ANESTHESIOLOGY

# Incidence, Severity, and Detection of Blood Pressure Perturbations after Abdominal Surgery

## A Prospective Blinded Observational Study

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## ABSTRACT

**Background:** Intraoperative and postoperative hypotension are associated with myocardial and kidney injury and 30-day mortality. Intraoperative blood pressure is measured frequently, but blood pressure on surgical wards is usually measured only every 4 to 6 h, leaving long intervals during which hypotension and hypertension may be undetected. This study evaluated the incidence and severity of postoperative hypotension and hypertension in adults recovering from abdominal surgery and the extent to which serious perturbations were missed by routine vital-sign assessments.

**Methods:** Blood pressure was recorded at 1-min intervals during the initial 48 h in adults recovering from abdominal surgery using a continuous noninvasive monitor. Caregivers were blinded to these measurements and depended on routine vital-sign assessments. Hypotension and hypertension were characterized as time under and above various mean arterial pressure thresholds.

**Results:** Of 502 available patients, 312 patients with high-quality records were analyzed, with a median measurement time of 48 [interquartile range: 41, 48] postoperative hours. Nearly a quarter experienced an episode of mean arterial pressure of less than 70 mm Hg lasting at least 30 min (24%; 95% CI, 20%, 29%), and 18% had an episode of mean arterial pressure of less than 65 mm Hg lasting at least 15 min. Nearly half the patients who had mean arterial pressure of less than 65 mm Hg for at least 15 min (47%; 95% CI, 34%, 61%) were undetected by routine vital-sign assessments. Episodes of mean arterial pressure greater than 110 mm Hg lasting at least 30 min were observed in 42% (95% CI, 37%, 48%) of patients; 7% had mean arterial pressure greater than 130 mm Hg for at least 30 min, 96% of which were missed by routine assessments. Episodes of mean arterial pressure less than 65 mm Hg and mean arterial pressure greater than 110 mm Hg captured by routine vital-sign assessments but not by continuous monitoring occurred in 34 and 8 patients, respectively.

**Conclusions:** Postoperative hypotension and hypertension were common, prolonged, profound, and largely undetected by routine vital-sign assessments in a cohort of adults recovering from abdominal surgery. Frequent or continuous blood pressure monitoring may detect hemodynamic perturbations more effectively and potentially facilitate treatment.

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## EDITOR'S PERSPECTIVE

### What We Already Know about This Topic

- Intraoperative and postoperative hypotension are associated with myocardial and kidney injury and 30-day mortality
- Intraoperative blood pressure is measured frequently, but blood pressure on surgical wards is usually measured only every 4 to 6 h

### What This Article Tells Us That Is New

- In adults recovering from abdominal surgery, continuous blood pressure recording with a noninvasive monitor revealed that both hypotension and hypertension were common, prolonged, and profound
- Many of these events were not detected by the routine intermittent vital-sign assessments at 4-h intervals

Preventable intraoperative mortality is now rare, but cardiac and respiratory complications are common on surgical wards and are largely unpredictable.[1–3] Postoperative mortality also remains common, at about 2% among inpatients at least 45 yr of age.[4,5] Myocardial injury is the leading cause of attributable death during the initial 30 postoperative days, with 94% of injury occurring during the initial 2 postoperative days.[4,5] Intraoperative, ward, and critical care unit hypotension is strongly associated with myocardial injury, acute kidney injury, stroke, and mortality.[1,6–9] Similarly, postoperative hypertension is common and associated with increased risk of bleeding, myocardial injury, and stroke.[10–14]

Intraoperative blood pressure is usually measured continuously or at 1- to 5-min intervals and typically managed aggressively. In contrast, there are no accepted standards for patient monitoring on surgical wards and only limited evidence to support any particular monitoring approach.[15] Consequently, vital signs on surgical wards are usually obtained at 4- to 6-h intervals. With such long measurement intervals, there is considerable potential for delayed detection of hemodynamic perturbations, and consequently, long periods during which blood pressures might be suboptimal. Delayed detection of hemodynamic perturbations may preclude timely escalations of care and institution of critical interventions.[16–18]

There is surprisingly little information about how common hemodynamic perturbations are on surgical wards.[19]

Monitoring advances have made it technically practical to continuously record vital signs including blood pressure in ambulatory ward patients. However, the few previous studies using continuous blood pressure measurements did not blind clinicians to the results[19]; the distinction is important because unblinded measurements presumably provoke interventions that preclude an objective evaluation of incidence and severity. The extent to which continuous blood pressure monitoring enhances intermittent vital sign evaluations therefore remains essentially unknown.

We therefore primarily descriptively evaluated the incidence and severity of hypotension below mean arterial pressure (MAP) thresholds ranging from 80 to 50 mm Hg during the initial 48 postoperative hours in adults recovering from elective abdominal surgery. We similarly evaluated the incidence and severity of hypertension exceeding MAP thresholds ranging from 110 to 140 mm Hg. We evaluated whether noninvasive continuous blood pressure monitoring detects more postoperative hypotension, defined by MAP thresholds less than 65 mm Hg and less than 70 mm Hg, and more hypertension, defined as MAP more than 110 mm Hg and MAP more than 130 mm Hg, than routine vital-sign assessments, usually at 4-h intervals.

