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Intraoperative hypotension burden and blood pressure variability in relation to in-hospital mortality after noncardiac surgery A retrospective cohort study using the MOVER database

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Abstract

Background

Intraoperative hypotension burden and blood pressure variability describe different aspects of hemodynamic instability. Their associations with mortality may depend on measurement quality and the severity of the patients included. We examined both measures in invasively monitored adults undergoing noncardiac surgery.

Methods

This retrospective cohort study used the EPIC component of the Medical Informatics Operating Room Vitals and Events Repository. The first eligible adult inpatient operation per patient was selected. Mean arterial pressure recordings required at least 20 valid measurements and 80% valid-interval coverage during an operating-room stay of at least 30 minutes. Hypotension burden was the time-weighted deficit below 65 mmHg over valid observed intervals; variability was the average absolute difference between consecutive measurements. Logistic models estimated associations with all-cause in-hospital mortality, adjusting for age, sex, American Society of Anesthesiologists physical status, operating-room duration, and procedure category.

Results

Among 3872 patients, 98 died in hospital (2.53%). In the jointly adjusted model, each interquartile-range increase in log-transformed hypotension burden was associated with higher mortality odds (odds ratio 1.295; 95% confidence interval 1.120–1.498). The variability estimate was imprecise (0.823; 0.636–1.065). Exploratory adjustment for preoperative hospital duration and documented circulatory support yielded estimates of 1.337 (1.157–1.545) for burden and 1.012 (0.776–1.321) for variability. The burden association attenuated after excluding the highest 1% of burden values (1.179; 0.967–1.436) or excluding physical status 5 patients with additional adjustment for preoperative hospital duration (1.166; 0.926–1.468). Stricter numerical quality checks yielded an estimate of 1.359 (1.173–1.573).

Conclusions

Higher observed hypotension burden was associated with in-hospital mortality in this selected cohort, whereas variability showed no clear conditional association. Attenuation after excluding extreme exposures or the most severely ill patients limits generalization. These findings do not establish a causal treatment effect or a safe blood pressure threshold.

Background

Arterial pressure is a central component of perioperative cardiovascular monitoring, but a brief pressure reading does not describe the full hemodynamic exposure experienced during surgery. Cohort studies have associated intraoperative hypotension with acute kidney injury, myocardial injury, and other adverse outcomes after noncardiac surgery [1, 2, 3, 4]. These associations depend on both the depth and duration of low pressure. A cumulative deficit measure can therefore describe exposure that a binary indicator of any hypotension would obscure.

Definitions also matter. Applying different published hypotension definitions to the same surgical cohort produces markedly different incidence estimates [5]. Blood pressure variability captures another dimension, but it is not synonymous with hypotension burden. In a large retrospective study, lower average pressure had a stronger association with mortality than variability measured using generalized average real variability [6]. A smaller prospective study found associations between systolic and diastolic coefficients of variation and mortality [7]. A systematic review subsequently identified heterogeneous definitions and directions of association [8]. These differences make it important to specify the variability metric, sampling interval, and accompanying hypotension measure rather than treating all variability indices as interchangeable.

Observational associations also do not identify the benefit of a pressure-target intervention. The INPRESS trial reported less postoperative organ dysfunction with an individualized pressure strategy, whereas POISE-3 and the more recent IMPROVE-multi trial did not demonstrate improvement in their respective primary outcomes with the tested higher-target or individualized strategies [9, 10, 11]. Differences in populations, interventions, and endpoints preclude a simple comparison, but they underscore the need to distinguish exposure associations from treatment effects.

The Medical Informatics Operating Room Vitals and Events Repository (MOVER) links perioperative physiological data with electronic health records [12]. Together with resources such as VitalDB, it enables evaluation of explicitly defined physiological measures in surgical cohorts [13]. We used MOVER to examine whether observed hypotension burden and average real variability were associated with all-cause in-hospital mortality when included in the same model. We also evaluated the sensitivity of these associations to recording coverage, available severity information, extreme exposures, and numerical-quality rules. The objective was an interpretable association analysis, not development of a clinical prediction model or identification of an optimal treatment threshold.

Methods

Study design and data source

We conducted a retrospective observational cohort study using the EPIC component of MOVER from the University of California, Irvine Medical Center [12, 14]. The source publication describes EPIC records from 2017–2022. Patient dates were shifted consistently within each patient but not across patients, and ages above 90 years were capped at 90. We therefore preserved within-patient chronology but did

not use shifted calendar dates for between-patient temporal validation. Numerical invasive arterial pressure records were analyzed; high-frequency waveform morphology was not analyzed. Reporting was organized with reference to STROBE and its RECORD extension [15, 16]. The reporting checklist and detailed operational definitions are supplied separately.

