

# Association between Intraoperative Hypotension and Hypertension and 30-day Postoperative Mortality in Noncardiac Surgery

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## ABSTRACT

**Background:** Although deviations in intraoperative blood pressure are assumed to be associated with postoperative mortality, critical blood pressure thresholds remain undefined. Therefore, the authors estimated the intraoperative thresholds of systolic blood pressure (SBP), mean blood pressure (MAP), and diastolic blood pressure (DBP) associated with increased risk-adjusted 30-day mortality.

**Methods:** This retrospective cohort study combined intraoperative blood pressure data from six Veterans Affairs medical centers with 30-day outcomes to determine the risk-adjusted associations between intraoperative blood pressure and 30-day mortality. Deviations in blood pressure were assessed using three methods: (1) population thresholds (individual patient sum of area under threshold [AUT] or area over threshold 2 SDs from the mean of the population intraoperative blood pressure values), (2) absolute thresholds, and (3) percent change from baseline blood pressure.

**Results:** Thirty-day mortality was associated with (1) population threshold: systolic AUT (odds ratio, 3.3; 95% CI, 2.2 to 4.8), mean AUT (2.8; 1.9 to 4.3), and diastolic AUT (2.4; 1.6 to 3.8). Approximate conversions of AUT into its separate components of pressure and time were SBP < 67 mmHg for more than 8.2 min, MAP < 49 mmHg for more than 3.9 min, DBP < 33 mmHg for more than 4.4 min. (2) Absolute threshold: SBP < 70 mmHg for more than or equal to 5 min (odds ratio, 2.9; 95% CI, 1.7 to 4.9), MAP < 49 mmHg for more than or equal to 5 min (2.4; 1.3 to 4.6), and DBP < 30 mmHg for more than or equal to 5 min (3.2; 1.8 to 5.5). (3) Percent change: MAP decreases to more than 50% from baseline for more than or equal to 5 min (2.7; 1.5 to 5.0). Intraoperative hypertension was not associated with 30-day mortality with any of these techniques.

**Conclusion:** Intraoperative hypotension, but not hypertension, is associated with increased 30-day operative mortality. (*ANESTHESIOLOGY* 2015; 123:307-19)

**I**NTRAOPERATIVE blood pressure variations outside of accepted physiologic ranges are common during noncardiac surgery. A recent publication analyzing blood pressure data from anesthesia information monitoring systems (AIMS) found hypotension (systolic blood pressure [SBP] < 80 for >5 min) in 26% and hypertension (SBP > 160 for >5 min) in 20% of 16,913 anesthetic cases.<sup>1</sup> Both hypotension and hypertension have been reported to be associated with postoperative complications or mortality.<sup>2-7</sup> Despite the widely assumed importance of blood pressure management on postoperative outcomes, there are no accepted definitions for intraoperative blood pressure levels requiring intervention.<sup>8</sup> A systematic literature

### What We Already Know about This Topic

- Although the American Society of Anesthesiologists recommends monitoring blood pressure during surgery, the association between blood pressure deviations during surgery and mortality are confounded by lack of agreed upon definitions

### What This Article Tells Us That Is New

- In a review of more than 18,000 patients undergoing noncardiac surgery within the Veterans Administration Hospital system, application of three definitions of blood pressure deviation based on population and individual patient level data showed that hypotension but not hypertension was associated with increased 30-day mortality

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review found 130 articles with 140 definitions of intraoperative hypotension.<sup>9</sup> When these various definitions were applied to a large cohort of adult patients undergoing noncardiac surgery, the occurrence of intraoperative hypotension varied from 5 to 99%.<sup>9</sup> The lack of accepted definitions for intraoperative hypotensive and hypertensive events requiring intervention likely exists because there are few studies linking observed intraoperative blood pressure levels with patient outcomes (*i.e.*, perioperative death or complications). Therefore, further research is needed to define the levels of hypotension and hypertension associated with adverse postoperative outcomes.

We have been unable to identify evidence-based guidelines for the maintenance of intraoperative blood pressures. The American Society of Anesthesiologists Standards for Basic Anesthetic Monitoring only state, "Every patient receiving anesthesia shall have arterial blood pressure and heart rate determined and evaluated at least every five minutes."<sup>10</sup>

In the current era of computers automatically recording and storing data on intraoperative vital signs (AIMS), physiologic data can be combined with outcomes data from perioperative registries to identify associations among hypotension, hypertension, and postoperative mortality.<sup>11</sup> The Veterans Affairs Surgical Quality Improvement Program (VASQIP) prospectively collects data on patient-related risks, operative procedures, and 30-day outcomes.<sup>12</sup> The objective of this retrospective cohort study was to combine blood pressure data collected by AIMS at six Veterans Affairs (VA) medical centers with patient-related risk, procedural, and 30-day mortality data from the VASQIP database to test two hypotheses: (1) There are levels of intraoperative hypotension below which 30-day operative mortality is increased and (2) there are levels of intraoperative hypertension above which 30-day operative mortality is increased. With input from anesthesia providers, these levels could then be incorporated into data-driven guidelines for maintaining intraoperative blood pressure.

## Materials and Methods

### Approvals

The study was approved by the University of Colorado Multiple Institutional Review Board (IRB), Denver, Colorado; the IRB at the Durham, NC VA Medical Center; the IRBs at each of the six participating VA medical centers (Cleveland, Dallas, Houston, Pittsburgh, Seattle, and Washington, D.C.); and the VA Surgical Quality Data Use Group, Brockton, Massachusetts.

### Data Sources

The data used for this study came from two sources: AIMS data for the years 2001 to 2008 and data from the same surgical cases in the VASQIP database. The six participating VA sites were the Cleveland, Dallas, Houston, Pittsburgh, Seattle, and Washington, DC Medical Centers.

The participating VA medical centers used AIMS systems from three different vendors—Draeger Medical Inc. (USA), Eko Systems Inc. (USA), and Phillips Healthcare (USA). For the current investigation, we combined AIMS data for intraarterial and

noninvasive SBP and diastolic blood pressure (DBP) measurements and calculated mean blood pressure (MAP). Noninvasive blood pressures were measured every 3 to 5 min, and invasive blood pressures were measured at 15- to 30-s intervals.

The VASQIP is a surgical quality improvement program, in existence in the VA since 1991, which collects data on preoperative risk factors, aspects of the operation, and 30-day postoperative mortality and morbidity outcomes for the majority of major surgical operations performed in the VA healthcare system.<sup>12–16</sup> These data are fed back to the Chiefs of Surgical Services at each VA medical center and the Director of the National Surgery Office for the VA in the form of both center-specific unadjusted and risk-adjusted mortality and complication rates to facilitate assessment and promote improvement in the quality of surgical care delivered. The VASQIP data are collected by a specially trained nurse at each VA medical center. A previous study has documented that the VASQIP data are complete and reliable.<sup>17</sup>

The primary outcome for this study is death from any cause within 30 days after surgery, as recorded in the VASQIP database. This outcome is almost 100% complete, because the VASQIP data are merged periodically with the VA Vital Status File to ensure that all 30-day deaths are captured.<sup>18,19</sup> The VASQIP database was also the source of preoperative demographic variables and risk factors used to perform risk-adjusted analyses for this report. Ten preoperative patient-related risk variables have been found to be the most important preoperative predictors of 30-day postoperative mortality in previous VASQIP studies: serum albumin, American Society of Anesthesiologist physical status classification, presence of disseminated cancer, emergency operation, patient age, a do not resuscitate order, the work relative value unit associated with the primary Current Procedural Terminology code (a measure of the complexity of the procedure), weight loss >10% of body weight in the 6 months before surgery, surgeon subspecialty, and serum creatinine.<sup>15,16</sup> The laboratory values used for risk adjustment were measured within 30 days before surgery. These preoperative risk factors along with intraoperative blood pressure measurements from the AIMS systems were used as the independent variables in multivariable logistic regression analyses in which death within 30 days of surgery was the dependent (outcome) variable.

The AIMS and VASQIP databases were matched using patient Social Security number and date of surgery. Only those operations that had both the AIMS and the VASQIP data available were retained for analysis. Patients who received only monitored anesthesia care or local anesthesia were excluded. For patients with more than one operation recorded in the database, only the first operation for each patient was retained for analysis.

### Cleaning and Summarizing the AIMS Data

A written detailed analysis plan was developed for cleaning and summarizing the AIMS data. This plan was reviewed and revised by the investigative team before analyzing any postoperative outcomes.