## Materials and Methods

We included patients 18 yr of age or older who had abdominal surgery between February 2015 and December 2017 scheduled to last at least 2 h with general anesthesia who participated in one of two ongoing clinical trials. Both underlying trials (ClinicalTrials.gov numbers NCT02156154 and NCT02996227) were approved by the Cleveland Clinic Institutional Review Board, and participating patients provided written informed consent. The first underlying trial is a randomized placebo-controlled double-blinded trial evaluating the effects of intravenous acetaminophen in adults having abdominal surgery. The second is a randomized trial comparing the effectiveness of bilateral transversus abdominis plane blocks with liposomal bupivacaine *versus* continuous epidural analgesia in the postoperative pain management of adults recovering from abdominal surgery.

Vital signs including blood pressure were continuously monitored from admission to the postanesthetic care unit until the first 48 h or discharge. The monitoring system was ViSi Mobile (Sotera Wireless, Inc., USA), which is approved by the U.S. Food and Drug Administration for continuous monitoring of vital signs. The system captures continuous electrocardiogram, continuous pulse-oximetry waveform, and intermittent noninvasive oscillometric blood pressure through standard arm-cuff measurements. These intermittent blood-pressure measurements are used to estimate continuous blood pressure, a process that mandates at least one oscillometric measurement per 24 h. As specified by the manufacturer, this is done by using the "pulse arrival time" technology with a 1 mm Hg resolution and an estimated mean error of at most 5 mm Hg (SD less than or equal to 8 mm Hg).[20]

ViSi Mobile blood pressures were obtained at 15-s intervals and averaged over four readings, with the resulting 1-min values being recorded. The continuous measurements were not available to the caregivers. Nurses therefore monitored vital signs conventionally, usually at 4-h intervals, but were free to monitor more often if clinically indicated. Per Cleveland Clinic's nursing practice, blood pressure measurements are performed on the arm using an appropriately selected cuff size. Calibration of the monitoring system was performed using the same cuff.

### Data Analysis

We excluded patients who had less than 12 h of continuous monitoring, who had monitoring gaps exceeding 4 h, or who had an overall unrecorded duration (cumulative duration of gaps in monitor records lasting at least 30 min) exceeding 30% of the total monitoring period. To assess the overall exposure to hypotension for each patient, we summarized the distribution of hypotensive minutes per monitored hour using incidence curves, defined by various MAP thresholds. Hypotensive minutes per hour under a given threshold were defined as: sum (minutes of MAP under threshold)/(total MAP reading hours – total gap), in which a gap was defined as more than 1 min between two consecutive measurements. That is, hypotensive minutes per hour were calculated as the minutes under a threshold from the total number of minutes in which readings were taken and available.

Second, we estimated the incidence of hypotensive episodes of varying duration under a range of MAP thresholds characterizing hypotension, along with 95% CI (exact binomial method). Gaps of less than 5 min were not included in the duration of a continuous episode (that is, only available data were included), with the episode calculation "stopped" for any gap of 5 min or more.

Hypotension recorded from the continuous monitor was compared with routine vital sign documentation over the periods of continuous blood pressure monitoring for each patient. The number of measurements made and the incidence of hypotension (MAP less than cutpoints ranging from 50 to 80 mm Hg) were calculated using nursing records as well as continuous monitoring data. We estimated the proportion of patients with hypotension identified by the continuous monitor that was missed by nurses with 95%

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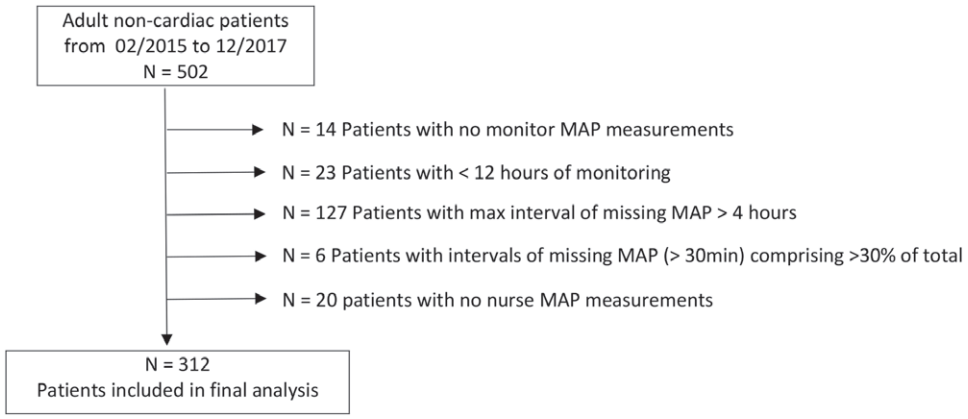


**Fig. 1.** Study diagram, showing enrollment, exclusions, and patients available for analysis. MAP, mean arterial pressure.