Participants and outcome

The source population comprised adult inpatient operations with valid operating-room entry and exit timestamps. An outcome-independent procedure-name algorithm identified a conservative set of named noncardiac operations. Cardiac and unresolved procedures, selected special populations (transplantation, dialysis-access and obstetric procedures), American Society of Anesthesiologists (ASA) physical status 6, and operations with recorded cardiopulmonary bypass, deep hypothermic circulatory arrest, or intra-aortic balloon support events were excluded. Some vascular and aortic operations remained eligible. Five procedure groups were defined: abdominal, cranial, musculoskeletal/spinal, vascular/amputation, and other eligible operations. This algorithm did not identify every possible noncardiac operation; its rules are described in Additional file 1.

The first eligible operation was selected for each patient before checking outcome completeness. We then required a recorded discharge disposition other than an unknown value or Coroner, hospital admission no later than operating-room entry, and discharge no earlier than operating-room exit. The outcome was all-cause in-hospital mortality, indicated by the discharge disposition Expired. Other eligible dispositions were coded as no recorded in-hospital death. Deaths after discharge were not captured by this endpoint. Neither cardiovascular mortality nor 30-day mortality was inferred from it. Patients were not required to have postoperative laboratory testing.

Blood pressure processing and exposures

Records were linked using both patient and operation identifiers and restricted to operating-room entry through exit. Mean arterial pressure (MAP) values outside 20–200 mmHg were excluded. Exact duplicates were removed, and discordant simultaneous MAP values were quarantined. Where paired measurements were available, systolic pressure had to be 30–300 mmHg and diastolic pressure 10–180 mmHg, with systolic pressure ≥ MAP ≥ diastolic pressure and systolic pressure greater than diastolic pressure. The initial analysis retained otherwise valid MAP records lacking a usable pair. Some unit fields were blank; mmHg was inferred from measurement labels and pressure semantics rather than directly verified in every record.

Valid intervals were positive adjacent time differences no longer than 120 seconds. Coverage was the total valid-interval duration divided by operating-room duration. Eligibility required an operating-room duration of at least 30 minutes, at least 20 valid MAP measurements, and coverage of at least 80%.

Intervals across longer gaps and unobserved boundary periods contributed neither exposure nor observed duration.

Hypotension burden, denoted TWA65, was the integral of the positive MAP deficit below 65 mmHg divided by valid observed time. Piecewise-linear interpolation between valid adjacent measurements accounted for threshold crossings. The denominator was observed valid-interval duration, not the entire operating-room stay; missing intervals were not assumed normotensive. Average real variability (ARV) was the arithmetic mean of absolute consecutive MAP differences across valid intervals. It was expressed in mmHg, not mmHg/min, and was distinct from time-normalized generalized ARV. Hypotension burden was transformed as log(1 + TWA65). Both exposures were divided by their respective interquartile ranges in the final main cohort, and these same scaling constants were retained in all sensitivity analyses.

Covariates and statistical analysis

Covariates were age per 10 years, recorded sex, ordinal ASA physical status (1–5), log-transformed operating-room duration, and the five procedure groups. ASA is a routinely recorded severity measure with recognized inter-rater limitations [17]. Missing ASA values were excluded. We used logistic generalized linear models with HC0 robust 95% confidence intervals to estimate unadjusted burden, adjusted burden, and jointly adjusted burden and ARV associations. Continuous exposure modeling avoided data-driven cutpoint selection [18, 19]. There was no stepwise variable selection or outcome-guided threshold search.

All eligible observations were used, without recruitment-based sample-size calculation. The joint model had 10 slope parameters and an intercept; its 98 deaths corresponded to 9.8 events per slope parameter. The severity-extended model had 12 slopes and an intercept (8.2 events per slope). These ratios do not guarantee reliable estimation, particularly in sparse strata [20, 21, 22]. Convergence was checked. Confidence intervals and descriptive P values were not adjusted for multiple analyses. All results were interpreted as exploratory associations rather than confirmatory hypothesis tests.

Sensitivity and exploratory analyses

The initial analysis specification included coverage thresholds of 70% and 90% and a complete-case model additionally adjusting for hemoglobin and log creatinine measured within 48 hours before operating-room entry. The last eligible same-patient, same-operation preoperative measurement was used after assay, unit, and discordance checks. Missing results were not imputed as normal. Laboratory-complete analysis changes the analyzed population and cannot by itself correct selective testing; missing-data assumptions remain consequential [23].

After reviewing the initial results, additional analyses examined preoperative hospital duration, documented circulatory support, the highest 1% of TWA65, exclusion of ASA 5, categorical ASA, 60-

second-only ARV, seven-day laboratory availability, stricter numerical quality, and functional form. Documented circulatory support required a qualifying positive-dose intravenous vasopressor or inotrope administration in the 24 hours strictly before the earlier of anesthesia start and operating-room entry. The definition excluded canceled, stopped, zero-dose, and local-anesthetic mixture records. A separate indicator required positive infusion-rate units. These indicators described documented treatment, not adjudicated shock or proof of ongoing support at operating-room entry. Lack of a qualifying record was not evidence that treatment had never occurred.