Of the many tables in the AIMS, the fields containing intraarterial and noninvasive blood pressure measurements were identified by the physician investigators based on the table identifiers, the amount of data present, and, when necessary, inspecting frequency distribution to confirm that values were compatible with the blood pressure variable under consideration. Nonphysiologic blood pressure values (defined as SBP <20 mmHg and >300 mmHg and DBP <20 mmHg and >200 mmHg) were excluded. MAP was calculated using the following formula:  $MAP = DBP + 1/3 \times (SBP - DBP)$ .

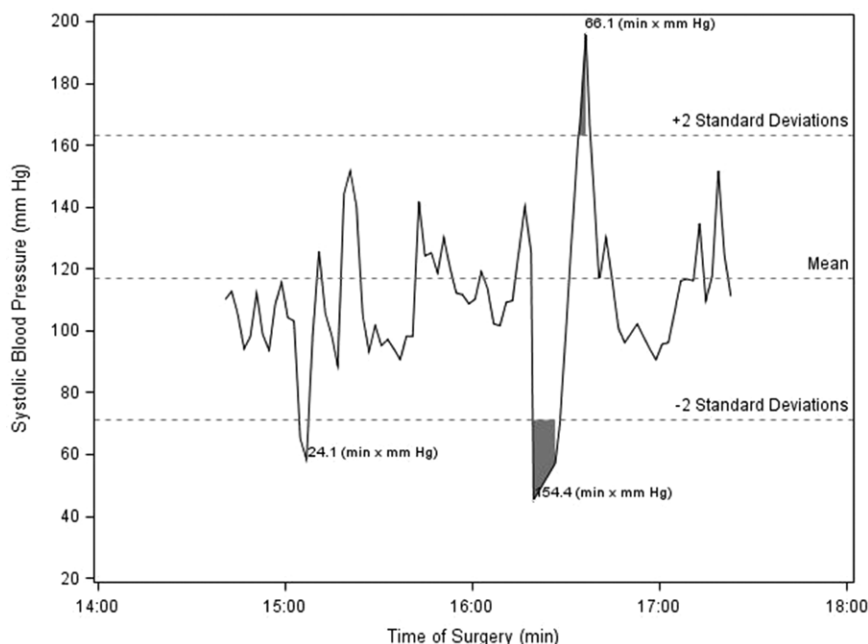
Our hypotheses testing analyses were limited to intraoperative blood pressures, which we identified by the appearance of expired carbon dioxide. All pressure values between the first and last expired carbon dioxide measurements were retained for analysis. For the few patients without end-tidal carbon dioxide measurements, all blood pressures were used. When duplicate pressures (occurring in the same patient, the same operation, and with the same date/time stamp) occurred, one was selected at random. Most of the duplicate pressures had the same value. In instances where either SBP or DBP were missing, or DBP was greater than SBP, or DBP was less than 20 mmHg below SBP, all pressures at that time point were deleted. Finally, we smoothed the intraarterial blood pressure data by calculating the median of all pressure values in consecutive 2-min epochs and then combined the smoothed intraarterial values with the noninvasive values. If a patient had both intraarterial and noninvasive pressures at the same time point, the intraarterial pressures were used preferentially.

### Statistical Analyses

Three distinct sets of statistical analyses were performed using different methods for assessing intraoperative blood pressure

deviations: (1) area over (AOT) and area under (AUT) the population-defined blood pressure thresholds, (2) absolute blood pressure thresholds, and (3) blood pressure thresholds relative to each patient's baseline blood pressure.

**Areas over and under the Population-defined Blood Pressure Thresholds.** Means and SDs for SBP, MAP, and DBP were calculated using all pressure values for all patients. Hypertensive and hypotensive thresholds were defined as the population mean  $\pm 2$  SDs from the mean. We made the *a priori* decision to define the acceptable blood pressure as the mean of the blood pressure data  $\pm 2$  SDs (about 95% of all observations), because this definition is commonly used to define a reference range for laboratory measurements.<sup>20</sup> Intuitively, abnormal intraoperative blood pressure has both magnitude and time or duration components. Therefore, the sum of all areas defined by the blood pressure curve above the upper threshold (AOT) is a measure of the severity of intraoperative hypertension; similarly, the sum of all areas defined by the blood pressure curve below the lower threshold (AUT) is a measure of the severity of intraoperative hypotension. The time component is calculated as the sum of the durations of all intraoperative hypertensive (time over the threshold [TOT]) or hypotensive episodes (time under the threshold [TUT]). Figure 1 illustrates the triangulation/trapezoidal method for calculation of AOT and AUT in mmHg  $\times$  minutes for two episodes of hypotension and one of hypertension. Area was calculated using the trapezoid method,  $area = (d_1 - d_2) \times b \times 0.5$ , where  $d_1$  and  $d_2$  are the first and second blood pressure deviations (mmHg), respectively, from the given threshold, and  $b$  is the time (minutes) between the two deviations. However, anesthesia providers commonly manage blood pressure in mmHg and are not



**Fig. 1.** Example of the triangulation/trapezoid method with slope estimates for the calculation of area over (163 mmHg) and under (71 mmHg) systolic blood pressure threshold for a single patient.

familiar with measures of AUT or AOT, so we also calculated the average pressure under the threshold (PUT) or pressure over the threshold (POT) as AUT/TUT and AOT/TOT, respectively. To estimate the relationship between severity of blood pressure aberration and mortality, patients were grouped into quartiles according to AUT, AOT, TUT, TOT, PUT, and POT separately for area, time, and pressure.

**Absolute Blood Pressure Thresholds.** Absolute thresholds were defined by a consensus of the clinicians in the research group after review of publications that used this method;<sup>21,22</sup> this resulted in a reference SBP of 90 to 159 mmHg, reference MAP of 60 to 109 mmHg, and the reference DBP of 50 to 99 mmHg. Gradients of aberration were defined in 10 mmHg intervals for durations of 2 to 4.9 and more than or equal to 5 min.

**Blood Pressure Thresholds Relative to Each Patient's Baseline Blood Pressure.** We also examined the effect of decreases and increases of SBP, MAP, and DBP of 30 to 39, 40 to 49, and more than or equal to 50% from each patient's preanesthesia blood pressures for durations of 2 to 4.9 and more than or equal to 5 min. The patient's preanesthesia baseline blood pressure was calculated by taking the average of all noninvasive blood pressure measurements before the appearance of end-tidal carbon dioxide.

Note that in all three types of analyses (population-defined blood pressure thresholds, absolute blood pressure thresholds, and blood pressure thresholds relative to each patient's baseline blood pressure), by definition, the hypotensive and hypertensive episodes cannot overlap. However, some patients have both hypotensive and hypertensive episodes.

The association of blood pressure deviations with operative mortality was assessed using separate logistic regression analyses for each of the three measures of blood pressure deviation for SBP, MAP, and DBP. The independent variables were the measures of blood pressure aberrancy and patient preoperative risk variables, and the 30-day postoperative mortality was the dependent variable. The statistical significance of the association between blood pressure and 30-day postoperative mortality was assessed with an overall *P* value, which assesses the simultaneous statistical significance of the difference in the odds ratios (ORs) from 1.0 across all blood pressure deviation groups. We only report the statistical significance of the ORs for individual blood pressure deviation groups of hypotension or hypertension when the overall *P* value was statistically significant ( $P \leq 0.05$ ). The *P* values were adjusted for multiple comparisons using the Bonferroni correction for each of the three sets of statistical analyses.

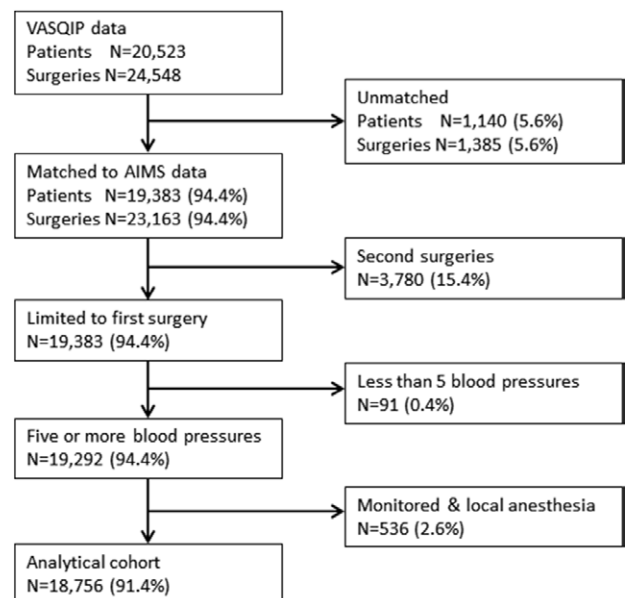
The VASQIP data were 100% complete, with the exception of preoperative serum albumin and creatinine in cases where these laboratory tests were not ordered for the patients. In the adjusted analyses, we imputed serum albumin using standard methods used in previous VASQIP publications,<sup>23,24</sup> and serum creatinine was assumed to be normal when it was missing. All statistical analyses were performed using SAS<sup>®</sup>, version 9.3 (SAS Inc., USA).