CI using the exact binomial method. For this comparison, hypotension was defined as at least one contiguous episode of MAP less than 65 mm Hg for at least 15 min and as MAP less than 70 mm Hg for at least 30 min. We then counted the number of patients who had hypotension according to the continuous monitor and estimated the proportion of these patients who were missed by nurses, with 95% CI. Among patients for whom no observed hypotension occurred according to the nursing records for a given threshold, we calculated the amount of hypotension detected by the monitor; specifically, the incidence of contiguous MAP less than 65 mm Hg lasting 15 min and less than 70 mm Hg lasting 30 min.

Similar methods were used to assess hypertension with various thresholds of MAP more than cutpoints ranging from 110 to 140 mm Hg. For comparison with nursing records, hypertension was defined as at least one contiguous episode of MAP over 110 or MAP more than 130 mm Hg lasting at least 30 min.

The statistical plan was developed and finalized before data analysis and was part of a full study protocol. Our primary aims were descriptive, and we used a convenience sample of all available patients, so we did not use formal agreement tests or conduct a sample size calculation. Descriptive data are presented as mean ± SD, n (%), or median [25th, 75th percentile]. All data analyses were performed using SAS 9.4 (SAS, USA).

## Results

Figure 1 shows the enrollment, exclusions, and patients available for analysis among 502 monitored patients. The most common exclusion was monitoring gaps exceeding 4 h. Most were due to patients disconnecting themselves, caregivers disconnecting patients for various clinical reasons such as physiotherapy sessions, or technical issues including electrodes or probe failures.

A total of 312 patients with adequate MAP data were included in our analysis. Demographic and morphometric characteristics, comorbidities, and surgical and anesthetic data are presented in table 1. The median (interquartile range [Q1, Q3]) number of hours of the continuous monitoring duration was 48 [41, 48] h. The median [Q1, Q3] number of observations per patient made by the nurses during the continuous monitoring study period was 13 [10, 16]. After removing gaps (any period of at least 2 min with no continuous monitoring), the median [Q1, Q3] continuous monitoring duration was 40 [32, 44] h.

Figure 2 displays samples of MAP-*versus*-time profiles for a randomly selected sample of 16 patients. They suggest that hypotensive episodes with MAP values between 75

**Table 1.** Summary of Baseline and Intraoperative Characteristics

| Factor | Total (N = 312) |
|---|---|
| Age, yr | 49 ± 15 |
| Male/female | 155 (50)/157 (50) |
| Race* | |
| White | 289 (93) |
| Black | 14 (4) |
| Hispanic | 2 (1) |
| Asian | 5 (2) |
| Other | 1 (0) |
| BMI, kg/m$^2$ | 27 ± 5 |
| ASA status | |
| I | 5 (2) |
| II | 135 (43) |
| III | 172 (55) |
| Cancer | 93 (30) |
| Surgical duration, h | 3.9 [2.5, 5.3] |

The data are presented as means ± SDs, medians [Q1, Q3], or N (%).

*n = 1 missing data point. ASA, American Society of Anesthesiologists; BMI, body mass index.