Stricter numerical-quality analysis required valid pressure triplets, removed isolated MAP spikes under an outcome-independent engineering rule, and reapplied the coverage criterion. Separate three-knot restricted cubic splines at the 10th, 50th, and 90th percentiles assessed departures from the linear modeled exposure scales. Fixed ridge penalties of 0.5, 1, and 2 applied to the summed logistic loss were used only to check coefficient stability; no penalized confidence intervals or bias-elimination claims were made. Additional file 1 details these procedures and all reported estimates.

The initial specification was saved before fitting these blood-pressure–mortality associations, but was not prospectively registered, and earlier analyses of other questions had already been performed in MOVER. Later extensions were developed after the initial findings and did not replace the original model. Analyses used Python with pandas 3.0.6, NumPy 2.5.3, and statsmodels 0.15.0. OpenAI Codex assisted with analysis code and literature organization. Statistical estimates were generated by executable code from local data.

Results

Cohort selection and clinical characteristics

The eligibility algorithm identified 22755 adult inpatient operations within the predefined procedure scope. Retaining the first eligible operation per patient yielded 17379 patients, of whom 17343 had interpretable discharge disposition and consistent admission–operation–discharge chronology. Cleaned invasive mean arterial pressure (MAP) measurements were available for 5125 patients. All had operating-room durations of at least 30 minutes; 5016 had at least 20 valid MAP measurements, and 3877 additionally met the 80% valid-interval coverage requirement. Five patients with missing American Society of Anesthesiologists (ASA) physical status, including one patient who died, were excluded from regression analyses. The final cohort comprised 3872 unique patients, including 98 in-hospital deaths (2.53%; Fig. 1).

The first box represents operations already meeting adult inpatient procedure-scope and timing criteria, not all MOVER operations. Subsequent boxes are patients after selection of their first eligible operation. MAP, mean arterial pressure; ASA, American Society of Anesthesiologists physical status; OR, operating room in this figure.

The median age was 61 years (interquartile range [IQR], 48–71), and 2166 patients (55.9%) were male. The median operating-room duration was 319 minutes (IQR, 238–457). ASA physical status was 3 in 2517 patients (65.0%), 4 in 633 (16.3%), and 5 in 166 (4.3%). Patients with ASA physical status 5 accounted for 46 of the 98 deaths (46.9%). Abdominal and cranial procedures accounted for 789 and 1016 patients, respectively (Table 1).

The median time-weighted MAP deficit below 65 mmHg over observed valid intervals (TWA65) was 0.19 mmHg (IQR, 0.05–0.53). TWA65 was 0.58 mmHg (IQR, 0.13–1.51) among patients who died and 0.19 mmHg (IQR, 0.05–0.52) among those discharged without a recorded death. Average real variability (ARV) was 4.24 mmHg (IQR, 3.44–5.24) overall. The Spearman correlation between TWA65 and ARV was 0.156. These descriptive comparisons were not used to select covariates.

Table 1
Characteristics of the analytic cohort

Characteristic	All (n = 3872)	No recorded death (n = 3774)	In-hospital death (n = 98)
Age, years (capped at 90)	61.00 [48.00, 71.00]	61.00 [48.00, 71.00]	65.00 [48.25, 75.00]
Male sex	2166 (55.9%)	2105 (55.8%)	61 (62.2%)
ASA 1	21 (0.5%)	21 (0.6%)	0 (0.0%)
ASA 2	535 (13.8%)	534 (14.1%)	1 (1.0%)
ASA 3	2517 (65.0%)	2501 (66.3%)	16 (16.3%)
ASA 4	633 (16.3%)	598 (15.8%)	35 (35.7%)
ASA 5	166 (4.3%)	120 (3.2%)	46 (46.9%)
Abdominal procedure	789 (20.4%)	744 (19.7%)	45 (45.9%)
Cranial procedure	1016 (26.2%)	994 (26.3%)	22 (22.4%)
Musculoskeletal/spinal procedure	771 (19.9%)	765 (20.3%)	6 (6.1%)
Vascular/amputation procedure	288 (7.4%)	282 (7.5%)	6 (6.1%)
Other eligible procedure	1008 (26.0%)	989 (26.2%)	19 (19.4%)
Operating-room duration, min	319.00 [238.00, 457.00]	322.00 [243.00, 458.75]	187.00 [139.25, 247.25]
Preoperative hospital duration, days	0.11 [0.08, 0.99]	0.11 [0.08, 0.95]	0.60 [0.06, 5.99]
Documented preoperative circulatory support	244 (6.3%)	202 (5.4%)	42 (42.9%)
Positive infusion-rate record	182 (4.7%)	144 (3.8%)	38 (38.8%)
Preoperative hemoglobin, g/dL	11.50 [9.50, 13.10]; missing 2262	11.60 [9.60, 13.20]; missing 2249	9.80 [8.20, 12.20]; missing 13
Preoperative creatinine, mg/dL	0.80 [0.70, 1.10]; missing 2313	0.80 [0.70, 1.10]; missing 2294	1.10 [0.80, 1.95]; missing 19
Valid-interval coverage, proportion	0.90 [0.86, 0.93]	0.90 [0.86, 0.93]	0.89 [0.85, 0.93]
Observed TWA65, mmHg	0.19 [0.05, 0.53]	0.19 [0.05, 0.52]	0.58 [0.13, 1.51]
ARV, mmHg	4.24 [3.44, 5.24]	4.23 [3.45, 5.23]	4.50 [3.33, 5.64]

