Intraoperative Blood Pressure

What Patterns Identify Patients at Risk for Postoperative Complications?

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While monitoring blood pressure is a routine part of intraoperative management, several methods have been proposed to characterize intraoperative hemodynamic patterns as predictors of postoperative complications. In this prospective study of a high-risk population of hypertensive and diabetic patients undergoing elective noncardiac surgery, one objective was to compare different approaches to the assessment of intraoperative hemodynamic patterns to identify those patterns most likely to be associated with postoperative complications. Twenty-one per cent of the 254 patients sustained cardiac or renal complications after operation. Patients with more than 1 hour of ≥20-mmHg decreases in mean arterial pressure (MAP) or patients with less than 1 hour of ≥20-mmHg decreases and more than 15 minutes of ≥20-mmHg increases were at highest risk for postoperative complications. Together these two patterns had a 46% sensitivity rate and a 70% specificity rate in predicting postoperative complications. Using 20% change in intraoperative MAP produced results nearly identical to 20-mmHg changes. When the duration of 20-mmHg changes was accounted for, changes of a greater magnitude (*e.g.*, 40 mmHg) were not significant independent predictors of complications. The use of the mean difference from preoperative MAP was misleading because patients who experienced both high and low MAPs tended to have nearly normal mean MAPs, but high complication rates. The absolute magnitude of intraoperative MAPs, regardless of the preoperative levels, also was evaluated. The overall mean intraoperative MAP was not a significant predictor of complications. Specific intraoperative MAPs (*e.g.*, less than 70 mmHg and more than 120 mmHg) also were evaluated. While neither was a significant predictor, there was a trend for increased complications among patients whose MAPs decreased to less than 70 mmHg. Intraoperative blood pressure should be analyzed in relation to the patient's preoperative blood pressure. Prolonged changes of more than 20 mmHg or 20% in relation to preoperative levels were significantly related to complications.

FOR MANY YEARS, anesthesiologists have recorded blood pressure and pulse every 5 minutes during operations. While these recordings are reviewed routinely by internists and surgeons to determine if their patients experienced clinically important intraoperative changes in blood pressure, the criteria for assessing intraoperative blood pressure vary widely in clinical practice and research.

In previous studies we found that the duration of changes of ≥20 mmHg in intraoperative mean arterial pressure (MAP), as well as preoperative characteristics and other intraoperative events, were significant predictors of postoperative congestive heart failure (CHF), myocardial infarction and ischemia, and renal dysfunction.[1-3] In other studies, investigators have defined change as a 20% to 30% decrease or increase in systolic pressure for more than 10 minutes,[4-9] as a 20% increase or decrease in MAP,[10] or as a 20- to 50-mmHg decrease in blood pressure.[11-13] Others have evaluated the actual MAP[14] or determined whether the systolic pressure was greater than 180 to 200 mmHg or less than 80 to 90 mmHg, or the diastolic pressure was more than 110 mmHg.[4,7,15] Some have reported the rate–pressure product,[16,17] while others have argued that this product is misleading.[18,19]

From a practical perspective, the issue concerns the optimal method to assess intraoperative changes in MAP. Would it be preferable to examine the absolute, percentage, or mean change in MAP, the overall mean intraoperative pressure, or the absolute intraoperative pressures regardless of preoperative MAP? To address this question,

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the clinical significance of changes in intraoperative blood pressure and pulse must be judged by their sensitivity and specificity as predictors of postoperative complications. Therefore this paper considers all renal and cardiac complications as relevant outcome events. Different approaches to the assessment of changes in intraoperative blood pressure and pulse are compared to ≥20-mmHg differences in MAP and ≥20 beat-per-minute differences in pulse as predictors of postoperative cardiac and renal complications.

Methods

Assembly of Study Population

All patients who had essential hypertension (high blood pressure) or diabetes mellitus who were undergoing elective general surgery were eligible for enrollment. The criteria for hypertension were treatment with any medication explicitly used to reduce blood pressure, which included all patients aged less than 30 years (n = 171); or for patients aged 30 years or older, a systolic ≥160 mmHg or diastolic ≥95 mmHg (n = 30). None of the patients had mean preoperative diastolic pressures more than 110 mmHg. Patients with secondary hypertension (*i.e.*, adrenocortical, proved renovascular hypertension, and so on) were excluded. The criteria for diabetes were (1) treatment with insulin or oral hypoglycemic agents before admission (n = 92), including treatment started during preoperative evaluation; and (2) elevated fasting glucose levels (plasma ≥140 mg/dL; whole blood ≥120 mg/dL) on more than one occasion before operation (n = 16). Patients who developed hyperglycemia after operation without meeting either of these criteria were not classified as diabetic.