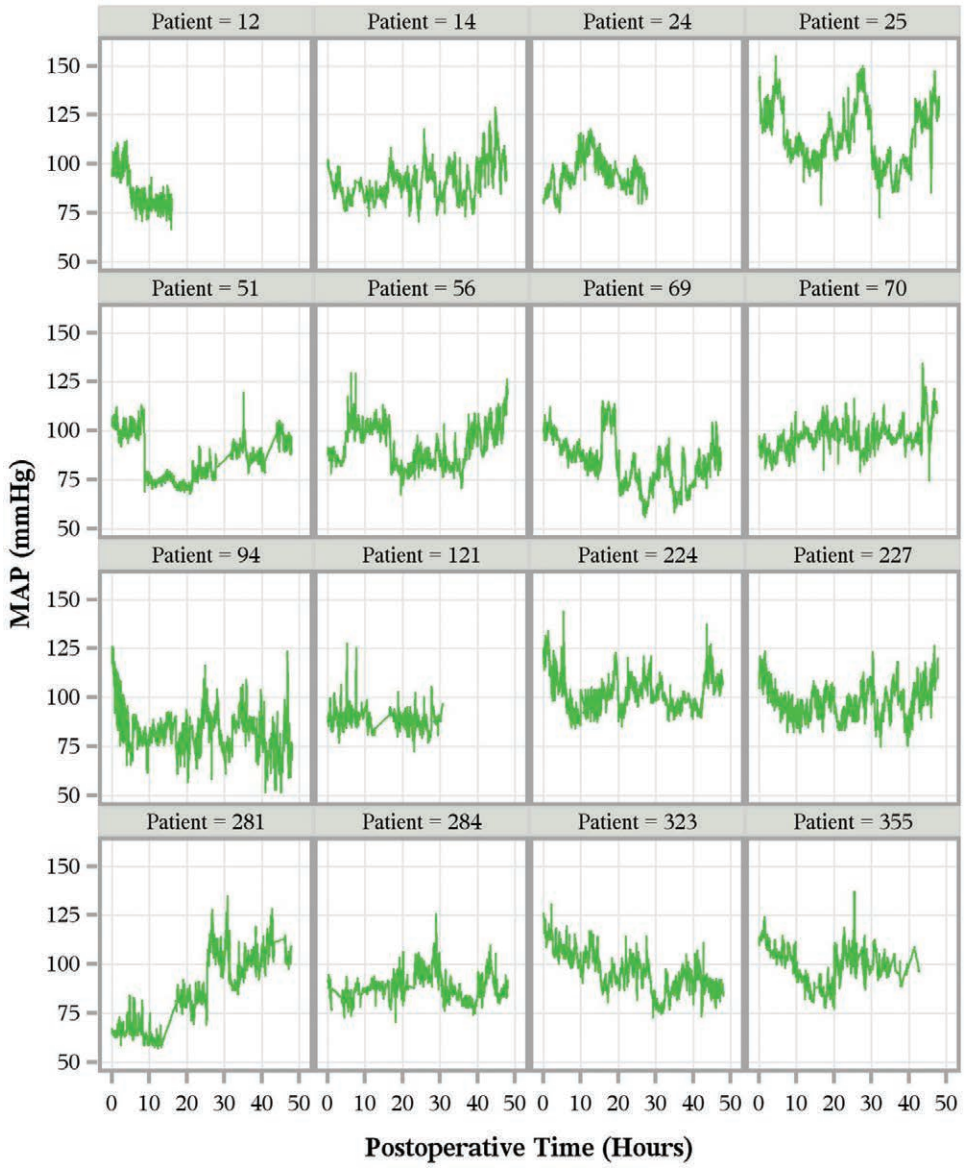


**Fig. 2.** Mean arterial pressure (MAP) over postoperative time in 16 randomly selected patients. Hypotensive episodes between 75 and 50 mm Hg and hypertensions (MAP more than 110 mm Hg) were common, and blood pressure varied considerably within patients over time.

and 50 mm Hg and hypertensive episodes with MAP more than 110 mm Hg are common and that blood pressure varies considerably within patients over time.

## Hypotension

Analysis of MAP profiles revealed that prolonged hypotensive episodes were common. The percentage of patients with given durations of hypotension per hour of monitoring is displayed in figure 3 for various hypotensive thresholds. For example, 20% (95% CI, 16%, 24%) of patients averaged at least 5 min per monitoring hour with MAP values less than 70 mm Hg, and 13% (10%, 17%) of patients averaged at least 10 min per monitoring hour below this threshold. Likewise, approximately 12% (9%, 16%) of patients averaged at least 5 min/h with MAP less than 65 mm Hg.

Similarly, figure 4 demonstrates the percentage of patients spending various contiguous times below various MAP thresholds. For example, 24% (20%, 29%) of patients had at least one episode of hypotension defined as MAP less than 70 mm Hg lasting 30 min or more, whereas 16% (13%, 21%) experienced one episode lasting 60 min or more below this threshold. Severely hypotensive episodes, defined as MAP

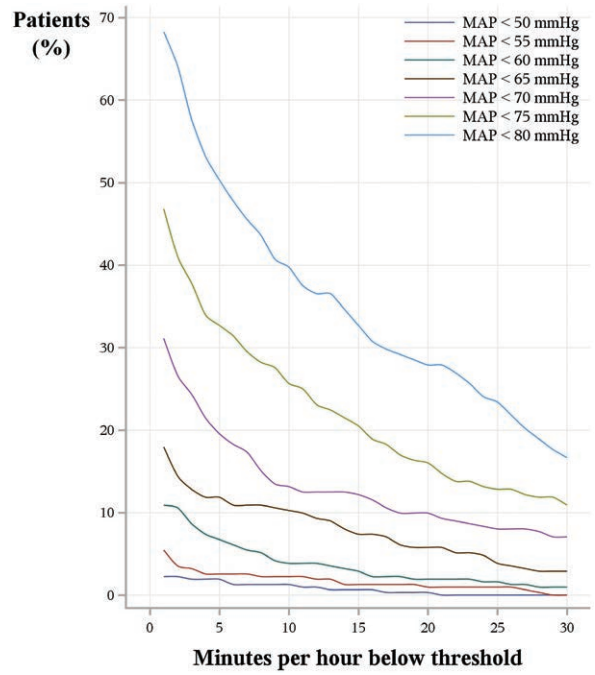


**Fig. 3.** Minutes per hour with mean arterial pressure (MAP) below various thresholds. For each patient, we computed the percentage of time observed with MAP readings below various thresholds. The percentage of patients with at least that many minutes below the threshold is plotted. For example, the *purple line* shows that about 20% of patients had at least 5 min/h of MAP less than 70 mm Hg.