Characteristic	All (n = 3872)	No recorded death (n = 3774)	In-hospital death (n = 98)
Observed time with MAP < 65, min	13.84 [3.75, 35.52]	13.66 [3.71, 34.98]	22.74 [5.90, 57.42]

Values are median [interquartile range] or n (%). Laboratory summaries use available measurements within 48 hours before operating-room entry; missing counts are shown. Other displayed characteristics are complete in this selected analytic cohort. No baseline significance tests were used. Documented support refers to qualifying preoperative intravenous vasopressor/inotrope records, not adjudicated shock. TWA65 uses valid observed time as its denominator. ASA, American Society of Anesthesiologists physical status; ARV, average real variability; MAP, mean arterial pressure.

Initial association analyses

Effect estimates for hypotension burden were expressed per one main-cohort IQR increase in log(1 + TWA65), corresponding to 0.38072 on that transformed scale. ARV estimates were expressed per a 1.79217-mmHg increase. Unadjusted hypotension burden was associated with in-hospital mortality (odds ratio [OR], 1.753; 95% confidence interval [CI], 1.536–2.001). Adjustment for age, sex, ordinal ASA physical status, log-transformed operating-room duration, and procedure category attenuated this association (OR, 1.271; 95% CI, 1.096–1.474).

In the initial jointly adjusted model, hypotension burden remained associated with mortality (OR, 1.295; 95% CI, 1.120–1.498), whereas the ARV estimate was imprecise and compatible with no conditional linear association (OR, 0.823; 95% CI, 0.636–1.065; Table 2). This model was specified before fitting the blood-pressure–mortality associations. It was not prospectively registered; previous analyses of other questions had already been conducted in the database.

Table 2
Initial associations with in-hospital mortality

Model	Exposure	Odds ratio (95% CI)
Unadjusted burden	log(1 + TWA65)	1.753 (1.536–2.001)
Initial adjusted burden	log(1 + TWA65)	1.271 (1.096–1.474)
Initial joint model	log(1 + TWA65)	1.295 (1.120–1.498)
Initial joint model	ARV	0.823 (0.636–1.065)

All models included 3872 patients and 98 deaths. Adjusted models included age, sex, ordinal ASA physical status, log operating-room duration, and procedure group; the joint model included both exposures. Estimates are per one main-cohort IQR: 0.38072 for log(1 + TWA65) and 1.79217 mmHg for ARV. CI, HC0 robust confidence interval. The IQR refers to the transformed exposure for TWA65, not a

one-mmHg change. Model specification preceded these association fits but was not prospectively registered.

Coverage and laboratory-data sensitivity analyses

With the coverage requirement relaxed to 70%, the joint analysis included 4430 patients and 123 deaths; the OR for hypotension burden was 1.298 (95% CI, 1.134–1.487). With coverage increased to 90%, 1823 patients and 41 deaths remained, and the corresponding OR was 1.248 (95% CI, 0.996–1.564). The latter interval included 1. Among 1496 patients with both hemoglobin and creatinine available within 48 hours before operating-room entry, 77 died. Additional adjustment for these measurements yielded an OR of 1.224 (95% CI, 1.039–1.443) for hypotension burden. All estimates, including those with intervals spanning the null, are provided in Table S1 (Additional file 1).

Exploratory assessment of severity-related confounding

A subsequent audit identified 3822 qualifying intravenous circulatory-support administration records in the 24 hours strictly preceding both anesthesia start and operating-room entry. These records involved 244 patients, of whom 42 died; 182 patients had documented positive infusion-rate records, including 38 deaths. The records were linked by both patient and operation identifiers, had positive numeric doses and qualifying administration actions, and were labeled PRE-OP in the source table. The indicator represented documented treatment during the preceding 24 hours, not adjudicated shock or necessarily ongoing support at operating-room entry.

In an exploratory extension adding preoperative hospital duration and documented circulatory support to the initial joint model, the hypotension-burden OR was 1.337 (95% CI, 1.157–1.545), and the ARV OR was 1.012 (95% CI, 0.776–1.321). Restricting the support indicator to positive infusion-rate records produced similar estimates (Table S1 (Additional file 1)).

