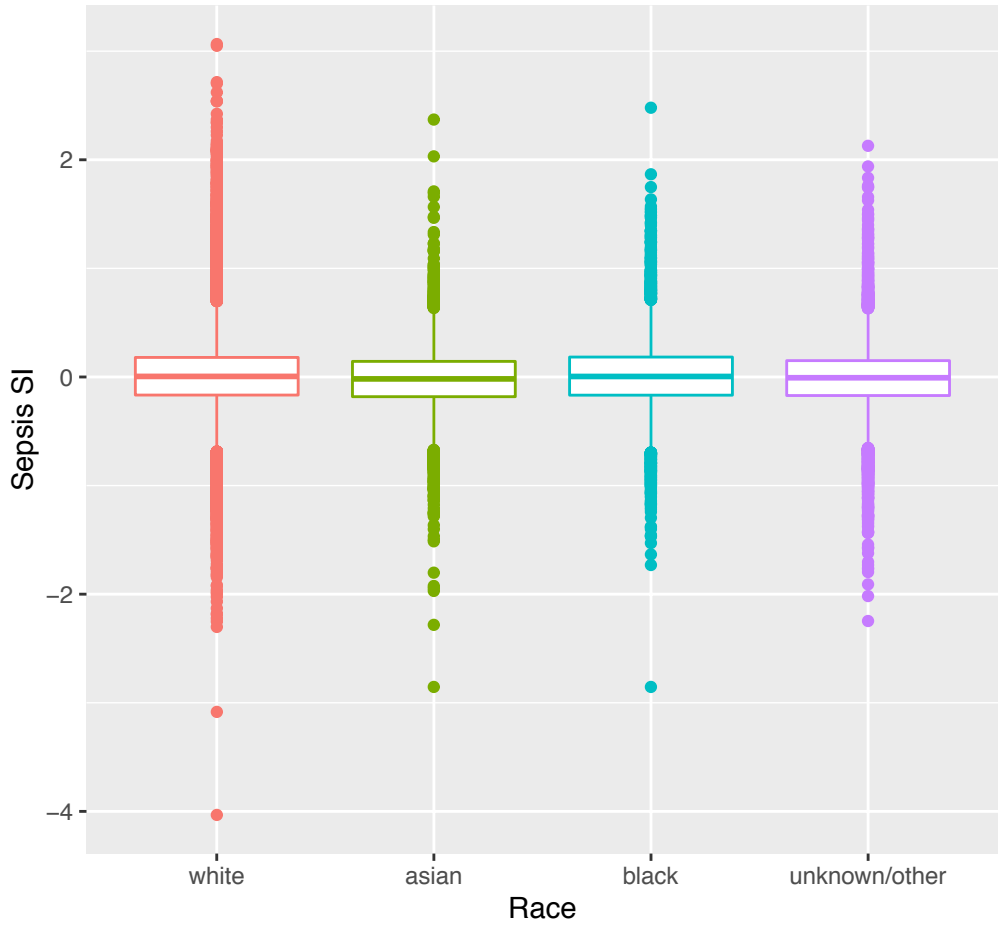


Figure E11. Association of the strain index and insurance among patients with sepsis (box plot)