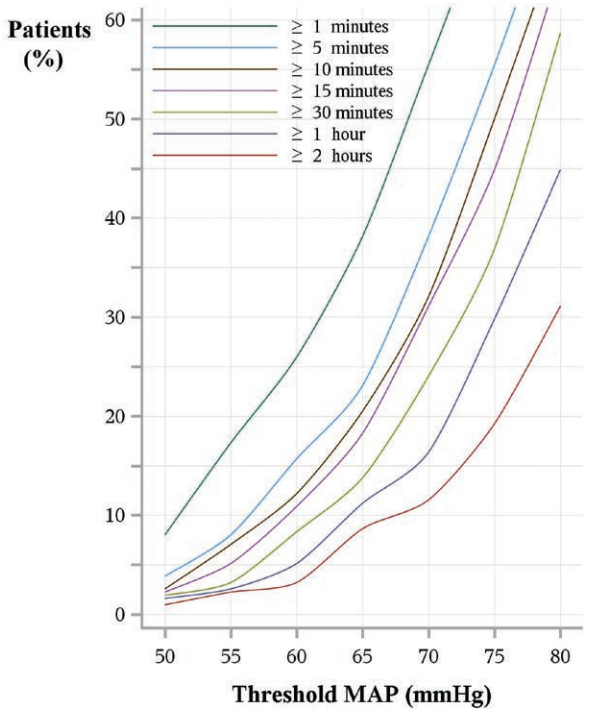


**Fig. 4.** Continuous hypotensive episodes of various durations under various thresholds. For each patient, we computed the total time of the observed longest continuous hypotensive episode (*i.e.*, no gap) with mean arterial pressure (MAP) readings below various thresholds. The percentage of patients with at least that many minutes below the threshold is plotted. For example, the *light green line* shows that 24% of patients had a continuous episode of MAP less than 70 mm Hg lasting at least 30 min.

less than 65 mm Hg for at least 30 min, were observed in 14% (10%, 18%) of patients.

Continuous blood pressure monitoring detected 57 of the 312 patients (18%) as having MAP less than 65 mm Hg for at least 15 continuous minutes. Among the 57 patients detected by continuous monitoring, 27 were missed by routine vital sign monitoring, with an estimated proportion of 47% (34%, 61%; table 2). Among the 248 patients without any nurse-recorded MAP values less than 65 mm Hg, the continuous monitor detected 27 patients (11%) who had at least 15 min of MAP less than 65 mm Hg and 17 (7%) who had an episode of MAP less than 65 mm Hg lasting at least 30 min. In addition, 34 patients were captured as having at least one MAP value less than 65 mm Hg by routine vital sign monitoring but not by the continuous monitor.

Continuous monitoring also detected 75 (24%) of 312 patients who had contiguous episodes lasting at least 30 min with MAP less than 70 mm Hg, of whom 21% (16 of 75; 95% CI, 13%, 32%) were missed by routine vital-sign assessments. Among the 181 patients without nurse-recorded MAP values less than 70 mm Hg, the continuous monitor detected 16 (9%) patients who had at least 30 contiguous minutes of MAP less than 70 mm Hg and 11 (6%) patients who had an episode of MAP less than 70 mm Hg lasting at least 60 min.

## Hypertension

Analysis of MAP profiles revealed that prolonged hypertensive episodes were also common. The percentage of patients with given durations of hypertension per hour is displayed in figure 5 for various thresholds. For example, 20% (95% CI, 16%, 25%) of patients averaged at least 15 min per monitoring hour with MAP values more than 110 mm Hg, and 10% (7%, 14%) of patients averaged at least 30 min/h above this threshold. Likewise, approximately 6% (4%, 10%) of patients averaged at least 5 min/h with MAP exceeding 130 mm Hg.

Similarly, figure 6 demonstrates the percentage of patients spending various contiguous times above various MAP thresholds. For example, 42% (95% CI 37%, 48%) of patients had one episode of hypertension defined as MAP more than 110 mm Hg lasting 30 min or more, whereas 20% (16%, 25%) experienced one episode lasting 2 h or more

**Table 2.** Hypotensive Patients Detected by Continuous Monitoring *versus* Routine 4-h Assessments (n = 312)

| MAP Threshold for Hypotension (mm Hg) | N, Detected by Continuous Monitoring, %* | Patients Missed by Routine Assessments among Those Detected by Continuous Monitoring | | N, Detected by Routine Vital-sign Assessments, %† |
|---|---|---|---|---|
| | | No. Missed by Routine Assessment/ No. Detected by Continuous Monitoring | Proportion (95% CI) | |
| < 50 | 7 (2%) | 6/7 | 86% (42, 100) | 4 (1%) |
| < 55 | 16 (5%) | 12/16 | 75% (48, 93) | 12 (4%) |
| < 60 | 34 (11%) | 18/34 | 53% (35, 70) | 26 (8%) |
| < 65 | 57 (18%) | 27/57 | 47% (34, 61) | 64 (21%) |
| < 70 | 97 (31%) | 26/97 | 27% (18, 37) | 131 (42%) |
| < 75 | 140 (45%) | 14/140 | 10% (6, 16) | 212 (68%) |
| < 80 | 204 (65%) | 6/204 | 2.9% (1.1, 6.3) | 258 (83%) |

*Continuous monitor detected at least one contiguous episode (without gap greater than or equal to 5 min) for at least 15 min below thresholds. †Defined by single measurements.