Results were sensitive to the composition of the analytic population. The highest 1% of TWA65 values comprised 39 patients and 10 deaths. Excluding these patients attenuated the burden estimate to 1.179 (95% CI, 0.967–1.436). Excluding patients with ASA physical status 5 and additionally adjusting for preoperative hospital duration left 3706 patients and 52 deaths, with an OR of 1.166 (95% CI, 0.926–1.468). These checks were initiated after examining the initial results; neither constituted a replacement primary population or a formal test of effect modification.

Exploratory numerical-quality and functional-form checks

An outcome-independent numerical sensitivity rule retained only valid systolic–mean–diastolic pressure triplets and removed isolated MAP spikes exceeding both neighboring values in absolute difference by more than 40 mmHg when the neighbors differed by at most 10 mmHg and both adjacent intervals were at most 120 seconds. Applying this rule and reapplying the original coverage criterion retained 3778 patients and 95 deaths. In the severity-extended joint model, the burden OR was 1.359 (95% CI, 1.173–1.573), and the ARV OR was 0.968 (95% CI, 0.729–1.287). Of the original 39 highest-burden patients, 38

remained eligible and all 10 deaths were retained. This numerical audit did not constitute independent waveform adjudication.

ARV calculated exclusively from 60-second intervals was strongly correlated with the original ARV measure (Spearman correlation, 0.995), and its association estimate remained compatible with the null. Separate three-knot restricted cubic spline checks did not identify clear departures from linearity on the modeled scales (nonlinear-term P = 0.899 for log-transformed burden and P = 0.620 for ARV). These results do not establish linearity or exclude thresholds. Fixed ridge penalties of 0.5, 1, and 2 applied to the summed logistic loss yielded burden ORs of approximately 1.337. This was a coefficient-stability check; it did not establish elimination of small-sample bias or provide penalized confidence intervals.

The burden estimates across the initial and exploratory analyses are displayed in Fig. 2.

Points denote odds ratios per one original-cohort IQR increase in log(1 + TWA65); bars denote 95% HC0 robust confidence intervals. Squares indicate analyses specified with the initial model; circles indicate later exploratory extensions. Hospital duration means preoperative hospital duration; support means documented preoperative circulatory support. Adjustment sets differ (Table S1, Additional file 1). Rows are correlated analyses and are not pooled. The vertical line marks an odds ratio of 1. No multiplicity correction was applied.

Discussion

In this selected cohort of invasively monitored noncardiac surgical patients, higher observed hypotension burden was associated with all-cause in-hospital mortality after adjustment for basic clinical and procedural characteristics. ARV did not show a clear conditional association when burden was included. The burden estimate remained above the null after additional measured severity adjustment and numerical-quality checks, but attenuated after excluding ASA 5 patients or the highest exposure tail. These findings support an association in the analyzed population while showing that its interpretation depends on which patients are included.

Interpretation in relation to cardiovascular injury

The burden association is compatible with studies relating the depth and duration of intraoperative hypotension to renal and myocardial injury [1, 2, 3, 4]. It does not identify which biological pathway accounted for deaths in MOVER. Myocardial injury after noncardiac surgery is a clinically important, often biomarker-defined condition, as shown in prospective studies with scheduled troponin assessment [24, 25]. Such surveillance and adjudication were not available for a comparable cardiovascular endpoint here. We therefore did not substitute all-cause mortality for myocardial injury or major adverse cardiovascular events.

Cardiovascular stress also involves more than MAP. The VISION analysis of intraoperative heart rate and systolic pressure found relationships involving both tachycardia and hypotension [26]. Studies

separating perioperative time windows have associated adverse outcomes with pressure abnormalities during different phases of care [27, 28]. Our exposure window spanned operating-room entry to exit and did not distinguish induction, surgical stimulation, bleeding, or postoperative pressure abnormalities. The burden estimate should consequently be viewed as a summary of observed perioperative physiology during that window, not a phase-specific mechanism.

Why variability and burden may give different results

Burden weights low-pressure exposure by its depth and duration. ARV weights successive changes without distinguishing upward recovery from downward deterioration or accounting for the pressure level at which either occurs. A patient may therefore have high burden with relatively little variability, or large changes while remaining above 65 mmHg. Joint modeling addressed this distinction. The small positive correlation between the two measures and the imprecise ARV estimate do not establish that variability is unimportant; they indicate that this particular ARV measure did not add a clear linear association conditional on burden and the measured covariates.

Comparison with previous variability studies requires care. Mascha and colleagues used generalized ARV with a time-normalized definition and a 30-day outcome, whereas Wiórek and Krzych assessed coefficients of variation from measurements at five-minute intervals [6, 7]. Differences in sampling, scaling, endpoints, and clinical populations can produce different associations. Our numerical-quality analysis and 60-second-only check address limited technical questions, but do not validate all variability metrics or resolve the heterogeneity reported in the systematic review [8].