Between July 1982 and September 1985, 278 patients were enrolled. Patients undergoing any elective general surgery were eligible for enrollment, including intra-abdominal procedures, peripheral vascular or aneurysm surgery, or other operations such as amputation or hemorrhoidectomy. To record the number of patients who were eligible but not entered, the anesthesiologists prospectively documented which patients undergoing general surgery during the study interval had hypertension and diabetes; unfortunately these records were inadvertently destroyed. Therefore to estimate the proportion of eligible patients who were entered into the study, we selected two types of operation (vascular surgery and cholecystectomy); the charts of all 1398 patients undergoing these operations during the same secular interval were reviewed. These operations accounted for 40% of the surgery performed in the prospective study. Of the 1398 patients who had a cholecystectomy or vascular surgery, 26% of eligible hypertensives and 34% of eligible diabetics were entered into the prospective study.[18]

Preoperative Evaluation

The protocol was reviewed and approved by the Institutional Human Rights Committee. Informed consent was obtained from all patients. Before operation basic demographic and clinical data were recorded and a physical examination was performed in a standardized manner.[20] The patient's right and left arm sitting blood pressure and pulse, as well as the recumbent and standing pulse and blood pressure were obtained. Blood pressure was recorded using a standard mercury manometer; Korotkoff Phase V was recorded as the diastolic pressure. The cuff was placed so that the lower margin was 2 to 3 cm above the antecubital space, with the bladder over the medial surface of the arm.[21] Blood pressures were obtained every 4 hours before surgery by the nursing staff. These systolic and diastolic blood pressures were recorded to delineate the patient's usual preoperative MAP, the standard deviation, and the minimum and maximum values.

Intraoperative Monitoring

On the day of surgery, a research assistant, blinded to the hypotheses of the study, recorded pulse and blood pressure immediately before induction, immediately after the induction agents were given, and immediately after intubation (the actual interval between these events varied from patient to patient), and every 5 minutes thereafter. The method of intraoperative blood pressure measurement was ultimately the decision of the anesthesiologist. In 52 patients intra-arterial measurements were made using a 20-gauge teflon catheter in the radial artery and connected to a Marquette 7000 (Marquette Electronics, Milwaukee, WI) dual pressure monitor calibrated before each use (accuracy of ± 1 mmHg); 71% of the patients who had an intra-arterial catheter were undergoing vascular surgery. The use of an indirect automatic device, the Omega 1000 (Vivo Research Labs, Tulsa, OK) (an accuracy of ±2 mmHg), which has been shown to generate reproducible and valid measurements of blood pressure while used in the operating room,[22] was encouraged in the remaining patients. The anesthesiologist actually used the indirect recorder in 72 patients. In 130 patients the anesthesiologist decided to use a standard mercury manometer instead of the Omega 1000; in these cases the research assistant obtained and recorded the blood pressures according to the procedures described previously. The proportion of the patients who had indirect device *versus* a mercury manometer did not differ according to the age of the patient, cardiac disease, the severity of hypertension, or diabetes. The indirect device was used more commonly in patients whose surgery lasted more than 2 hours ($p < 0.05$).

Standard electrocardiogram monitoring was performed during all operations. The research assistant recorded all pharmacologic agents used during each 5-minute interval of the operation. The use of anesthetic agents and adjuvants was recorded. Major intraoperative events, such as skin incision, reversal of anesthesia, aortic cross-clamping, drainage of ascites, and changes in position also were recorded.

In 24 patients (8.6%), the research assistant was not present in the operating room to record events and blood pressures. Because the purpose of this analysis is to assess the intraoperative blood pressure and pulse in relation to cardiac and renal complications, we have omitted these 24 patients (seven of whom had complications) because the intraoperative data was not recorded by an independent observer. The remaining sections of this paper will concentrate on the 254 patients for whom intraoperative data were recorded by an independent observer.

Postoperative Follow-up

All patients were followed daily for 7 days after operation or until death, discharge, or reoperation, with clinical examinations, serum creatinine measurements, electrocardiograms, and creatine kinase isoenzyme measurements. All the events and evidence were prospectively documented by physicians and/or research assistants.

After discharge the evidence was reviewed for all patients who developed dyspnea, palpitations, chest pain, signs of CHF, electrocardiographic changes, elevated CK-MB levels, or increased serum creatinine levels (by 0.4 mg/dL) by two physicians who were blinded to the patient's preoperative status and intraoperative course. These physicians determined whether the patients who were suspected of having myocardial ischemia, blood pressure, or postoperative renal impairment met the diagnostic criteria.[23,24]

Definition of Outcomes

A cardiac death was a death in the setting of myocardial ischemia, infarction, ventricular tachycardia, or cardiogenic shock, with the clinical events leading to death compatible with a primary cardiac etiology.

Most of the cardiac deaths, arrests, or myocardial infarction or ischemia occurred within the first 3 days after surgery, with the risk declining sharply after the second postoperative day; events occurring after the sixth postoperative day were not counted as postoperative complications.