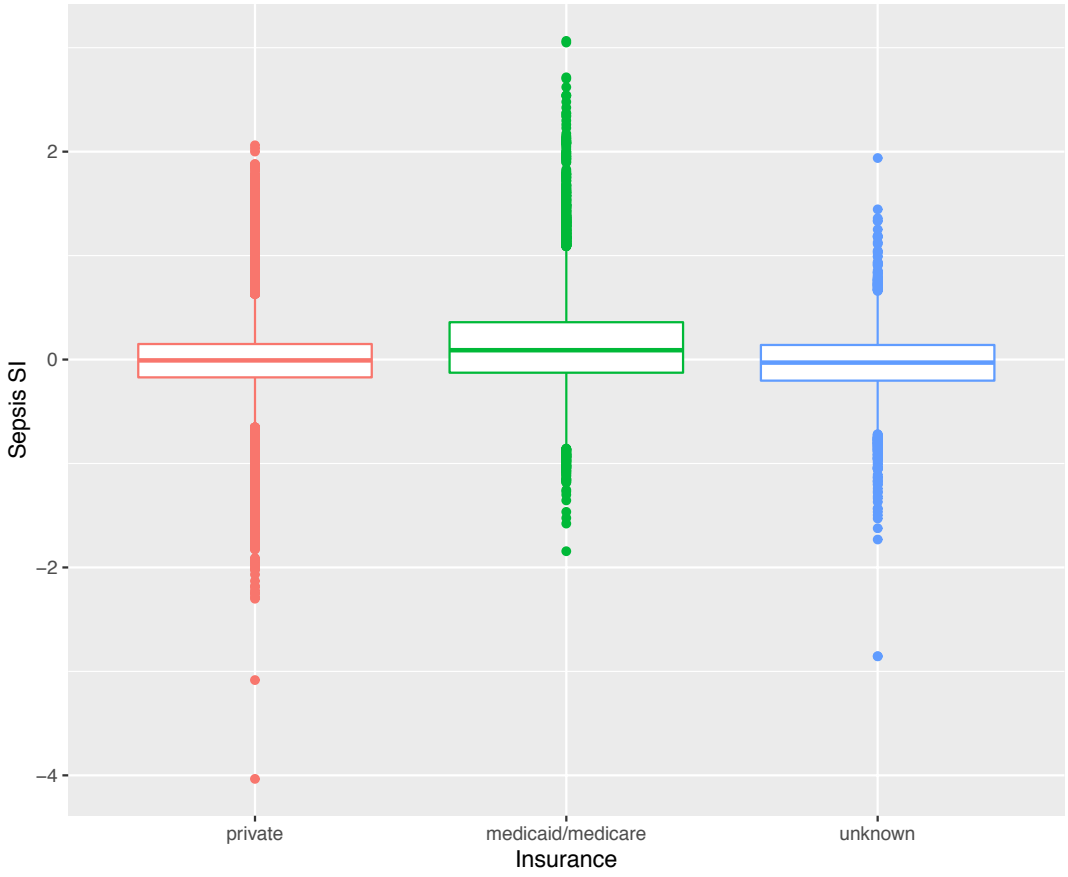


Figure E12. Association of the strain index and LAPS2 among patients with ARF (box plot)

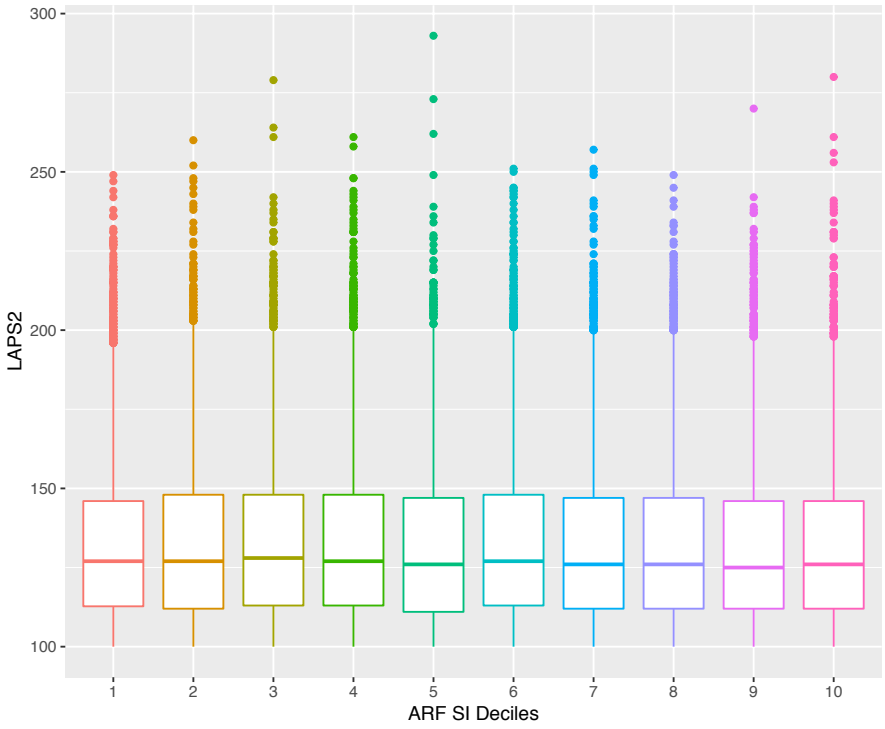


Figure E13. Association of the strain index and LAPS2 among patients with ARF (scatter plot)