Case mix and measurement selection

ASA 5 patients represented 4.3% of the cohort but 46.9% of deaths. Their exclusion substantially changed both the clinical population and available outcome information. Likewise, removing the highest 1% of burden values removed 10 deaths. The attenuated estimates could reflect greater susceptibility in severely ill patients, residual confounding, exposure-range restriction, reduced precision, or a combination of these explanations. We did not perform a definitive interaction analysis, and overlapping confidence intervals do not establish a between-group difference.

The preoperative circulatory-support audit strengthened temporal separation from intraoperative treatment, but its binary indicator cannot capture the cause or severity of instability. Documented doses may also reflect incomplete recording. The extended association is therefore not proof that baseline shock, urgency, bleeding, or other confounding was adequately controlled. ASA itself is subjective, and a broad procedure category cannot replace detailed operative indications [17]. Stricter numerical filters reduce some implausible measurements but cannot adjudicate catheter artifacts without waveform review.

Monitoring also creates selection. Randomized trials of continuous pressure monitoring have demonstrated reductions in measured hypotension, and an early-warning trial similarly reduced its depth and duration [29, 30, 31]. These studies show that the monitoring-and-response process can affect the

exposure being summarized. Our requirement for invasive MAP and high coverage selected a minority of the outcome-eligible patients. The results cannot be assumed to apply to lower-risk patients monitored only intermittently, nor do they show that selecting invasive monitoring improves survival.

Clinical implications and limitations

Perioperative consensus statements emphasize pressure monitoring and management while recognizing uncertainty about individualized harm thresholds and treatment strategies [32, 33]. Our 65-mmHg threshold was an operational exposure definition, not a newly established safety boundary. The contrasting findings of INPRESS, POISE-3, and IMPROVE-multi further argue against interpreting an observational odds ratio as the effect of raising MAP [9, 10, 11]. Clinical management should account for the cause of hypotension and the patient's broader condition; this study did not compare management strategies.

Several limitations constrain inference. This was a single-center, retrospectively selected cohort using a conservative procedure-name algorithm. Reliable preoperative cardiovascular disease, shock, and emergency-status variables were unavailable for adequate adjustment. Intraoperative blood loss, fluid administration, anesthetic management, and postoperative care were not incorporated. Some may be causes, consequences, or mediators of hypotension, and their appropriate role requires an explicitly causal design. Complete-case laboratory subsets were highly selected. Ninety-eight deaths supported only limited adjustment, and HC0 intervals and ridge stability checks do not eliminate sparse-data bias [22]. Multiple exploratory analyses increase uncertainty, and a nonsignificant spline test does not establish linearity or absence of clinically relevant thresholds.

Finally, discharge-based mortality differs from fixed-duration follow-up and may be influenced by transfers and discharge practice. The VISION cohort documented a substantial proportion of 30-day deaths after discharge, illustrating why these endpoints cannot be equated [34]. We did not establish cause of death, incremental predictive performance, external validity, or a treatment effect. Future work should replicate the exposure definitions in an independent perioperative dataset with harmonized outcomes and richer preoperative severity information before considering clinical risk-model development.

Conclusions

Higher observed intraoperative hypotension burden was associated with all-cause in-hospital mortality in this selected MOVER cohort. ARV showed no clear conditional association, and the burden estimate attenuated after removing the most severely ill patients or extreme exposures. The findings support careful characterization of low-pressure exposure and case mix, but do not establish a causal treatment benefit or a safe MAP threshold.

Abbreviations

ARV
average real variability
ASA
American Society of Anesthesiologists
CI
confidence interval
IQR
interquartile range
MAP
mean arterial pressure
MOVER
Medical Informatics Operating Room Vitals and Events Repository
OR
odds ratio
RECORD
REporting of studies Conducted using Observational Routinely-collected health Data
STROBE
Strengthening the Reporting of Observational Studies in Epidemiology
TWA65
time-weighted MAP deficit below 65 mmHg over valid observed intervals.

Declarations

Ethics approval and consent to participate

The original MOVER data collection and release were approved by the Institutional Review Boards at the University of California, Irvine Medical Center and the main University of California, Irvine campus. The requirement for individual informed consent was waived because protected health information was removed or deidentified [12]. This study was a secondary analysis of deidentified data obtained through the MOVER access process. No additional ethics approval or participant consent was required for this secondary analysis.

Clinical trial number

not applicable.

Consent for publication

Not applicable. No identifiable individual participant information is presented.

Competing interests

The authors declare that they have no competing interests.

Additional files

Additional file 1. Additional_file_1.docx. Supplementary methods and association estimates. Detailed cohort and measurement definitions, model specifications, and Table S1 containing 28 reported exposure estimates.