The diagnosis of postoperative pulmonary edema required a pulmonary capillary wedge pressure of more than 20 cm H_2O (pulmonary artery catheters were placed in all patient suspected of having pulmonary edema) and a typical roentgenologic image showing pulmonary edema. The diagnosis of postoperative congestive heart failure required at least two of the following: S_3 gallop, typical roentgenologic image, bibasilar rales involving more than one third of the lung fields, or an elevated central venous pressure (more than 18 cm H_2O). Congestive heart failure was considered a postoperative complication only if it began within the first 3 postoperative days. Heart failure began on the day of operation in 6 patients, on the first postoperative day in 1 patient, and on the second postoperative day in 6 patients.

Postoperative renal dysfunction was defined as an increase in the serum creatinine level of ≥20%, persisting for 48 hours or more, which began in the first 3 days after surgery. In identifying patients whose serum creatinine levels remained persistently elevated at discharge from the hospital, an increase in the serum creatinine of ≥20% persisting for more than 48 hours had a true-positive rate of 93% and a false-positive rate of 7%.[24] Increases of ≥20% in creatinine level that began on the fourth postoperative day or thereafter could not be attributed to intraoperative events and were not considered in this analysis.

Analysis

To standardize the definition of the MAPs with the different techniques, MAPs were calculated as the diastolic pressure plus one third (systolic–diastolic). The primary analysis of intraoperative blood pressure was based on the differences between intraoperative MAPs and preoperative MAPs. The preoperative pressures all were obtained by mercury manometer and the intraoperative pressures were obtained by mercury manometer, intra-arterial catheter, or indirect oscillometric device. Intraoperative pressures obtained by manometer therefore were not adjusted because they were obtained by the same method. The MAPs obtained by the Omega 1000 *versus* mercury manometer, after adjusting for differences between arms, were 0.4 mmHg lower than the mercury manometer pressure, so 0.4 mmHg was added to all pressures obtained using the Omega device (the 95% confidence interval was −0.6 to +1.3 mmHg).[21]

The difference between the intra-arterial direct MAPs and the mercury manometer pressures, as expected, were greater; the mean intra-arterial pressure was 3.4 mmHg lower than simultaneous assessments with a mercury manometer (95% confidence interval: −5.1 to −1.6 mmHg); thus, for the adjustment, 3.4 was added to all intraoperative pressures obtained by arterial catheter. The correlation between indirect measurements and intra-arterial measurements may differ substantially from patient to patient, although the differences do not increase with age.[25] It would have been preferable to adjust for the intrapatient differences. In 25 of the 51 patients with arterial catheters, detailed calibrational data were available for such intrapatient adjustments; in the others it was not available. For the patients in whom it was possible to make the intrapatient adjustments, the hemodynamic patterns were re-evaluated using the patient-specific adjustments. These adjustments did not significantly alter the classification of patients according to 20-mmHg changes or other classifications.

Logistic regression was performed using the CATMOD program that uses the maximum likelihood method in SAS.[26] The likelihood ratio compares the specified model with the unrestricted model and is a goodness-of-fit test and was used to compare the overall predictive ability of the different models.[26] The chi square test for each effect is a Wald test based on the information matrix from the likelihood calculations and is the basis for the reported levels of statistical significance.[27] Each potential cutoff point for alternate methods of characterizing the intraoperative hemodynamic course (*e.g.*, a decrease in MAP to less than 70 mmHg) was initially examined in a simple model to determine the optimal duration to use as a cutoff point for that variable considered alone. Once the optimal cutoff point was determined, multiple logistic regression was used to determine the contribution of that variable at its optimal cutoff *versus* the definitions of change in intraoperative MAP based on the 20-mmHg strata defined previously. To account for potential confounders, those covariates that were found previously to be significant predictors of cardiac and renal complications (preoperative cardiac disease, diabetes, and less than 300 cc per hour of intraoperatively administered saline-containing fluids) were entered into the models designed to test the contribution of different methods of characterizing the intraoperative hemodynamic pattern.

Results

Among the 254 patients, 4% (10) had life-threatening complications: 3 had cardiac death; 2 had pulmonary edema and cardiac arrest; 2 had myocardial infarction and cardiac arrest; and 3 had definite or probable myocardial infarction. In addition 4% (10) of patients had postoperative CHF. Seven per cent of patients had a possible myocardial infarction (2) or definite myocardial ischemia with electrocardiogram changes (18); 12 of these patients had elevated CK-MB levels, and the eight patients without ≥3% CK-MB levels had ST-T changes that persisted more than 48 hours. In addition one patient had unstable angina without electrocardiographic changes and two patients had definite angina by the Rose criteria. Six per cent (16) had postoperative renal dysfunction. In total 21% of patients (54 of 254) had at least one cardiac or renal complication.

We originally defined intraoperative hypotension or hypertension as operative increases or decreases of ≥20 mmHg in MAP from the patient's preoperative MAP. Intraoperative hypotension lasting 60 minutes or longer and intraoperative hypertension lasting 15 minutes or more in combination with hypotension lasting less than 60 minutes were significant predictors of ischemic cardiac and renal complications.[1-3] In addition postoperative myocardial infarction or ischemia occurred significantly more often among patients with a previous infarction or cardiomegaly on chest radiograph.[3] Postoperative renal dysfunction occurred significantly more often among patients with decompensated CHF and among those who received less than 300 cc/hour of saline-containing fluids during operation.[1] Postoperative CHF occurred significantly more often in patients with cardiac disease, especially diabetics, and more frequently in patients who had ≥20 mmHg, but especially ≥40-mmHg changes in intraoperative MAP.[2] Therefore, considering the preoperative status of the patients, changes in intraoperative MAP ≥20 mmHg have been shown to be a significant predictor of postoperative cardiac and renal complications.