## Results

### Patient Population

The initial AIMS data included 46,496 operations on 30,650 patients. As shown in the Strengthening the Reporting of Observational Studies in Epidemiology diagram<sup>25</sup> (fig. 2), the VASQIP data included 24,548 operations on 20,523 patients. After matching AIMS data with VASQIP data, there were 23,163 operations on 19,383 patients. Exclusions included the second or more operations for 3,780 patients with 2 or more operations, 91 patients with fewer than 5 intraoperative blood pressures, and 536 patients who received only monitored anesthesia care or local anesthetics. The final cohort for analysis included 18,756 patients. The contribution of data from each VA site to the final database was Cleveland, 6,223 patients; Houston, 3,898 patients; Dallas, 3,728 patients; Seattle, 2,715 patients; Pittsburgh, 1,626 patients; and Washington, 566 patients. The average number of blood pressure readings per case was  $52 \pm 33$  for noninvasive blood pressure monitoring and  $617 \pm 432$  for invasive blood pressure monitoring.

The preoperative, intraoperative, and postoperative characteristics of the 18,756 patients are shown in table 1. Consistent with a VA population, this was an older (mean age, 59.5 yr), largely male (92.8%) cohort. Race/ethnicity was unknown for 16% of the sample, but for those with known race/ethnicity, 61% were Caucasian, 20% were African American, and 3% were Hispanic. The 30-day postoperative mortality rate was 1.8% in patients who had surgery with general anesthesia, 1.8% with spinal anesthesia, and 2.3% with epidural anesthesia.



**Fig. 2.** STROBE diagram of included patients with matched VASQIP and AIMS blood pressure data. AIMS = anesthesia information monitoring systems; STROBE = Strengthening the Reporting of Observational Studies in Epidemiology; VASQIP = Veterans Affairs Surgical Quality Improvement Program.

**Table 1.** Preoperative, Intraoperative, and Postoperative Patient Characteristics

| Characteristics                                 | n = 18,756     |
|---|----------------|
| Age (yr), mean (SD)                             | 59.5 (12.8)    |
| Male, n (%)                                     | 17,412 (92.8)  |
| Race/ethnicity, n (%)                           |                |
| White   | 11,515 (61.4)  |
| Black   | 3,707 (19.8)   |
| Hispanic  | 478 (2.6)      |
| Other   | 3,056 (16.3)   |
| Preoperative albumin* (g/dl), mean (SD)         | 3.9 (0.7)      |
| Disseminated cancer, n (%)                      | 367 (2.0)      |
| Do not resuscitate status, n (%)                | 133 (0.7)      |
| >10% loss body weight in past 6 mo, n (%)       | 910 (4.9)      |
| Preoperative creatinine >1.2 mg/dl, n (%)       | 3,479 (18.6)   |
| Emergency case, n (%)                           | 1,414 (7.5)    |
| ASA classification, n (%)                       |                |
| 1   | 497 (2.7)      |
| 2   | 4,890 (26.1)   |
| 3   | 10,889 (58.1)  |
| 4   | 2,443 (13.0)   |
| 5   | 37 (0.2)       |
| Work RVU, mean (SD)                             | 15.2 (8.7)     |
| Operative time (h), median (IQR)                | 2.0 (1.2–3.1)  |
| Postoperative length of stay† (d), median (IQR) | 5.0 (2.0–10.0) |
| 30-d mortality, n (%)                           | 334 (1.8)      |
| Surgeon specialty, n (%)                        |                |
| General surgery                                 | 5,905 (31.5)   |
| Orthopedic surgery                              | 4,252 (24.1)   |
| Peripheral vascular surgery                     | 2,187 (11.7)   |
| Urology   | 2,030 (10.8)   |
| Neurosurgery                                    | 1,050 (5.6)    |
| Thoracic surgery                                | 1,010 (5.4)    |
| Other surgery                                   | 2,049 (10.9)   |

\* A total of 5,109 (27.2%) patients were missing preoperative albumin. † A total of 5,351 (28.5%) patients were missing postoperative length of stay. ASA = American Society of Anesthesiologists; IQR = interquartile range; RVU = relative value unit.

**Areas over and under Population-defined Blood Pressure Thresholds**

**Unadjusted Mortality.** Table 2 presents the sample sizes and unadjusted 30-day mortality rates for the patient groups in the population-defined blood pressure threshold analyses. In this analysis, the reference range for SBP was 71 to 163 mmHg, MAP was 55 to 119 mmHg, and DBP was 35 to 95 mmHg (table 2). The reference group (no hypotension or hypertension during surgery) for SBP included 40% (7,573) of the patients compared with 9% (1,714) with only hypotension, 41% (7,648) with only hypertension, and 10% (1821) with both hypotensive and hypertensive episodes during surgery (table 2). There is a severalfold increase in unadjusted operative mortality for the fourth quartile of hypotensive AUT, TUT, and PUT with generally graded intermediate mortality rates for the first three quartiles. Similar mortality gradients by AUT, TUT, and PUT were seen for MAP and DBP. However, the unadjusted death rates increased modestly or not at all for hypertensive AOT, TOT, and POT for SBP, MAP, and DBP. The mortality rate was 3% for the patients who experienced both hypotension

and hypertension during the surgical procedure, which is similar to the rate in the hypotension-only group (table 2).

**Risk-adjusted Mortality.** The c-index for predicting 30-day mortality using only VASQIP preoperative patient characteristics was high at 0.908. When intraoperative blood pressure variables from each of the three analysis techniques were added to the model, the c-index values were essentially unchanged. Likewise, the addition of intraoperative erythrocyte transfusion and sepsis or year of surgery did not appreciably change the c-index or improve the model.

The risk-adjusted results for the population-defined threshold are presented in table 3. After adjustment for the patient preoperative risk variables, the ORs for mortality for AUT, TUT, and PUT measures of SBP, MAP, and DBP hypotension groups were statistically significant compared with the reference groups (overall  $P < 0.007$ ), whereas there were no statistically significant results for the hypertension groups. Conversions of AUT into its separate components of pressure and time allow us to define approximate thresholds for increased mortality (table 3): (1) SBP < 67 mmHg (OR, 1.7; 95% CI, 1.1 to 2.7) with duration of more than 8.2 min (3.3; 2.2 to 4.8), (2) MAP < 49 mmHg (3.0; 2.0 to 4.5) for more than 3.9 min (1.8; 1.1 to 2.9), and (3) DBP < 33 mmHg (1.8; 1.2 to 2.9) for more than 4.4 min (2.0; 1.2 to 3.1). These data are also graphically represented in figures 3 and 4.

**Absolute Blood Pressure Thresholds**

Table 4 presents unadjusted and risk-adjusted results for the analyses based on the absolute blood pressure thresholds. In this analysis, the reference range for SBP was 90 to 159 mmHg, MAP 60 to 109 mmHg, and DBP 50 to 99 mmHg. Again, the unadjusted results show a generally increasing gradient of mortality with greater severity of intraoperative hypotension; this gradient is substantially less for hypertension. In risk-adjusted analyses, the association between operative mortality and hypotension is statistically significant (overall  $P < 0.001$ ) with ORs of 2.9 (95% CI, 1.7 to 4.9) for SBP < 70 mmHg for more than or equal to 5 min, 2.4 (1.3 to 4.6) for MAP < 49 mmHg for more than or equal to 5 min, and 3.2 (1.8 to 5.5) for DBP < 30 mmHg for more than or equal to 5 min. There is no statistically significant relationship between hypertension and mortality in the risk-adjusted analyses.