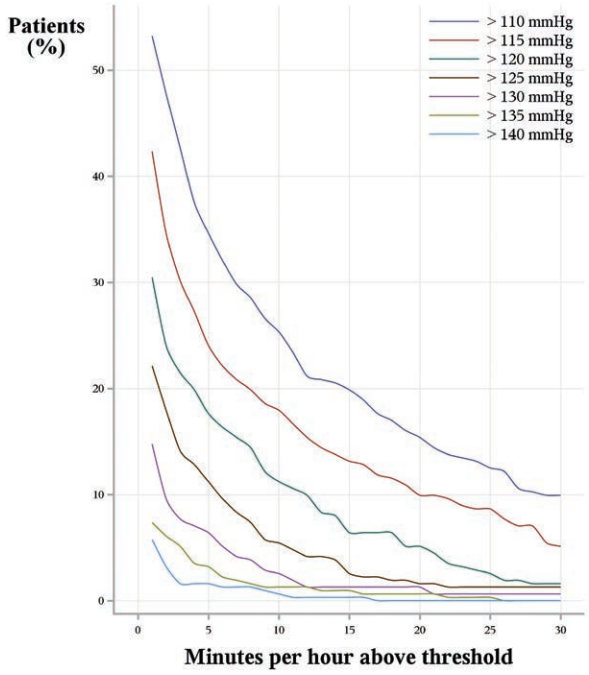


**Fig. 5.** Minutes per hour of mean arterial pressure (MAP) above various thresholds. For each patient, we computed the percentage of time observed with MAP readings above various thresholds. The percentage of patients with at least that many minutes above the threshold is plotted. For example, the *purple line* shows that about 7% of patients had at least 5 min/h of MAP more than 130 mm Hg.

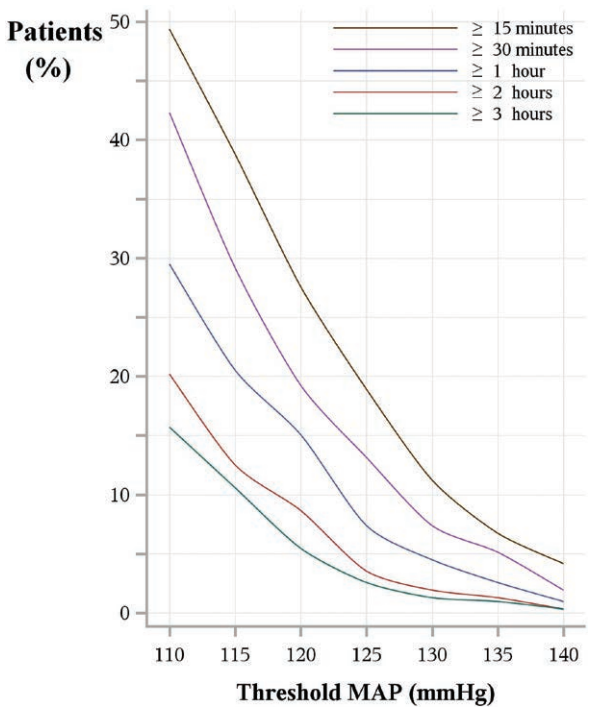


**Fig. 6.** Continuous hypertensive episodes of various durations above various thresholds. For each patient, we computed the total time of the observed longest continuous hypotensive episodes (*i.e.*, no gap) with mean arterial pressure (MAP) readings above various thresholds. The percentage of patients with at least that many minutes above the threshold is plotted. For example, the *purple line* shows that 42% of the patients had an episode of MAP more than 110 mm Hg lasting at least 30 min.

above this threshold. Approximately 4% (3%, 7%) of patients averaged at least 1 h with MAP more than 130 mm Hg.

Only 44 of 312 (14%) patients had MAP more than 110 mm Hg according to the nursing flow sheets. Continuous monitoring detected 132 of 312 patients (42%) who had MAP more than 110 mm Hg for at least

30 contiguous minutes. Among these 132 patients detected by continuous monitoring, 96 were missed by routine vital-sign assessments, with an estimated proportion of 73% (95% CI, 64%, 80%; table 3). Among the 268 patients without nurse-recorded MAP more than 110 mm Hg, the continuous monitor detected 96 (36%) patients who had an episode of MAP more than 110 mm Hg lasting at least 30 min, 60 (22%) who had an episode lasting at least 60 min, and 33 (12%) who had an episode lasting at least 120 min. Eight patients had at least a single MAP value more than 110 mm Hg captured by routine vital sign monitoring only but not by the continuous monitor.