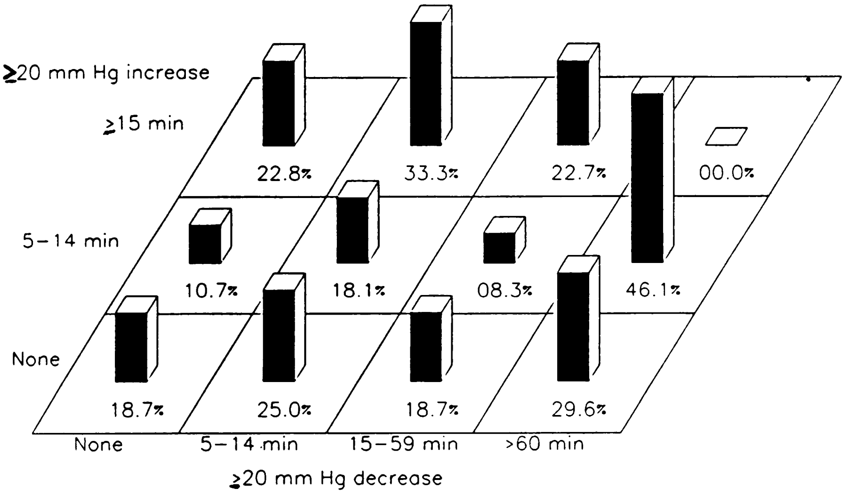
Because this definition differs from those most often used in clinical practice and clinical research, the subsequent analysis is designed to compare the predictive ability of different strategies for characterizing intraoperative hemodynamic patterns to predict postoperative complications.

20-mmHg Changes in Intraoperative MAP

In total 62% of patients experienced at least 5 minutes of ≥20-mmHg intraoperative decrease in MAP below their preoperative MAP. The duration of the 20-mmHg decreases was important in predicting complications: 31% of patients with decreases lasting more than 1 hour had complications compared to 17% of those with decreases lasting less than 1 hour. In comparison 17% of patients without such decreases had complications. At any cutoff point less than 1 hour, patients with a longer duration of ≥20-mmHg decreases had higher complication rates than patients with those of shorter duration; however 1 hour was the optimal cutoff as judged by likelihood ratios. When other significant predictors of postoperative complications (*e.g.*, cardiac disease, diabetes, cardiomegaly, and intraoperative fluid management) were accounted for using logistic regression, more than 1 hour of MAP decreases of more than 20 mmHg was a significant predictor of postoperative complications ($p < 0.04$).

In addition 62% of patients experienced at least 5 minutes of ≥20-mmHg intraoperative increases in MAP above their preoperative MAP. The duration of 20-mmHg increases was important in predicting complications: 50% of patients who had ≥20-mmHg increases lasting 60 minutes or longer had complications compared to 19% for those with increases lasting less than 1 hour. In contrast 22% of patients who did not have 20-mmHg increases had complications. Logistic regression confirmed that 1 hour of ≥20-mmHg increases was a significant predictor

FIG. 1. Postoperative complications according to the duration of ≥20-mmHg intraoperative changes in MAP.



Number of patients per group			
35	18	22	14
28	11	24	13
32	8	32	27

of postoperative complications ($p < 0.02$), taking other covariates into account, and had the highest likelihood ratio. It should be noted, however, that only eight patients had increases lasting more than 1 hour.

Figure 1 shows the complication rates according to the duration of ≥20-mmHg changes, with the duration of decreases plotted on the x axis and the duration of increases plotted on the y axis. The height of the bars represents the percentage of patients in each group with cardiac or renal complications. Patients with 60 minutes or more of decreases had increased complication rates. Complications also were increased rates among patients who had both decreases and increases in MAP. When different durations were analyzed (excluding those with either ≥1 hour of increases or ≥1 hour of decreases), the complication rates were significantly increased among patients with more than 15 minutes of ≥20-mmHg increases and 5 to 59 minutes of ≥20-mmHg decreases ($p < 0.04$). In total 29% of 85 patients in these two high-risk groups had postoperative cardiac or renal complications, while 17% of the 170 patients without either of these hemodynamic patterns had complications.

Because preoperative cardiac disease was an important predictor of postoperative complications, patients were stratified accordingly in Figure 2. To preserve adequate numbers in the strata, in this figure patients with no increases and those with less than 14 minutes of increases were grouped together; patients with 5 to 29 and 30 to 59 minutes of decreases also were grouped together. Among patients without cardiac disease, 24% of those in either of the high-risk groups had complications compared to 13% of those not in either high-risk group. Among those with cardiac disease, 45% of those in the high-risk groups had complications compared to 28% of those in neither group.