**Blood Pressure Thresholds Relative to Each Patient's Baseline Blood Pressure**

Table 5 presents unadjusted and risk-adjusted analyses based on the blood pressure thresholds relative to each patient's baseline blood pressure before expired carbon dioxide measurements. Only 12,675 (67.6%) of the 18,756 subjects had baseline blood pressure measurements in AIMS; these patients tended to be at a lower risk than those without baseline blood pressure measurements (e.g., less emergent surgery, fewer other preoperative risk factors, and lower 30-day postoperative mortality and morbidity rates). In the risk-adjusted analyses, the only clinically meaningful association with 30-day mortality

**Table 2.** Patient Counts and 30-day Mortality Rates by Area under Curve,\* Total Time, and Absolute Pressure Deviations from Population-defined Thresholds (n = 18,756)

| Thresholds†                         | Systolic           |            | Mean               |            | Diastolic         |            |
|-------------------------------------|--------------------|------------|--------------------|------------|-------------------|------------|
|                                     | N                  | Deaths (%) | N                  | Deaths (%) | N                 | Deaths (%) |
| <b>Hypotension</b>                  | Threshold 71 mmHg  |            | Threshold 55 mmHg  |            | Threshold 35 mmHg |            |
| Area under threshold (min × mmHg)   |                    |            |                    |            |                   |            |
| Reference                           | 7,573              | 99 (1.3)   | 6,480              | 101 (1.6)  | 6,706             | 111 (1.7)  |
| First quartile                      | 884                | 25 (2.8)   | 851                | 22 (2.6)   | 817               | 22 (2.7)   |
| Second quartile                     | 883                | 23 (2.6)   | 852                | 26 (3.1)   | 817               | 17 (2.1)   |
| Third quartile                      | 884                | 16 (1.8)   | 852                | 23 (2.7)   | 818               | 32 (3.9)   |
| Fourth quartile                     | 884                | 60 (6.8)   | 852                | 46 (5.4)   | 817               | 39 (4.8)   |
| Time under threshold (min)          |                    |            |                    |            |                   |            |
| Reference                           | 7,573              | 99 (1.3)   | 6,480              | 101 (1.6)  | 6,706             | 111 (1.7)  |
| First quartile                      | 883                | 29 (3.3)   | 851                | 21 (2.5)   | 817               | 26 (3.2)   |
| Second quartile                     | 884                | 20 (2.3)   | 852                | 24 (2.8)   | 817               | 14 (1.7)   |
| Third quartile                      | 884                | 16 (1.8)   | 852                | 28 (3.3)   | 818               | 29 (3.5)   |
| Fourth quartile                     | 884                | 59 (6.7)   | 852                | 44 (5.2)   | 817               | 41 (5.0)   |
| Pressure under threshold (mmHg)     |                    |            |                    |            |                   |            |
| Reference                           | 7,573              | 99 (1.3)   | 6,480              | 101 (1.6)  | 6,706             | 111 (1.7)  |
| First quartile                      | 890                | 21 (2.4)   | 849                | 20 (2.4)   | 817               | 19 (2.3)   |
| Second quartile                     | 877                | 20 (2.3)   | 854                | 29 (3.4)   | 817               | 29 (3.5)   |
| Third quartile                      | 884                | 32 (3.6)   | 852                | 23 (2.7)   | 818               | 24 (2.9)   |
| Fourth quartile                     | 884                | 51 (5.8)   | 852                | 45 (5.3)   | 817               | 38 (4.7)   |
| <b>Hypertension</b>                 | Threshold 163 mmHg |            | Threshold 119 mmHg |            | Threshold 95 mmHg |            |
| Area over threshold (min × mmHg)    |                    |            |                    |            |                   |            |
| Reference                           | 7,573              | 99 (1.3)   | 6,480              | 101 (1.6)  | 6,706             | 111 (1.7)  |
| First quartile                      | 2,367              | 30 (1.3)   | 2,648              | 49 (1.9)   | 2,553             | 41 (1.6)   |
| Second quartile                     | 2,367              | 41 (1.7)   | 2,648              | 37 (1.4)   | 2,553             | 37 (1.4)   |
| Third quartile                      | 2,368              | 46 (1.9)   | 2,649              | 41 (1.5)   | 2,553             | 40 (1.6)   |
| Fourth quartile                     | 2,367              | 54 (2.3)   | 2,648              | 55 (2.1)   | 2,553             | 42 (1.6)   |
| Time over threshold (min)           |                    |            |                    |            |                   |            |
| Reference                           | 7,573              | 99 (1.3)   | 6,480              | 101 (1.6)  | 6,706             | 111 (1.7)  |
| First quartile                      | 2,368              | 34 (1.4)   | 2,648              | 52 (2.0)   | 2,554             | 43 (1.7)   |
| Second quartile                     | 2,366              | 41 (1.7)   | 2,648              | 40 (1.5)   | 2,552             | 38 (1.5)   |
| Third quartile                      | 2,368              | 41 (1.7)   | 2,649              | 41 (1.5)   | 2,553             | 41 (1.6)   |
| Fourth quartile                     | 2,367              | 55 (2.3)   | 2,648              | 49 (1.9)   | 2,553             | 38 (1.5)   |
| Pressure over threshold (mmHg)      |                    |            |                    |            |                   |            |
| Reference                           | 7,573              | 99 (1.3)   | 6,480              | 101 (1.6)  | 6,706             | 111 (1.7)  |
| First quartile                      | 2,367              | 38 (1.6)   | 2,648              | 42 (1.6)   | 2,594             | 40 (1.5)   |
| Second quartile                     | 2,367              | 35 (1.5)   | 2,648              | 46 (1.7)   | 2,512             | 37 (1.5)   |
| Third quartile                      | 2,368              | 39 (1.6)   | 2,649              | 45 (1.7)   | 2,553             | 33 (1.3)   |
| Fourth quartile                     | 2,367              | 59 (2.5)   | 2,648              | 49 (1.9)   | 2,553             | 50 (2.0)   |
| <b>Hypotension and hypertension</b> |                    |            |                    |            |                   |            |
| Reference                           | 7,573              | 99 (1.3)   | 6,480              | 101 (1.6)  | 6,706             | 111 (1.7)  |
| Both                                | 1,821              | 60 (3.3)   | 1,724              | 66 (3.8)   | 1,431             | 47 (3.3)   |
| Only hypotension                    | 1,714              | 64 (3.7)   | 1,683              | 51 (3.0)   | 1,838             | 63 (3.4)   |
| Only hypertension                   | 7,648              | 111 (1.5)  | 8,869              | 116 (1.3)  | 8,781             | 113 (1.3)  |

\* See text for definition. † Thresholds were established in relationship to the population mean pressure ± 2 SDs.

was a MAP decrease of more than 50% from baseline for more than or equal to 5 min (OR, 2.7; 95% CI, 1.5 to 5.0). The reduced sample size with this technique may have contributed to broad CIs and decreased power to detect associations.

## Discussion

### Overview of Results

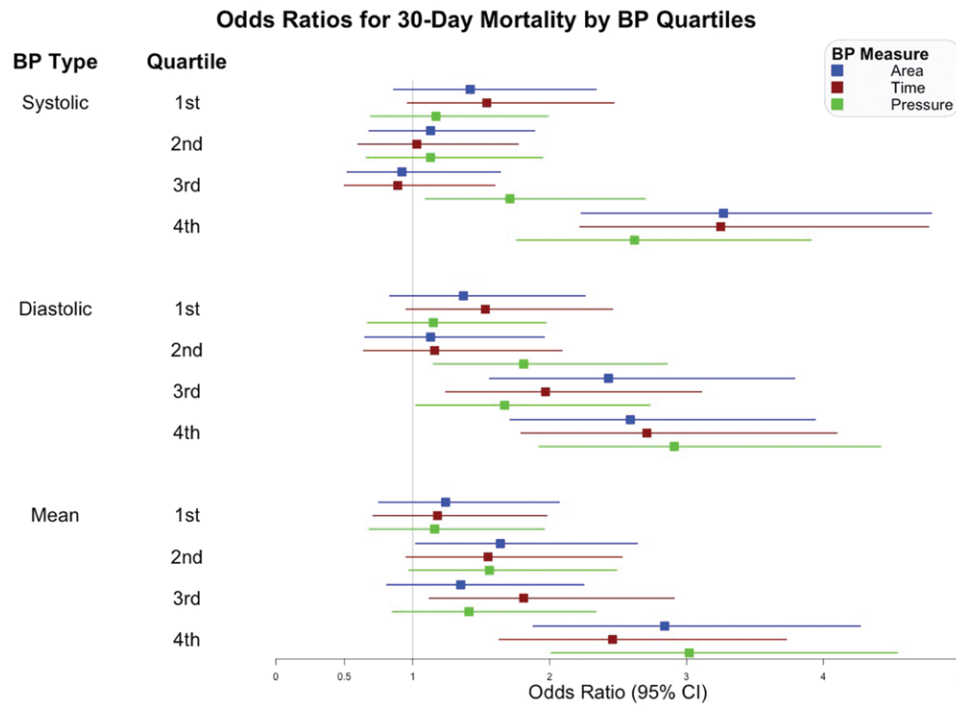
Intraoperative hypotension and hypertension were assessed from AIMS data in 18,756 major surgical procedures using

three different methods: (1) AUT (hypotension) or AOT (hypertension), which incorporates simultaneously the magnitude and duration of the pressure aberration; (2) absolute thresholds based on our clinical judgment and the literature; and (3) relative thresholds, defined as percent change from a patient's preoperative baseline blood pressure. The first two methods showed statistically significant associations between increased 30-day mortality and hypotension in multiple cells (tables 3 and 4); however, in the third analysis using the patient's