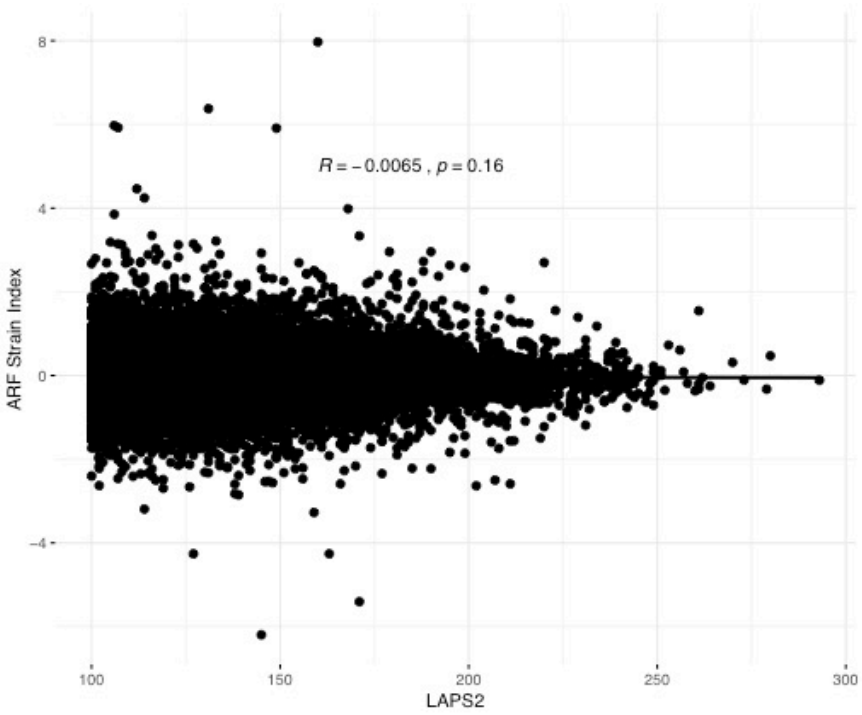


Figure E14. Association of the strain index and COPS2 among patients with ARF (box plot)

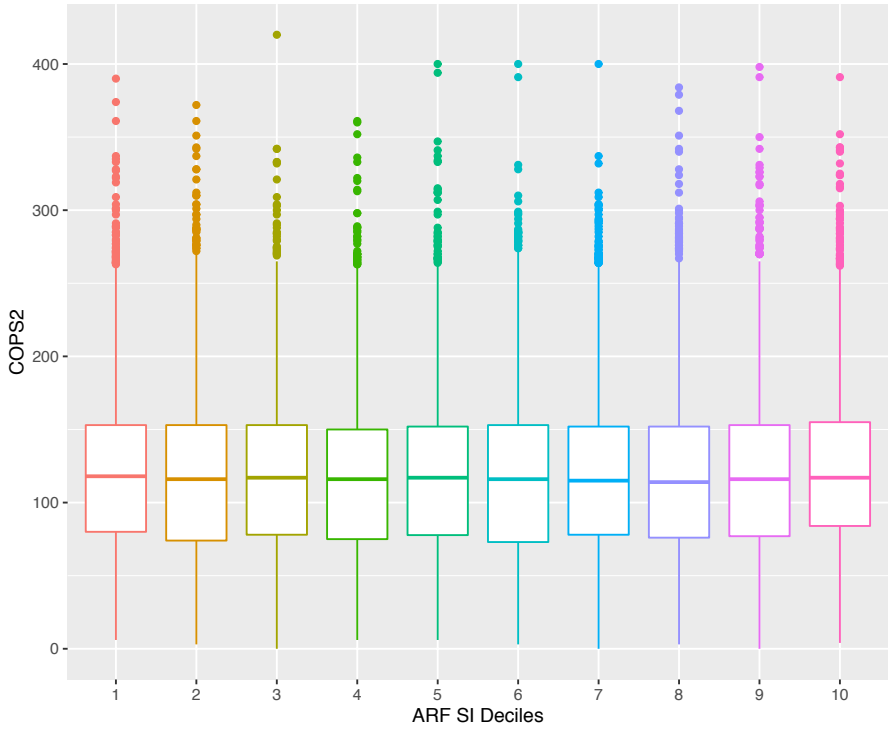


Figure E15. Association of the strain index and COPS2 among patients with ARF (scatter plot)