Together these two high-risk hemodynamic patterns had a 46% sensitivity and a 70% specificity rate; the positive predictive value was 29% and the negative predictive value was 83%.

Changes in Intraoperative MAP: 20 mmHg and 40 mmHg

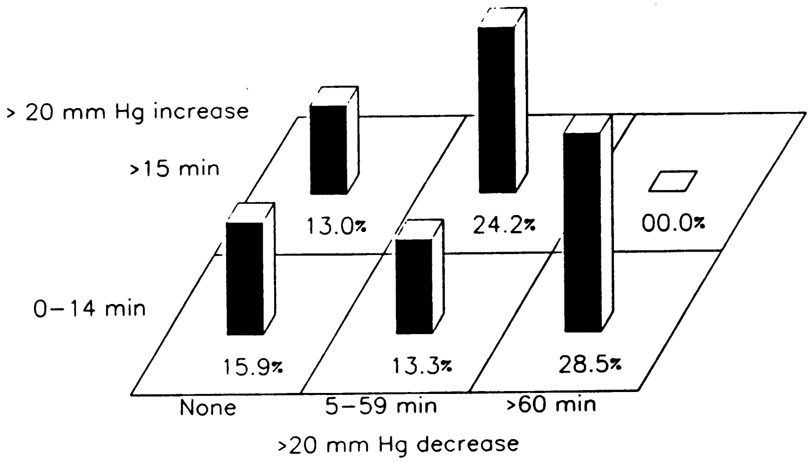
To address the issue of whether the magnitude of the changes was important, a cutoff point of ≥40 mmHg for increases or decreases in intraoperative MAP also was evaluated. Among the patients who had any ≥40-mmHg increase in intraoperative MAP, the complication rate was 22% (*versus* 21% with no increase). Figure 3a shows the complication rates for those with ≥40-mmHg increases according to the duration of ≥20-mmHg increases. When logistic regression was used to assess the importance of any ≥40-mmHg increases relative to ≥20-mmHg increases, the ≥40-mmHg increases were not a significant predictor. It should be noted, however, that two thirds (31 of 46) of the patients developed such ≥40-mmHg increases in the setting of more than 15 minutes of ≥20-mmHg increases.

Among the patients who had ≥40-mmHg decreases in intraoperative MAP, the complication rate was 30% (*versus* 19% with no such decrease). However, as shown in Figure 3b and confirmed by logistic regression, when the duration of the ≥20-mmHg decreases was accounted for, patients with ≥40-mmHg decreases did not have increased complications. It should be noted that 57% (26 of 46) of the ≥40-mmHg decreases occurred in patients who sustained more than 1 hour of ≥20-mmHg decreases in MAP.

Therefore patients who had 40-mmHg changes in MAP did not have significantly greater complication rates once the duration of the 20-mmHg changes were taken into account. However it must be noted that ≥40-mmHg