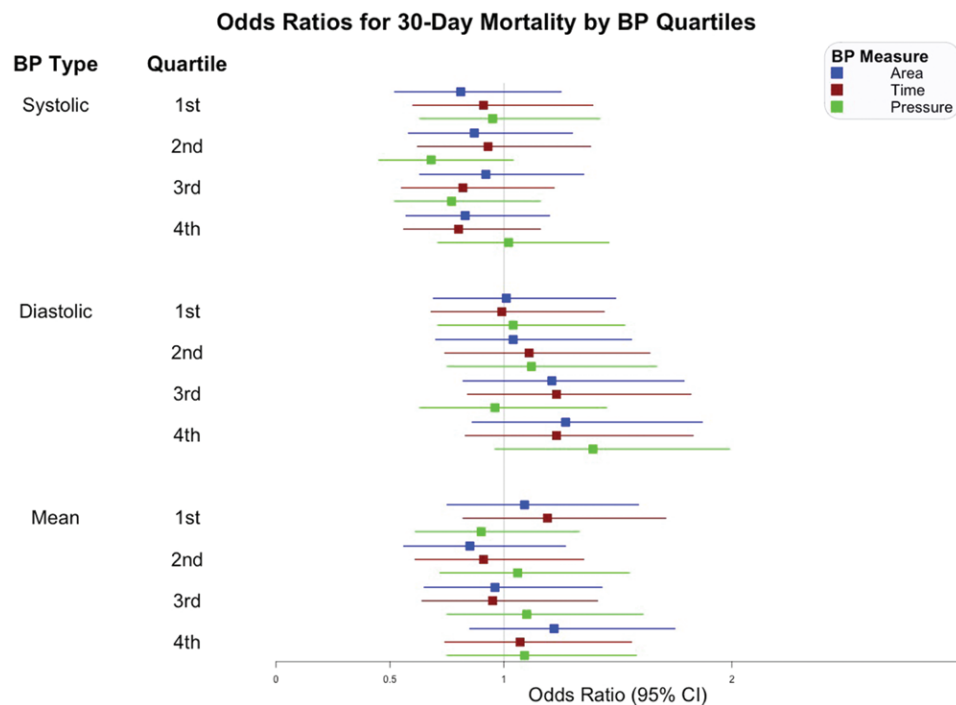
**Table 3.** Area, Total Time, and Absolute Pressure Deviations from Population-defined Thresholds and Adjusted Odds Ratios for 30-day Mortality (n = 18,756)

| Thresholds*   | Systolic            |                         |          | Mean                |                         |          | Diastolic           |                         |          |
|---|---------------------|-------------------------|----------|---------------------|-------------------------|----------|---------------------|-------------------------|----------|
|   | Median (IQR)        | OR (95% CI)             | P Value† | Median (IQR)        | OR (95% CI)             | P Value† | Median (IQR)        | OR (95% CI)             | P Value† |
| <b>Hypotension</b>                                    |                     |                         |          |                     |                         |          |                     |                         |          |
| Area under threshold (min × mmHg)                     |                     |                         |          |                     |                         |          |                     |                         |          |
| First quartile  | 0.5 (0.2-1.0)       | 1.42 (0.86-2.34)        | <0.0001  | 0.5 (0.2-1.0)       | 1.24 (0.75-2.07)        | <0.001   | 0.6 (0.2-1.0)       | 1.37 (0.83-2.26)        | <0.001   |
| Second quartile                                       | 3.9 (2.6-5.5)       | 1.13 (0.68-1.89)        |          | 3.3 (2.3-4.9)       | <b>1.64 (1.02-2.64)</b> |          | 3.4 (2.3-4.8)       | 1.13 (0.65-1.96)        |          |
| Third quartile  | 13.4 (10.0-17.8)    | 0.92 (0.52-1.64)        |          | 12.2 (9.1-17.0)     | 1.35 (0.81-2.25)        |          | 12.6 (9.2-17.8)     | <b>2.43 (1.56-3.79)</b> |          |
| Fourth quartile                                       | 51.5 (35.2-92.9)    | <b>3.27 (2.23-4.79)</b> |          | 46.8 (30.6-81.6)    | <b>2.84 (1.88-4.27)</b> |          | 63.9 (36.5-131.2)   | <b>2.59 (1.71-3.94)</b> |          |
| Time under threshold (min)                            |                     |                         |          |                     |                         |          |                     |                         |          |
| First quartile  | 0.5 (0.3-0.7)       | 1.54 (0.96-2.47)        | <0.0001  | 0.6 (0.3-0.8)       | 1.18 (0.71-1.98)        | 0.007    | 0.5 (0.3-0.8)       | 1.53 (0.95-2.46)        | <0.001   |
| Second quartile                                       | 1.5 (1.2-1.9)       | 1.03 (0.60-1.77)        |          | 1.8 (1.4-2.2)       | 1.55 (0.95-2.53)        |          | 1.7 (1.3-2.1)       | 1.16 (0.64-2.09)        |          |
| Third quartile  | 3.2 (2.7-3.9)       | 0.89 (0.50-1.60)        |          | 3.9 (3.3-4.8)       | <b>1.81 (1.12-2.91)</b> |          | 4.4 (3.4-5.9)       | <b>1.97 (1.24-3.11)</b> |          |
| Fourth quartile                                       | 8.2 (6.1-12.8)      | <b>3.25 (2.22-4.77)</b> |          | 11.1 (8.2-17.9)     | <b>2.46 (1.63-3.73)</b> |          | 19.1 (11.5-37.7)    | <b>2.71 (1.79-4.10)</b> |          |
| Pressure under threshold + threshold pressure (mmHg)* |                     |                         |          |                     |                         |          |                     |                         |          |
| First quartile  | 70 (69.8-70.5)      | 1.17 (0.69-1.99)        | 0.001    | 54.3 (54.0-54.5)    | 1.16 (0.68-1.96)        |          | 34.3 (34.0-34.5)    | 1.15 (0.67-1.97)        | <0.001   |
| Second quartile                                       | 68.6 (68.3-69)      | 1.13 (0.66-1.95)        |          | 53.2 (53.0-53.5)    | 1.56 (0.97-2.49)        | <0.001   | 33.1 (33.0-33.5)    | <b>1.81 (1.15-2.86)</b> |          |
| Third quartile  | 66.7 (66-67.4)      | <b>1.71 (1.09-2.70)</b> |          | 51.9 (51.5-52.3)    | 1.41 (0.85-2.34)        |          | 32.0 (31.5-32.4)    | <b>1.67 (1.02-2.73)</b> |          |
| Fourth quartile                                       | 63.0 (60.5-64.3)    | <b>2.62 (1.76-3.91)</b> |          | 49.3 (47.8-50.3)    | <b>3.02 (2.01-4.54)</b> |          | 29.7 (28.6-30.5)    | <b>2.91 (1.92-4.42)</b> |          |
| <b>Hypertension</b>                                   |                     |                         |          |                     |                         |          |                     |                         |          |
| Area over threshold (min × mmHg)                      |                     |                         |          |                     |                         |          |                     |                         |          |
| First quartile  | 3.7 (1.1-7.8)       | 0.81 (0.52-1.25)        | 1.0      | 2.6 (0.8-5.6)       | 1.09 (0.75-1.59)        | 1.0      | 2.1 (0.7-4.3)       | 1.01 (0.69-1.49)        | 1.0      |
| Second quartile                                       | 33.2 (22.6-46.8)    | 0.87 (0.58-1.30)        |          | 23.8 (15.8-33.8)    | 0.85 (0.56-1.27)        |          | 18.3 (12.5-25.7)    | 1.04 (0.70-1.56)        |          |
| Third quartile  | 118.1 (88.6-154.9)  | 0.92 (0.63-1.35)        |          | 78.9 (60.5-103.6)   | 0.96 (0.65-1.43)        |          | 66.0 (49.1-85.9)    | 1.21 (0.82-1.79)        |          |
| Fourth quartile                                       | 410.7 (280.2-699.9) | 0.83 (0.57-1.20)        |          | 256.4 (182.7-413.6) | 1.22 (0.85-1.75)        |          | 227.0 (158.8-376.4) | 1.27 (0.86-1.87)        |          |
| Time over threshold (min)                             |                     |                         |          |                     |                         |          |                     |                         |          |
| First quartile  | 1.2 (0.6-1.9)       | 0.91 (0.60-1.39)        | 1.0      | 1.2 (0.6-1.8)       | 1.19 (0.82-1.71)        | 1.0      | 1.0 (0.5-1.5)       | 0.99 (0.68-1.44)        | 1.0      |
| Second quartile                                       | 4.3 (3.4-5.3)       | 0.93 (0.62-1.38)        |          | 4.2 (3.3-5.2)       | 0.91 (0.61-1.35)        |          | 3.5 (2.8-4.4)       | 1.11 (0.74-1.64)        |          |
| Third quartile  | 9.9 (8-12.2)        | 0.82 (0.55-1.22)        |          | 9.7 (7.8-11.8)      | 0.95 (0.64-1.41)        |          | 8.4 (6.7-10.5)      | 1.23 (0.84-1.82)        |          |
| Fourth quartile                                       | 27.0 (19.8-41.1)    | 0.80 (0.56-1.16)        |          | 24.7 (18.4-37.0)    | 1.07 (0.74-1.56)        |          | 24.2 (17.5-37.7)    | 1.23 (0.83-1.83)        |          |
| Pressure over threshold + threshold pressure (mmHg)*  |                     |                         |          |                     |                         |          |                     |                         |          |
| First quartile  | 165.5 (164.5-166.6) | 0.95 (0.63-1.42)        | 1.0      | 120.7 (120.0-121.5) | 0.90 (0.61-1.33)        | 1.0      | 96.5 (96.0-97.3)    | 1.04 (0.71-1.53)        | 1.0      |
| Second quartile                                       | 170 (168.8-171.0)   | 0.68 (0.45-1.04)        |          | 123.8 (123.0-124.6) | 1.06 (0.72-1.55)        |          | 99.5 (98.7-100.2)   | 1.12 (0.75-1.67)        |          |
| Third quartile  | 174.8 (173.5-176.4) | 0.77 (0.52-1.16)        |          | 127.2 (126.3-128.3) | 1.10 (0.75-1.61)        |          | 102.6 (101.7-103.6) | 0.96 (0.63-1.45)        |          |
| Fourth quartile                                       | 183.2 (180.3-187.9) | 1.02 (0.71-1.46)        |          | 133.4 (131.1-137.0) | 1.09 (0.75-1.58)        |          | 108.5 (106.3-112.7) | 1.39 (0.96-1.99)        |          |