Additional file 2. Additional_file_2.csv. Machine-readable association estimates corresponding to Table S1, including analysis status and cohort event counts.

Additional file 3. Additional_file_3.csv. Procedure-name classification dictionary. Exact named-procedure scope and group assignments without patient identifiers.

Additional file 4. Additional_file_4.zip. Analysis scripts and execution notes. Scripts for cohort selection, exposure extraction, and statistical analyses; authorized source data and local intermediate tables are required.

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Author Contribution

BZ and SAUS: conceptualization, methodology, data curation, formal analysis, and writing the original draft. BL and YY: clinical interpretation, methodology, and supervision. XZ and YQ: data curation and validation. ZL, MY, and LZ: literature review, interpretation, and critical revision. MG and KZ: validation and visualization. YY: project administration. BZ and SAUS contributed equally.

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Availability of data and materials

The source data are available through the MOVER repository (https://doi.org/10.24432/C5VS5G), subject to its access requirements and data usage agreement [14]. Patient-level source data are not redistributed with this manuscript. Aggregate results and operational definitions are provided in the article and Additional files 1–3. Analysis scripts are supplied in Additional file 4. Their execution requires authorized source data and locally prepared intermediate tables; participant-level intermediate files are not redistributed.

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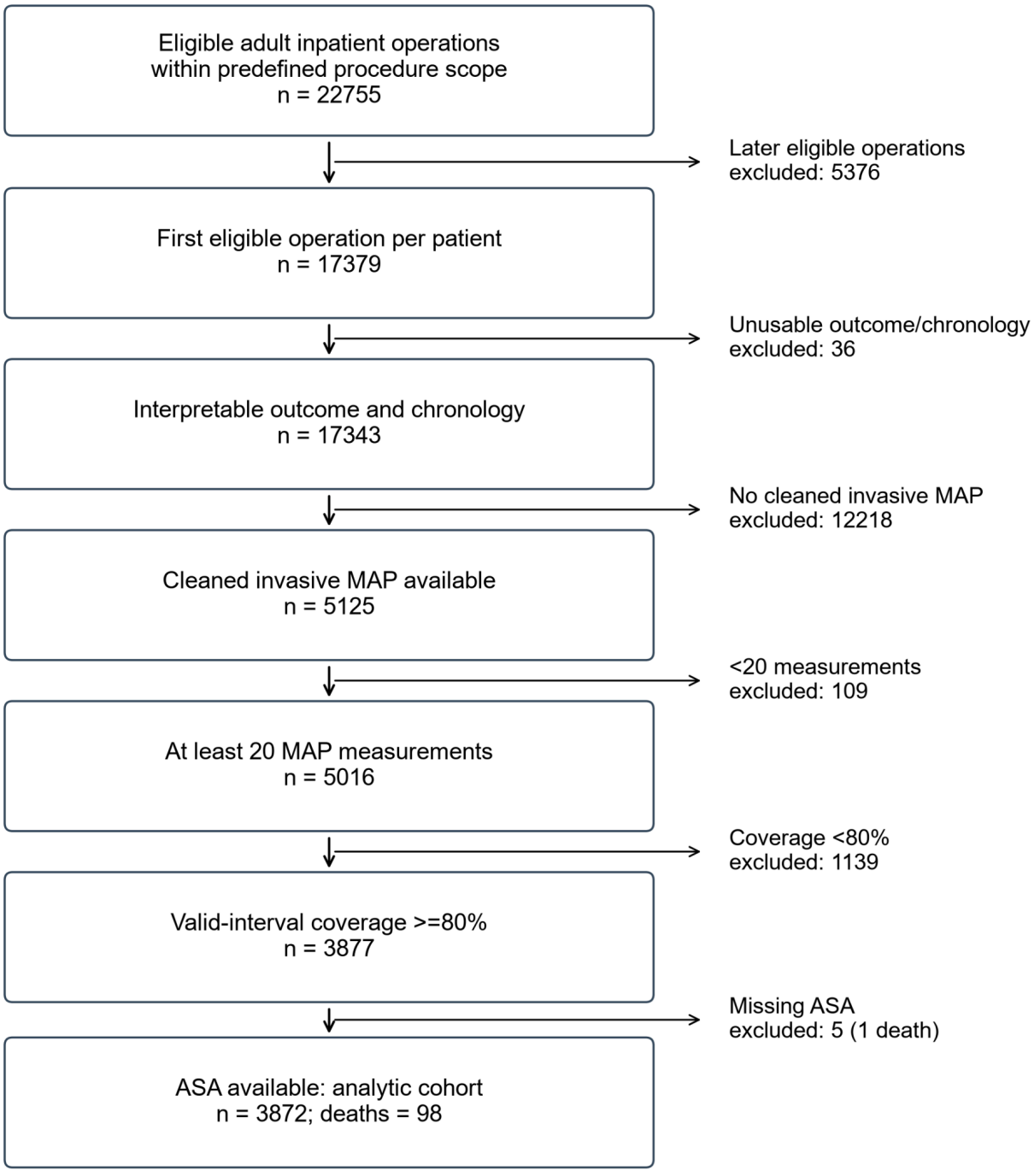
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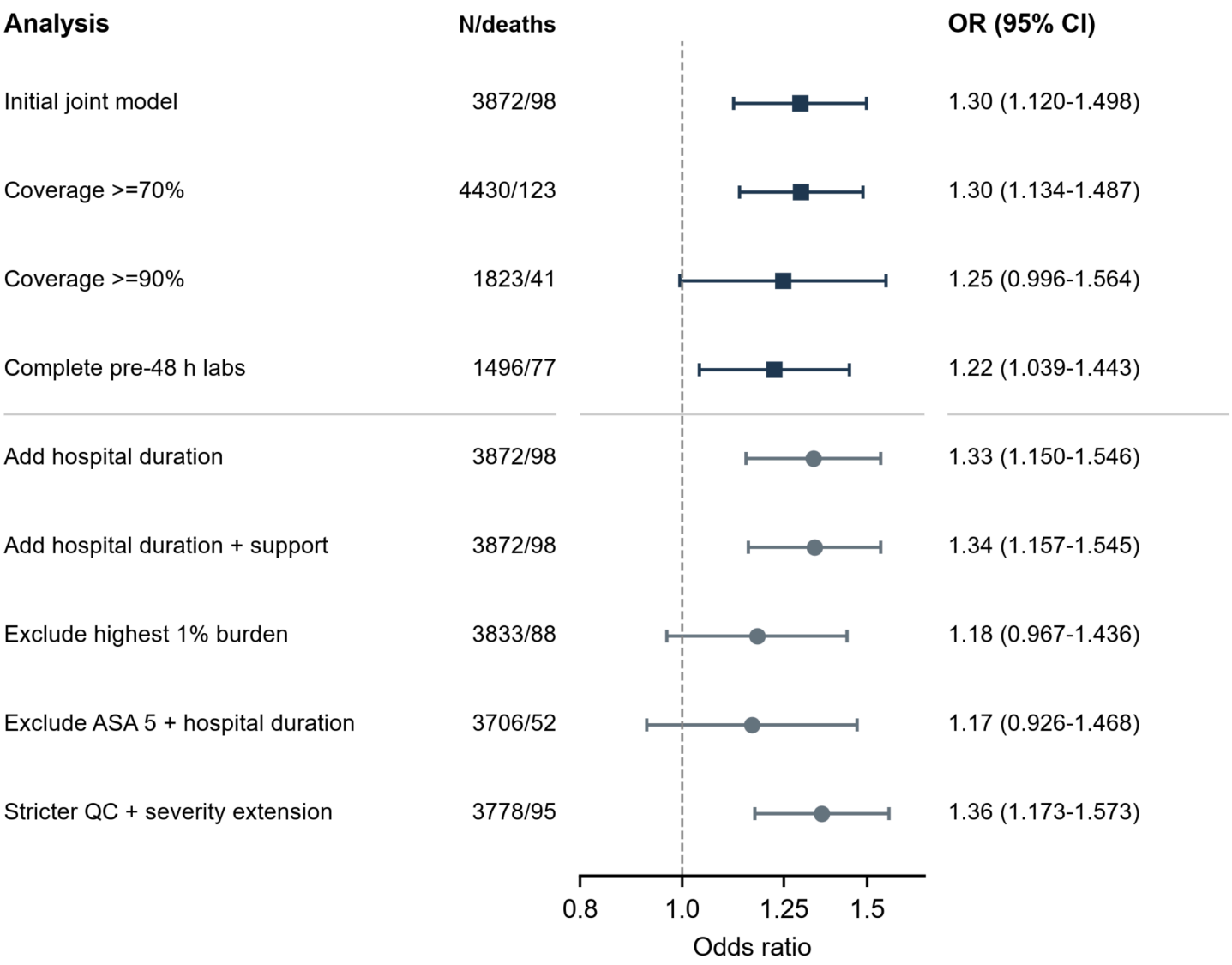
Figures



All 5125 patients with invasive MAP had OR duration >=30 min.
The first denominator is operations; subsequent denominators are patients.

Figure 1

Selection of the analytic cohort



Squares: initial plan. Circles: later exploratory extensions.
Correlated analyses; no pooling. Covariate sets differ (see Supplementary Table S1).

Figure 2

Hypotension burden and in-hospital mortality across analyses

Supplementary Files

This is a list of supplementary files associated with this preprint. Click to download.

- Additionalfile2.csv
- Additionalfile4.zip
- Additionalfile1.docx

- Additionalfile3.csv