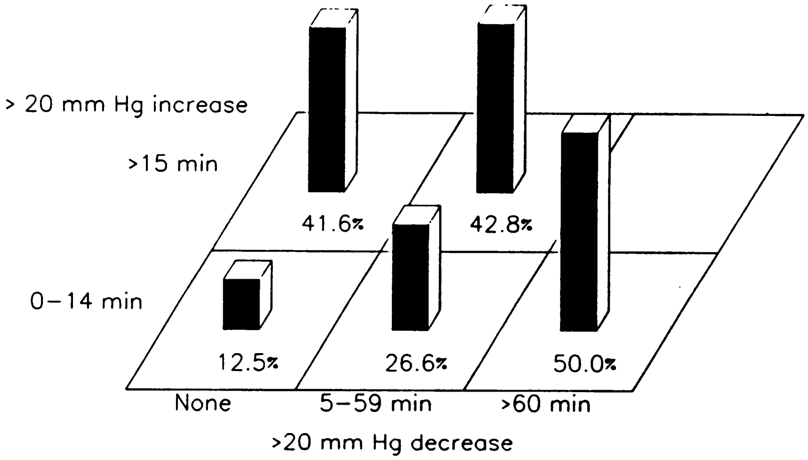
a. No cardiac disease

Number of patients per group		
22	32	4
42	55	27



b. Cardiac disease

Number of patients per group		
12	9	0
18	20	13



c. All patients

Number of patients per group		
34	41	40
60	75	0

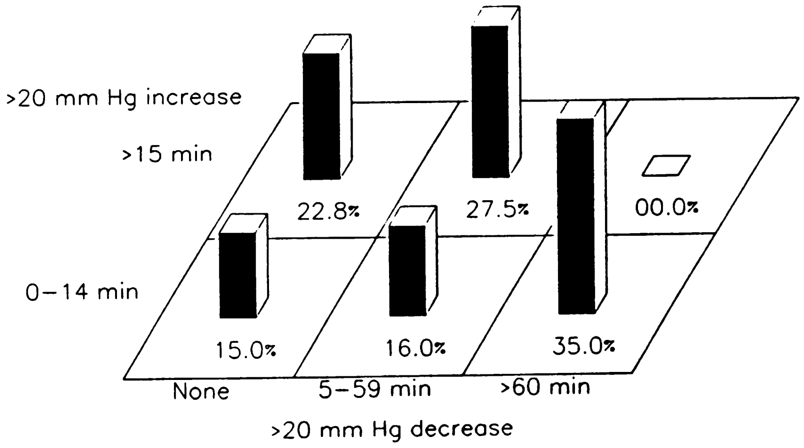
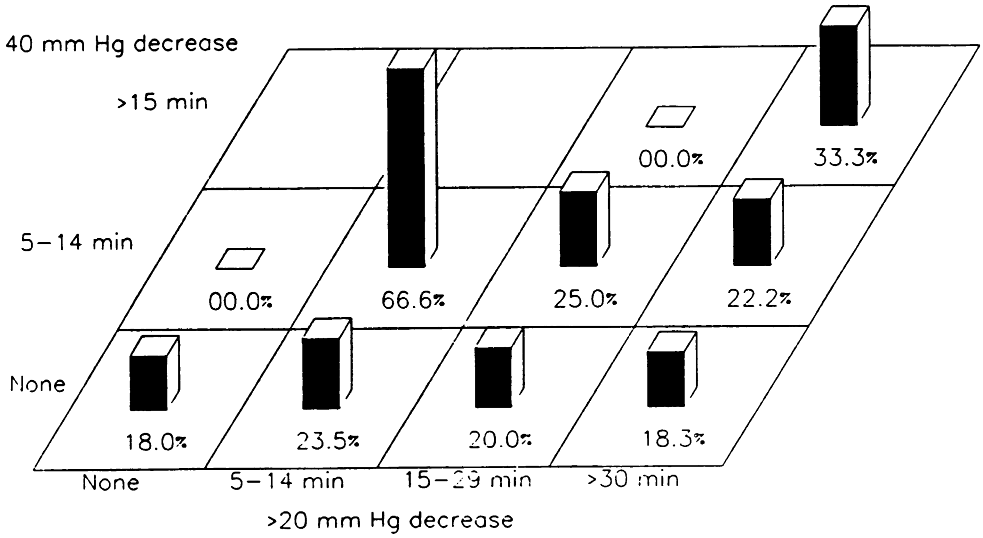


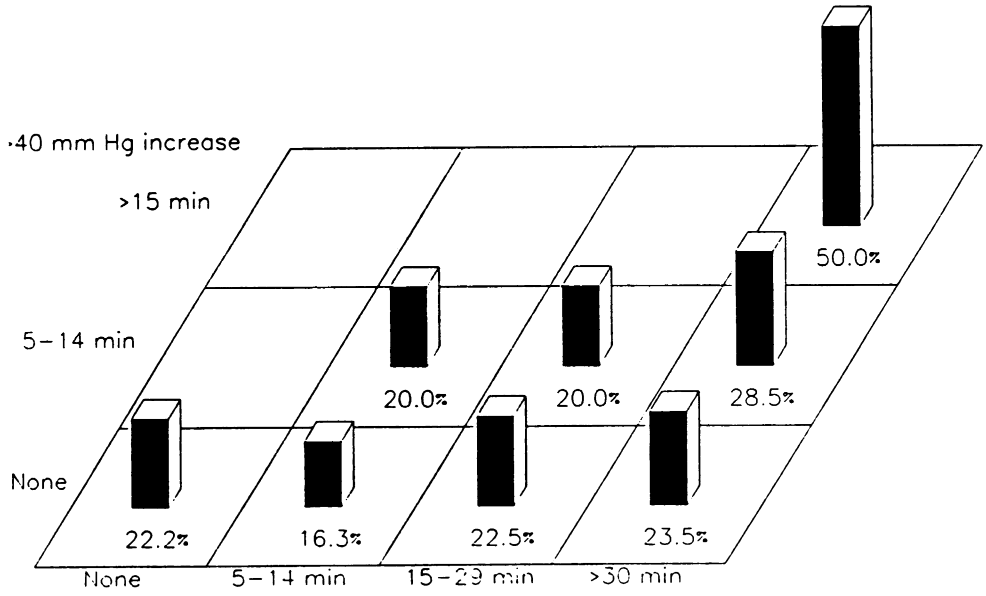
FIG. 2. Postoperative complications according to the duration of ≥20-mmHg intraoperative changes in MAP.

a. 20 mm Hg decrease vs 40 mm Hg decreases



Number of patients per group			
-	-	1	21
1	3	12	9
94	34	30	49

b. 20 mm Hg increases vs 40 mm Hg increases



Number of patients per group			
-	-	-	2
-	15	15	14
99	61	31	17

FIGS. 3a and b. Postoperative complications according to duration and magnitude of intraoperative increases in MAP.

changes usually occurred in the setting of more than 1 hour of ≥20-mmHg changes.