\* Thresholds were established in relationship to the population mean ± 2 SDs of the mean. † The Bonferroni method was used to adjust for the 18 multiple comparisons, and bolded adjusted P values are less than or equal to 0.05. IQR = interquartile range; OR = odds ratio.



**Fig. 3.** Forest plots depicting odds ratios and 95% CI for the association between population-based blood pressure (BP) thresholds for hypotension and 30-day operative mortality.



**Fig. 4.** Forest plots depicting odds ratios and 95% CI for the association between population-based blood pressure (BP) thresholds for hypertension and 30-day operative mortality.

baseline blood pressure, a significant association between mortality and relative reduction from baseline was only seen for MAP decreases of more than 50% for more than or equal to 5 min (table 5). Each of the first two methods arrived at similar magnitudes and duration of hypotension associated

with increased mortality (SBP < 67 to 70 mmHg for >5 to 8 min, MAP < 49 mmHg for 4 to 5 min, and DBP < 30 to 33 mmHg for >4 to 5 min). None of the three methods showed a significant association between hypertension and operative mortality. We believe the third method (percent change from



**Table 4.** Patient Counts, 30-day Mortality Rates, and Adjusted Odds Ratios for Absolute Thresholds (n = 18,756)

| Threshold                           | Unadjusted     |           | Risk Adjusted*               |                   |
|-------------------------------------|----------------|-----------|------------------------------|-------------------|
|                                     | Total Patients | Death (%) | OR (95% CI)                  | P Value           |
| <b>Systolic absolute threshold</b>  |                |           |                              |                   |
| Reference (90–159 mmHg)             | 2,728          | 25 (0.92) |                              | <b>&lt;0.0001</b> |
| SBP 80–89 mmHg for 2–4.9 min        | 1,936          | 37 (1.91) | 1.092 (0.632–1.888)          |                   |
| SBP 80–89 mmHg for >5 min           | 3,718          | 57 (1.53) | 1.063 (0.640–1.764)          |                   |
| SBP 70–79 mmHg for 2–4.9 min        | 2,361          | 41 (1.74) | 0.889 (0.518–1.524)          |                   |
| SBP 70–79 mmHg for >5 min           | 1,954          | 31 (1.59) | 0.953 (0.539–1.682)          |                   |
| SBP < 70 mmHg for 2–4.9 min         | 1,553          | 39 (2.51) | 1.377 (0.795–2.385)          |                   |
| SBP < 70 mmHg for >5 min            | 961            | 57 (5.93) | <b>2.898 (1.719–4.886)</b>   |                   |
| Reference (90–159 mmHg)             | 2,728          | 25 (0.92) |                              | 1.0               |
| SBP 160–169 mmHg for 2–4.9 min      | 1,607          | 32 (1.99) | 1.277 (0.726–2.247)          |                   |
| SBP 160–169 mmHg for >5 min         | 1,048          | 18 (1.72) | 0.984 (0.513–1.887)          |                   |
| SBP 170–179 mmHg for 2–4.9 min      | 1,490          | 16 (1.07) | 0.560 (0.287–1.094)          |                   |
| SBP 170–179 mmHg for >5 min         | 745            | 14 (1.88) | 0.816 (0.405–1.643)          |                   |
| SBP > 180 mmHg for 2–4.9 min        | 2,245          | 43 (1.92) | 0.988 (0.578–1.690)          |                   |
| SBP > 180 mmHg for >5 min           | 2,919          | 63 (2.16) | 0.904 (0.545–1.500)          |                   |
| <b>Mean absolute threshold</b>      |                |           |                              |                   |
| Reference (60–109 mmHg)             | 2,906          | 48 (1.65) |                              | <b>&lt;0.0001</b> |
| MAP 50–59 mmHg for 2–4.9 min        | 2,136          | 51 (2.39) | 1.093 (0.704–1.697)          |                   |
| MAP 50–59 mmHg for >5 min           | 2,239          | 54 (2.41) | 1.083 (0.698–1.681)          |                   |
| MAP 40–49 mmHg for 2–4.9 min        | 730            | 19 (2.60) | 1.232 (0.677–2.242)          |                   |
| MAP 40–49 mmHg for >5 min           | 352            | 17 (4.83) | <b>2.433 (1.285–4.608)</b>   |                   |
| MAP < 40 mmHg for 2–4.9 min         | 102            | 7 (6.86)  | 2.415 (0.965–6.047)          |                   |
| MAP < 40 mmHg for >5 min            | 39             | 14 (35.9) | <b>20.826 (8.884–48.822)</b> |                   |
| Reference (60–109 mmHg)             | 2,906          | 48 (1.65) |                              | 1.0               |
| MAP 110–119 mmHg for 2–4.9 min      | 1,738          | 30 (1.73) | 0.807 (0.490–1.328)          |                   |
| MAP 110–119 mmHg for >5 min         | 2,347          | 27 (1.15) | 0.685 (0.414–1.135)          |                   |
| MAP 120–129 mmHg for 2–4.9 min      | 2,095          | 36 (1.72) | 0.913 (0.569–1.465)          |                   |
| MAP 120–129 mmHg for >5 min         | 1,770          | 20 (1.13) | 0.577 (0.331–1.003)          |                   |
| MAP > 130 mmHg for 2–4.9 min        | 2,782          | 47 (1.69) | 0.900 (0.580–1.397)          |                   |
| MAP > 130 mmHg for >5 min           | 3,333          | 60 (1.80) | 0.947 (0.624–1.435)          |                   |
| <b>Diastolic absolute threshold</b> |                |           |                              |                   |
| Reference (50–99 mmHg)              | 3,171          | 39 (1.23) |                              | <b>&lt;0.001</b>  |
| DBP 40–49 mmHg for 2–4.9 min        | 1,883          | 29 (1.54) | 1.120 (0.670–1.871)          |                   |
| DBP 40–49 mmHg for >5 min           | 4,677          | 74 (1.58) | 0.960 (0.631–1.461)          |                   |
| DBP 30–39 mmHg for 2–4.9 min        | 1,831          | 51 (2.79) | 1.571 (0.991–2.491)          |                   |
| DBP 30–39 mmHg for >5 min           | 2,188          | 59 (2.70) | 1.391 (0.890–2.172)          |                   |
| DBP < 30 mmHg for 2–4.9 min         | 755            | 21 (2.78) | 1.645 (0.918–2.948)          |                   |
| DBP < 30 mmHg for >5 min            | 508            | 28 (5.51) | <b>3.181 (1.826–5.540)</b>   |                   |
| Reference (50–99 mmHg)              | 3,171          | 39 (1.23) |                              | 1.0               |
| DBP 100–109 mmHg for 2–4.9 min      | 1,952          | 32 (1.64) | 1.269 (0.761–2.118)          |                   |
| DBP 100–109 mmHg for > 5 min        | 1,401          | 16 (1.14) | 0.681 (0.359–1.292)          |                   |
| DBP 110–119 mmHg for 2–4.9 min      | 1,459          | 22 (1.51) | 1.166 (0.659–2.063)          |                   |
| DBP 110–119 mmHg for >5 min         | 630            | 6 (0.95)  | 0.788 (0.319–1.949)          |                   |
| DBP > 120 mmHg for 2–4.9 min        | 1,431          | 23 (1.61) | 1.075 (0.611–1.889)          |                   |
| DBP > 120 mmHg for >5 min           | 729            | 16 (2.19) | 1.357 (0.714–2.580)          |                   |