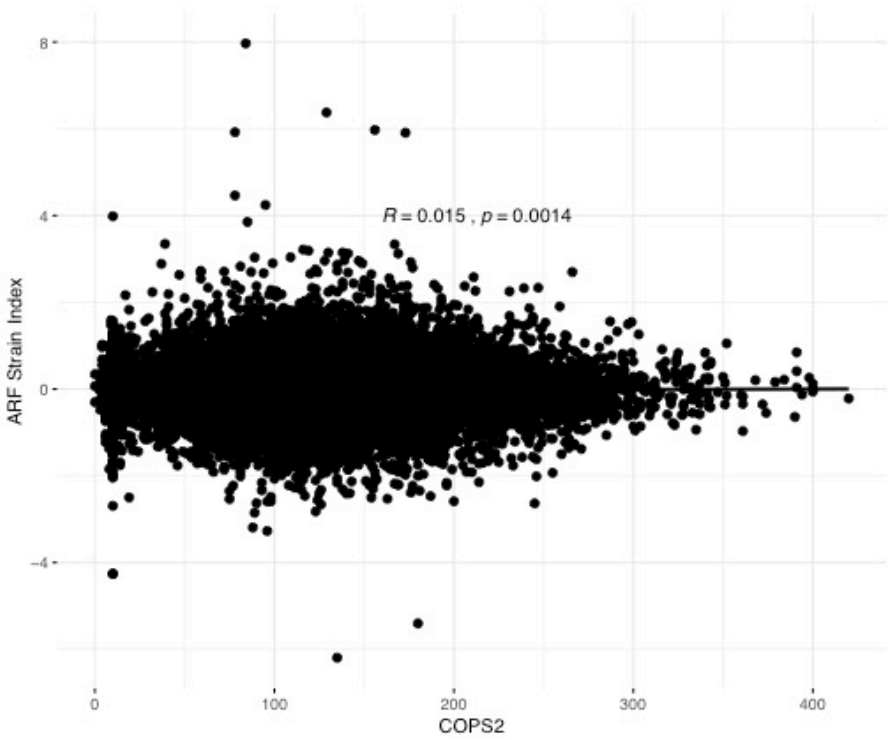


Figure E16. Association of the strain index and race among patients with ARF (box plot)