Changes in Intraoperative MAP: 20%, 33%, 40%, and 50%

Because 20% changes in MAP have been used to characterize the intraoperative course,[10] 20% changes were evaluated in relation to 20-mmHg changes. When the patients with 20% increases in MAP were compared to those with 20-mmHg increases above preoperative MAP, 87% of the patients were identically classified according to the magnitude and duration of the changes ($R^2 = 0.74$). Similarly when decreases of 20 mmHg were compared to decreases of 20%, 85% of the patients had changes of identical duration ($R^2 = 0.94$). In short the results of analyzing the intraoperative patterns using 20% changes in MAP were virtually identical to using 20 mmHg. As a result the sensitivity, specificity, and predictive value of 20% changes in MAP were nearly identical to those for 20-mmHg changes. Similarly 40% changes and 40-mmHg changes resulted in nearly identical classification of patients.

Because a 50% decrease in intraoperative MAP of any duration or a 33% decrease for more than 10 minutes have been used[4] to characterize the intraoperative course, these definitions also were evaluated. In this study there was no difference in the complication rates of patients with and without a 50% decrease in MAP (21% of the 14 patients with such a decrease and 21% of the 240 patients without). Consequently the sensitivity of a 50% decrease in MAP was low (5%), and the specificity was high (95%), while the positive predictive value was 21%. Among the 44 patients with a 33% decrease for 10 minutes or more, 25% had complications (*versus* 21% without a 33% decrease). A 33% decrease had a sensitivity rate of 24%, and a specificity rate of 83%, with a positive predictive value of 26%. In both instances of these larger-magnitude percentage changes, the sensitivity was relatively low and the specificity was relatively high in predicting complications. Logistic regression confirmed that neither was a significant predictor once other covariates were taken into account.

Changes in Intraoperative MAP: Mean difference in Intraoperative MAP

With modern monitoring devices that can record intraoperative blood pressure for computer analysis, the simplest method to assess the difference between preoperative MAPs and intraoperative MAPs would be to calculate the mean difference between the preoperative and intraoperative MAPs for the whole operation. A 20-mmHg mean difference in intraoperative MAPs in relation to the baseline preoperative MAPs was evaluated. Figure 4 shows the mean differences in intraoperative MAP plotted *versus* the duration of ≥20-mmHg increases and the duration of ≥20-mmHg decreases. Figure 4a shows the 10 patients who had a mean intraoperative MAP that was ≥20 mmHg higher than their preoperative MAPs; most of these patients had more than 15 minutes of ≥20-mmHg increases in MAP. Figure 4c shows the 24 patients who had a mean intraoperative MAP that was ≥20 mmHg less than their usual mean; these patients had prolonged 20-mmHg decreases. This was as expected.

However the methodologic difficulty with using mean difference is shown in Figure 4b. In total 220 patients had a mean intraoperative MAP that was within 20 mmHg of their usual MAP. Use of a mean difference would have missed the increased complication rate in many patients who had more than 1 hour of ≥20-mmHg decreases and in many patients who had more than 15 minutes of ≥20-mmHg increases and ≥20-mmHg decreases in MAP. Logistic regression confirmed that the mean difference from preoperative levels was not a significant predictor of complications. While simpler to use, the mean difference from preoperative MAPs would have obscured the hemodynamic pattern in those 66 patients who had both important intraoperative increases and decreases in MAP.

Mean Intraoperative MAP Regardless of Preoperative MAP

Another method of evaluating the intraoperative course is to assess the mean intraoperative blood pressures without regard to preoperative values.[14] For example 9% of the patients had overall mean intraoperative MAPs less than 80 mmHg; 43% had MAPs between 80 and 94 mmHg; 30% had MAPs between 95 and 109 mmHg; and 14% had MAPs ≥105 mmHg. Simple logistic regression suggested that the complication rate was increased when the MAP was less than 80 mmHg.

Forty-two per cent of patients with overall mean MAPs less than 80 mmHg had complications compared to 19% of those with overall mean MAPs more than 80 mmHg. However, as shown in Figure 5, the complication rates were not increased significantly unless the mean MAP, less than 80 mmHg, represented more than 1 hour of MAPs that were ≥20 mmHg less than preoperative baseline values. The sensitivity of overall intraoperative mean MAPs less than 80 mmHg in predicting complications was 18%, the specificity was 93%, and the positive predictive value was 41%. Logistic regression confirmed that overall mean intraoperative MAP was not a significant predictor of postoperative complications once the other covariates were taken into account.