\* The Bonferroni method was used to adjust for the six multiple comparisons, and bolded adjusted P values are less than or equal to 0.05. DBP = diastolic blood pressure; MAP = mean blood pressure; OR = odds ratio; SBP = systolic blood pressure.

baseline) is flawed because almost a third of procedures had no baseline or only a single blood pressure recorded in the AIMS data, and patients with baseline blood pressure measurements

tended to have fewer preoperative risk factors and were more likely to be having elective surgery compared with those without baseline blood pressure measurements.

**Table 5.** Patient Counts, 30-day Mortality Rates, and Adjusted Odds Ratios for Percent Change from Baseline Thresholds (n = 12,675)

| Threshold                               | Unadjusted     |           | Risk Adjusted*             |         |
|---|----------------|-----------|----------------------------|---------|
|   | Total Patients | Death (%) | OR (95% CI)                | P Value |
| <b>Percent change from baseline SBP</b> |                |           |                            |         |
| Reference (≤ 29%)                       | 2,288          | 23 (1.01) |                            |         |
| SBP decrease 30%–39% for 2–4.9 min      | 1,017          | 13 (1.28) | 0.783 (0.379–1.618)        |         |
| SBP decrease 30%–39% for >5 min         | 2,665          | 25 (0.94) | 0.568 (0.310–1.039)        |         |
| SBP decrease 40%–49% for 2–4.9 min      | 1,276          | 16 (1.25) | 0.619 (0.311–1.231)        | 0.16    |
| SBP decrease 40%–49% for >5 min         | 2,124          | 33 (1.55) | 0.786 (0.439–1.405)        |         |
| SBP decrease ≥50% for 2–4.9 min         | 896            | 24 (2.68) | 1.306 (0.701–2.436)        |         |
| SBP decrease ≥50% for >5 min            | 1,075          | 28 (2.60) | 1.338 (0.738–2.423)        |         |
| Reference (≤ 29%)                       | 2,288          | 23 (1.01) |                            |         |
| SBP increase 30%–39% for 2–4.9 min      | 981            | 25 (2.55) | 1.428 (0.757–2.693)        |         |
| SBP increase 30%–39% for > 5 min        | 489            | 5 (1.02)  | 0.581 (0.208–1.619)        |         |
| SBP increase 40%–49% for 2–4.9 min      | 623            | 7 (1.12)  | 0.560 (0.224–1.400)        | 1.0     |
| SBP increase 40%–49% for >5 min         | 274            | 4 (1.46)  | 0.769 (0.242–2.438)        |         |
| SBP increase ≥50% for 2–4.9 min         | 646            | 19 (2.94) | 1.530 (0.764–3.063)        |         |
| SBP increase ≥50% for >5 min            | 542            | 18 (3.32) | 1.307 (0.651–2.622)        |         |
| <b>Percent change from baseline MBP</b> |                |           |                            |         |
| Reference (<29%)                        | 2,697          | 27 (1.00) |                            |         |
| MBP decrease 30–39% for 2–4.9 min       | 1,088          | 17 (1.56) | 1.059 (0.551–2.035)        |         |
| MBP decrease 30–39% for >5 min          | 2,928          | 30 (1.02) | 0.688 (0.394–1.204)        |         |
| MBP decrease 40–49% for 2–4.9 min       | 1,266          | 21 (1.66) | 1.240 (0.671–2.293)        | 0.005   |
| MBP decrease 40–49% for >5 min          | 1,924          | 28 (1.46) | 0.999 (0.564–1.770)        |         |
| MBP decrease >50% for 2–4.9 min         | 627            | 15 (2.39) | 1.421 (0.707–2.856)        |         |
| MBP decrease >50% for >5 min            | 656            | 25 (3.81) | <b>2.721 (1.489–4.974)</b> |         |
| Reference (<29%)                        | 2,697          | 27 (1.00) |                            |         |
| MBP increase 30–39% for 2–4.9 min       | 1,013          | 17 (1.68) | 1.423 (0.724–2.796)        |         |
| MBP increase 30–39% for >5 min          | 511            | 8 (1.57)  | 1.179 (0.496–2.803)        |         |
| MBP increase 40–49% for 2–4.9 min       | 596            | 11 (1.85) | 1.492 (0.683–3.260)        | 0.97    |
| MBP increase 40–49% for >5 min          | 248            | 3 (1.21)  | 0.888 (0.246–3.199)        |         |
| MBP increase >50% for 2–4.9 min         | 587            | 13 (2.21) | 1.653 (0.783–3.492)        |         |
| MBP increase >50% for >5 min            | 385            | 15 (3.90) | 2.800 (1.376–5.694)        |         |
| <b>Percent change from baseline DBP</b> |                |           |                            |         |
| Reference (<29%)                        | 1,520          | 13 (0.86) |                            |         |
| DBP decrease 30–39% for 2–4.9 min       | 953            | 7 (0.73)  | 0.648 (0.248–1.688)        |         |
| DBP decrease 30–39% for >5 min          | 2,335          | 22 (0.94) | 0.987 (0.477–2.039)        |         |
| DBP decrease 40–49% for 2–4.9 min       | 1,239          | 23 (1.86) | 1.560 (0.754–3.226)        | 0.06    |
| DBP decrease 40–49% for >5 min          | 1,931          | 31 (1.61) | 1.578 (0.790–3.150)        |         |
| DBP decrease >50% for 2–4.9 min         | 1,266          | 22 (1.74) | 1.630 (0.782–3.397)        |         |
| DBP decrease >50% for >5 min            | 1,728          | 43 (2.49) | 2.359 (1.204–4.625)        |         |
| Reference (<29%)                        | 1,520          | 13 (0.86) |                            |         |
| DBP increase 30–39% for 2–4.9 min       | 1,159          | 17 (1.47) | 1.464 (0.674–3.182)        |         |
| DBP increase 30–39% for >5 min          | 547            | 6 (1.10)  | 0.965 (0.345–2.700)        |         |
| DBP increase 40–49% for 2–4.9 min       | 795            | 9 (1.13)  | 1.216 (0.494–2.988)        | 1.0     |
| DBP increase 40–49% for >5 min          | 307            | 5 (1.63)  | 1.287 (0.418–3.960)        |         |
| DBP increase >50% for 2–4.9 min         | 1,111          | 24 (2.16) | 2.227 (1.069–4.639)        |         |
| DBP increase >50% for >5 min            | 879            | 21 (2.39) | 1.975 (0.934–4.174)        |         |

\* The Bonferroni method was used to adjust for the six multiple comparisons, and bolded adjusted P values are less than or equal to 0.05. DBP = diastolic blood pressure; MBP = mean blood pressure; OR = odds ratio; SBP = systolic blood pressure.