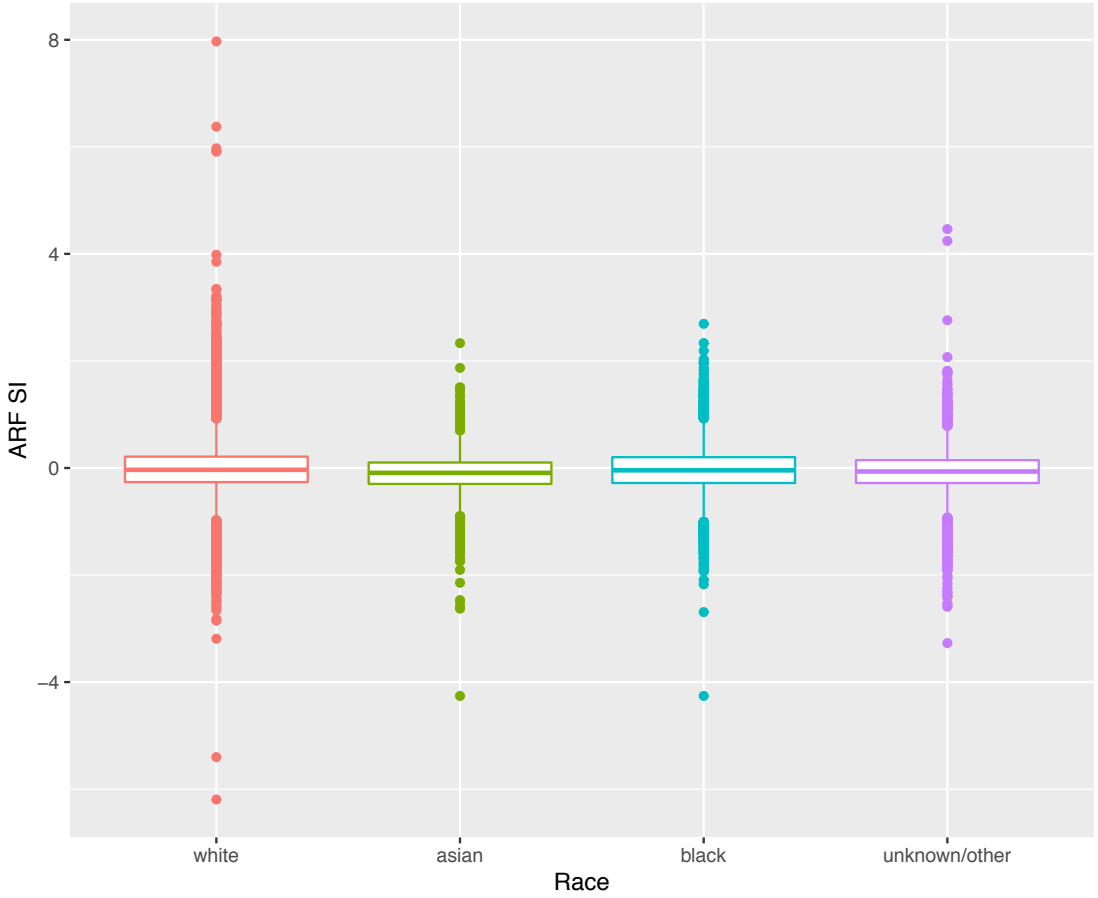
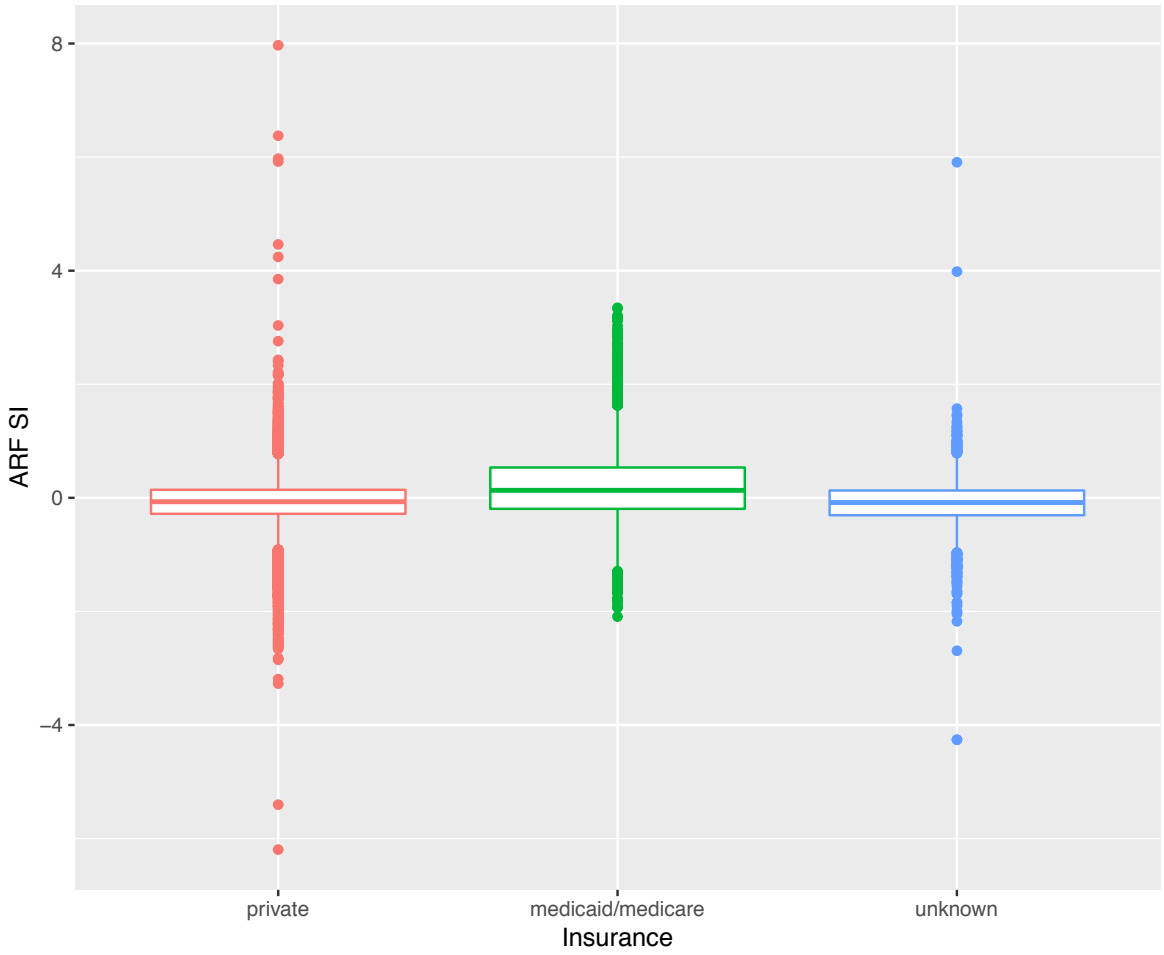


Figure E17. Association of the strain index and insurance among patients with ARF (box plot)



References to the Online Data Supplement

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