Continuous monitoring detected 23 of 312 patients (7%) with MAP more than 130 mm Hg for at least 30 contiguous minutes. Routine vital-sign assessment identified MAP more than 130 mm Hg in only 2 of 312 patients (0.64%). Routine vital-sign assessments missed 96% (22 of 23; 95% CI, 78%, 100%) of the 23 patients detected by continuous monitoring. Among the 310 patients without nurse-recorded MAP more than 130 mm Hg, the continuous monitor detected 22 patients (7%) who had an episode of MAP more than 130 mm Hg lasting at least 30 min, 13 (4%) who had an episode lasting at least 60 min, and 5 (2%) who had an episode lasting at least 120 min.

## Discussion

Our study found that postoperative hypotension and hypertension were common, prolonged, and often severe. For example, 24% of patients experienced a hypotensive episode with MAP less than 70 mm Hg for at least 30 continuous minutes, and 18% spent at least 15 consecutive minutes with MAP less than 65 mm Hg. Similarly, more than 40% of the patients had MAP exceeding 110 mm Hg for at least 30 continuous minutes, and 7% had severe hypertension (MAP more than 130 mm Hg) for at least 30 min.

Postoperative hypotension and hypertension were not only common but also largely undetected because much of the "exposure" happened between routine vital-sign assessments. For example, among the 18% of patients who experienced an episode of MAP less than 65 mm Hg lasting at least 15 min, nearly half did not have even a single value less than 65 mm Hg at any time in their hospital records. Hypertensive events also went largely undetected by vital-sign assessments every 4 h. Among 23 patients (7%) who sustained at least 30 min of MAP exceeding 130 mm Hg, routine vital-sign assessments failed to detect even a single blood pressure exceeding 130 mm Hg at any time in all but one patient.

Postoperative hypotension is associated with myocardial injury and infarction, kidney damage, stroke, and mortality. Although there are many well-established risk factors for postoperative cardiovascular events, hypotension is among the few that are modifiable. Consistent with this theory, a recent trial demonstrated that tight control of blood pressure targeted to within 10% of patients' baseline systolic pressure during surgery and for several hours afterward significantly reduced the risk of postoperative organ dysfunction by 25%.[21]

We chose to define postoperative hypotension and hypertension by various absolute thresholds. Although using relative perturbations from baseline preoperative values seems more reasonable, the actual preoperative blood pressure is often not available, and measurements obtained on the morning of surgery might not adequately represent patients' baseline. Furthermore, a previous large analysis demonstrated that relative reduction from baseline and absolute thresholds had a similar ability to predict risk.[8]

General anesthesia reduces metabolic rate about 30%, which presumably reduces tissue perfusion requirements and possibly the blood pressure needed to prevent organ injury.[22] During surgery, mean arterial pressures less than

**Table 3.** Hypertensive Patients Detected by Continuous Monitoring *versus* Routine 4-h Assessments (n = 312)

| MAP Threshold for Hypertension (mm Hg) | Detected by Continuous Monitoring, N (%)* | Patients Missed by Routine Assessments among Those Detected by Continuous Monitoring | | Detected by Routine Vital-sign Assessments, N (%)† |
|---|---|---|---|---|
| | | No. Missed by Routine Assessment/ No. Detected by Continuous Monitoring | Proportion (95% CI) | |
| > 110 | 132 (42%) | 96/132 | 73% (64, 80) | 44 (14%) |
| > 115 | 91 (29%) | 72/91 | 79% (69, 87) | 23 (7%) |
| > 120 | 60 (19%) | 52/60 | 87% (75, 94) | 10 (3%) |
| > 125 | 41 (13%) | 40/41 | 98% (87, 100) | 2 (0.6%) |
| > 130 | 23 (7%) | 22/23 | 96% (78, 100) | 2 (0.6%) |
| > 135 | 16 (5%) | 16/16 | 100% (79, 100) | 1 (0.3%) |
| > 140 | 6 (2%) | 6/6 | 100% (54, 100) | 1 (0.3%) |

*Continuous monitor detected at least one contiguous episode (without gap greater than or equal to 5 min) for at least 30 min above thresholds. †Defined by single measurements.

65 mm Hg are associated with myocardial and kidney injury, and when MAP reaches 55 mm Hg, only a few minutes of exposure appears necessary.[8] However, the postoperative harm threshold is less obvious. Systolic pressures less than 90 mm Hg that require intervention are strongly associated with myocardial infarction during surgery, later on the day of surgery, and during the subsequent days of hospitalization.[9] Because the postoperative harm threshold remains unclear, we report various cutoff pressures. To avoid short-lived artifactual values, we required at least 15 continuous minutes of hypotension to qualify as an episode. Doing so, we only analyzed hypotensive episodes we believe were both real and clinically important.