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### Comparison with Previous Studies

Anesthesia providers have long assumed that a smooth intraoperative course with minimal blood pressure aberrations is associated with better postoperative outcomes.<sup>26</sup> However, there is limited and conflicting evidence to support this assumption. In 1978, Goldman *et al.*<sup>2</sup> reported in a multivariable analysis that a more than 33% decrease from baseline for more than 10 min in intraoperative SBP was associated with postoperative cardiac death. In 1990, Charlson *et al.*<sup>3</sup> reported that prolonged increases or decreases in intraoperative MAP > 20 mmHg resulted in an increase in serious postoperative complications. Bijker *et al.*<sup>22</sup> found no association between intraoperative hypotension and risk-adjusted 1-yr mortality after general or vascular surgery in 1,705 adults. Monk *et al.*<sup>5</sup> reported a statistically significant association between duration of SBP < 80 mmHg and 1-yr risk-adjusted mortality in 1,064 patients undergoing major noncardiac surgery. In the largest (33,330 noncardiac surgeries) and most recently published study, Walsh *et al.*<sup>7</sup> reported that patients with a MAP < 55 mmHg for 1 to 5, 6 to 10, 11 to 20, and more than 20 min had graded increases in their risk for acute kidney injury or myocardial injury.

### Strengths

**Population-based Thresholds.** In a systematic literature review, Bijker *et al.*<sup>9</sup> identified 140 different definitions of intraoperative hypotension. This plethora of definitions led us to the concept that intraoperative blood pressure thresholds should be population based and that definitions of intraoperative hypotension and hypertension should be based on the association of deviations from these thresholds. We defined the thresholds for hypotension and hypertension as 2 SDs below and above the population mean, respectively. We hypothesized that the adverse effects from both hypotension and hypertension were likely due to both the magnitude of the deviations from these thresholds and the duration of these deviations. One way to capture both magnitude and duration is the area between the threshold and the pressure curve, which has units of mmHg × minutes. We also assumed that any adverse effect of these deviations is additive if the patient has more than one deviation (as is common) during the operation; thus, we summed these areas. Finally, we assumed that hypotension and hypertension were likely to have different effects on operative mortality as their pathophysiologic effects are very different; therefore, we tested separate hypotheses for hypotension and hypertension.

**Similar Results with Two Analytic Techniques.** The estimation of the magnitude and duration of hypotension significantly associated with increased 30-day mortality was virtually identical between population-based thresholds and the absolute thresholds. However, the results based on the blood pressure thresholds relative to each patient's baseline blood pressure seem to be much less sensitive in detecting an association with mortality. There are several factors that might explain this difference between the techniques: (1) approximately 31% of the patients did not have a baseline blood pressure measurement in the

AIMS data and were not included in this analysis; (2) patients with baseline blood pressure measurements differed from those without in ways that suggest lower risk (*e.g.*, fewer preoperative risk factors and greater likelihood of having elective surgery compared with those without baseline blood pressures); and (3) preoperative anxiety may have resulted in higher baseline blood pressures. This phenomenon of “white coat” hypertension has been well studied in ambulatory care and is usually felt to be benign.<sup>27</sup> Regardless, we did not find a statistically significant risk-adjusted increase in mortality with intraoperative hypertension with any of our three analytic methods. Despite these limitations, we included the percent change from baseline technique because a decrease in SBP of more than 20 to 30% below baseline is one of the most frequently used definitions of intraoperative hypotension in the literature.<sup>9</sup> Bijker *et al.*<sup>9</sup> reviewed 111 definitions of intraoperative hypotension and found that only 50% of the manuscripts actually defined the baseline blood pressure, and in those that did, baseline blood pressure was most frequently based on the blood pressure measurements taken immediately before the induction of anesthesia. A previous publication also stated that a prolonged intraoperative change of 20% from preoperative blood pressure levels was significantly related to complications.<sup>3</sup> In our analysis, we also defined the baseline blood pressure as the mean blood pressures in the operating room immediately before the appearance of end-tidal carbon dioxide. The lack of agreement of this technique with the population-based and absolute threshold technique suggests that the percent change from baseline technique is flawed, most likely because it is extremely difficult to define valid, reproducible baseline blood pressure, especially if it is based on blood pressures obtained in the operating room.

**Large Sample Size.** Our sample size of 18,756 is one of the largest we have identified in the literature, exceeded only by the study by Walsh *et al.*,<sup>7</sup> which studied 33,330 noncardiac surgeries at the Cleveland Clinic. They reported a significantly increased risk of 30-day mortality with a MAP < 55 mmHg for more than 20 min, which differs only modestly with our finding of an increased risk for MAP ≤ 49 mmHg for more than 5 min.<sup>7</sup>

**Risk-adjusted Outcomes.** By using the risk factors in the VASQIP database, the c-index for predicting 30-day postoperative mortality in our model was 0.91. We found that the addition of blood pressure variables or intraoperative sepsis and erythrocyte transfusion to this robust risk model did not appreciably change the c-index, suggesting that preoperative comorbidity, not intraoperative anesthesia management, is the major predictor of mortality after noncardiac surgery.

### Limitations

First and most importantly, this is an observational study and therefore can only address association and not causality. Despite our risk adjustment model based on more than 20 yr experience with risk-adjusting surgical outcomes in the VASQIP program, the probability of bias (*i.e.*, that the larger proportion of patients dying within 30 days in the more severely hypotensive

groups were at a greater risk to begin with because of unmeasured variables) remains, as in all observational studies. Hypotension may be a marker of other direct causes of death (*i.e.*, hemorrhage, sepsis, frailty), and it is unknown whether interventions to improve or maintain blood pressure would improve outcome. Although the usual response to this uncertainty is to conduct a randomized trial, we agree with the statement by Freundlich and Kheterpal,<sup>28</sup> “it is ethically – and morally – not feasible to randomly assign patients to a potentially detrimental intervention that deviates from accepted standards of care.” We acknowledge that randomized trials of deliberate hypotensive anesthesia have been conducted in the past, but these patient populations were generally healthy.<sup>29,30</sup> Currently, it would likely be impossible to obtain IRB approval for such trials.

A second limitation is the nonrepresentative nature of the patients in this analysis who received their surgery in VA hospitals. Patients who use the VA health services tend to be predominately male, older, less well educated, sicker, and of lower socioeconomic status than the overall U.S. population as a whole.<sup>31</sup> Therefore, it is possible that these differences between VA and U.S. populations limit the generalizability of our findings to non-VA populations.

Another limitation is that the data for this study were collected between 2001 and 2008, and anesthesia practice has changed since 2001. To adjust the analysis for secular trends in practices, the year of surgery was included in the model, but the results were not changed. The c-index for predicting 30-day mortality using only VASQIP preoperative patient characteristics was already high at 0.908, and the addition of additional variables such as year of surgery or intraoperative blood pressure variables did not appreciably change the predictive power of the model. This finding is in agreement with previous studies demonstrating that the patient’s preoperative comorbidities are the most important determinants of intermediate- and long-term mortality.<sup>5,32</sup>

### Clinical Implications

When our results are combined with the findings of Walsh *et al.*<sup>7</sup> we believe that there is strong evidence that intraoperative hypotension, namely SBP < 70 mmHg, MAP < 50 mmHg, and DBP < 30 mmHg, is associated with excess operative morbidity and mortality. The only evidence-based guideline, from the American Society of Anesthesiologists, for the management of intraoperative blood pressure states that blood pressure should be measured intraoperatively at least at 5-min intervals. Clearly, additional guidelines should be developed, but first, confirmatory data from a third observational study with a population of 50,000 to 100,000 operations are needed. Fortunately, a study of this size may soon be feasible with electronic information management of AIMS datasets and risk and outcome datasets, such as VASQIP.

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### Competing Interests

The authors declare no competing interests.

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