The extent to which postoperative hypertension might be harmful is poorly established, largely based on relatively old studies of patients having cardiac or major vascular surgery, and usually limited to the first few postoperative hours.[14,23,24] A somewhat arbitrary definition of severe postoperative hypertension necessitating immediate intervention is consecutive blood pressure measurements with either systolic values greater than 190 mm Hg or diastolic values greater than 100 mm Hg. By this definition, postoperative hypertension is associated with myocardial ischemia, infarction, arrhythmias, congestive heart failure with resulting pulmonary edema, stroke, and bleeding.[10–14] In patients recovering from cardiac surgery, it is common to start antihypertensive treatment when MAP reaches 105 mm Hg.[11,13] We chose MAP values of 110 and 130 mm Hg as thresholds for hypertension and severe hypertension, and again to avoid short-lived artifacts, we required episodes to last at least 30 min. Again, these cutoffs and durations presumably reflect actual and clinically significant hypertensive episodes.

Hypotension is the most common trigger for repeated vital-sign assessments on medical and surgical wards.[25] There was often considerable delay between a trigger blood pressure and a confirmatory measurement. Other investigators have also identified hypotension as the most common postoperative event and the most common reason for transfer from wards to intensive care units.[26,27] Just as intermittent vital sign measurements missed much postoperative hypotension, they also fail to detect hypoxemic events.[3] To the extent that hypoxemia and hypotension are indeed clinically important, as seems likely, continuous monitoring of patients on the regular nursing floors may well improve patients' safety and outcomes.

The ViSi Mobile device is a validated and Food and Drug Administration–approved system intended for continuous monitoring of patients on hospital wards. The device is a small, relatively comfortable wearable battery-powered system. Blood pressure is continuously calculated using the "pulse arrival time" technology by using data captured by a pulse oximeter and electrocardiograph electrodes and is calibrated to actual cuff measurements at least once every 24 h. The continuous blood pressure feature is accurate within 5 mm Hg to radial intraarterial pressure measurements.[20] We calibrated the system to oscillometric pressure twice a day, using the patients' own cuff, as selected by the ward nurses according to patients' habitus, so that both measurement methods used the same cuff. Because we were interested in the natural history of ward blood pressure, we blinded clinicians to the continuous monitor output. Nurses were also blinded to alerts related to lead disconnections and battery exhaustion. It seems likely that data acquisition would have been more complete were technical alerts available to the ward nursing team.

We had usable continuous blood pressure records from only 62% of enrolled patients. If exclusions were purely technical and therefore random, they are of little consequence, but a potential bias is that the monitors may have been intentionally disconnected more often by patients who were either recovering better or had a more complicated postoperative course. We compared patients excluded from the analysis to those included on several characteristics and found no difference in mean age, comorbidities, and length of surgery or hospitalization. Excluded patients had a slightly higher American Society of Anesthesiologists physical score. If sicker patients were actually more often excluded because of inadequate data quality, we might have underestimated the population risk of hypotension and hypertension. We also note that the Cleveland Clinic Main Campus cares for high-risk patients; for example, more than half the included patients had an American Society of Anesthesiologists physical status score of 3. Presumably, healthier patients have fewer hemodynamic disturbances than we observed.

Another limitation is that we cannot refer to the continuous monitoring measurements as "gold standard." Some events were captured by the nursing records and not by the monitor (as evident by the difference between the number of cases captured by the monitor and missed by nurses and the total cases captured by nurses; table 2 and table 3), and we cannot guarantee that hypotension or hypertension were not real in these events. We are unable to assess whether the discrepancies are due to the monitor's erroneous reading (mainly caused by the lack of recent calibration to cuff-measured blood pressure) or due to incorrect spot-check measurements. To avoid short-lived artifacts, we limited the definition of events captured by the continuous monitor to those lasting at least 15 (hypotensive) or 30 (hypertensive) min. Because of the nature of spot-check measurements, we could not apply the same rules to the nursing blood pressure recordings, so we compared long-lasting events from the monitor to single measurement events by nurses, potentially explaining why some events were detected by the nurses but not by the ViSi Mobile. Indeed, in a *post hoc* analysis of these events, we found that in more than half of the hypotensive events captured by spot checks and not by the monitor, low MAP was actually recorded by the monitor in the same time but did not qualify for the necessary length.

In summary, continuous blood pressure monitoring in adults recovering from abdominal surgery with general

anesthesia showed that both hypotension and hypertension are common, prolonged, and profound. Many of these events were not detected by routine intermittent vital-sign assessments at 4-h intervals. Although it seems likely that moderating hemodynamic perturbations will improve outcome, large randomized trials are necessary to determine the extent to which risk can be reduced.

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## Competing Interests

Drs. Sessler and Maheshwari are consultants for Edwards Lifesciences, Irvine, California. Dr. Khanna is a consultant for Medtronic, Dublin, Ireland, and La Jolla Pharmaceuticals, San Diego, California. The other authors declare no competing interests.

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