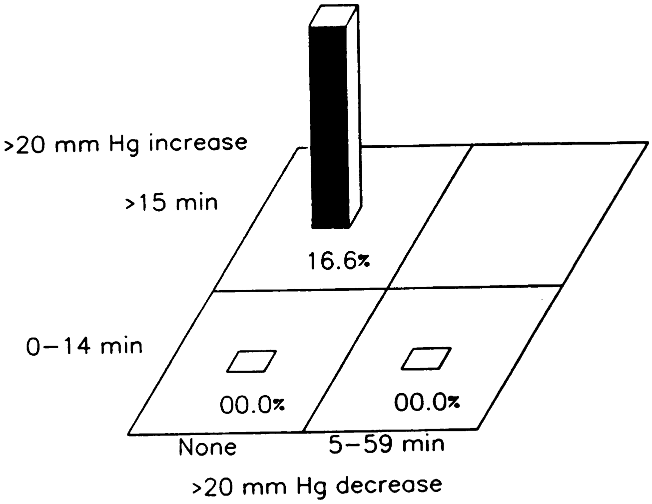
Absolute Intraoperative MAPs Regardless of Preoperative MAP: Less than 70 mmHg or More than 120 mmHg

Another alternative for evaluating intraoperative pressures has been to evaluate a specific MAP level as a

Mean difference in intra-operative MAP

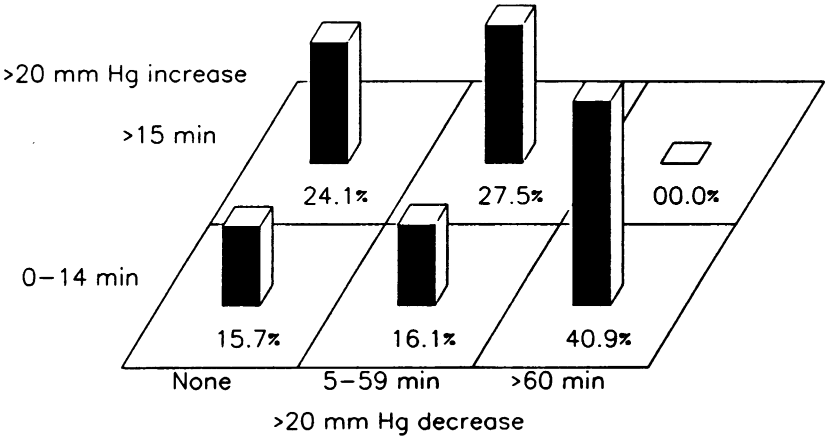
a. ≥ 20 mm Hg above baseline

Number of patients per group	
6	-
3	1



b. Within 20 mm of baseline

Number of patients per group		
29	40	4
57	68	22



c. >20 min below baseline

Number of patient per group	
6	18

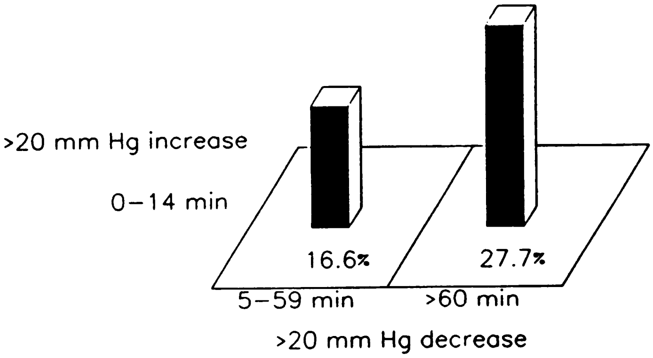
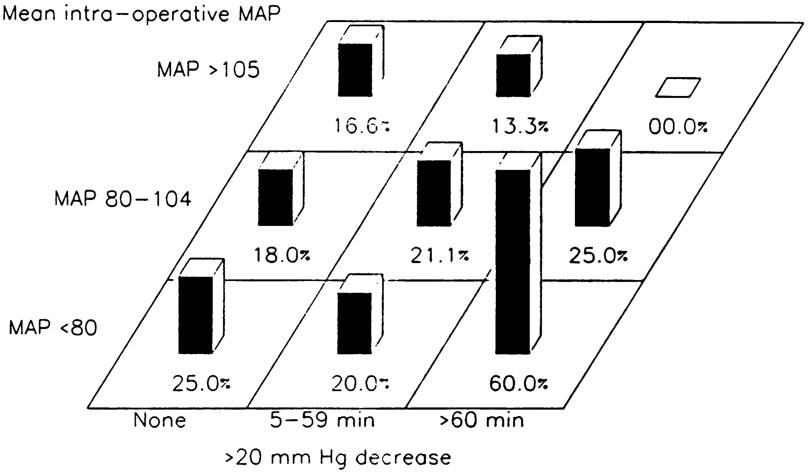


FIG. 4a–c. Postoperative complications according to the duration of 20-mmHg changes in MAP and the mean difference in MAP in intraoperative MAP in relation to baseline.



Number of patients per group		
30	15	2
61	90	32
4	10	10

FIG. 5. Postoperative complications according to the duration of 20-mmHg change in MAP and the mean intraoperative MAP, regardless of preoperative MAP.

threshold level below or above which complications are believed to increase. For example 70 to 80 mmHg has been used as a critical threshold for intraoperative MAPs.[28,29]

Of those with more than 15 minutes of MAPs ≤70 mmHg, 31% had complications *versus* 20% of patients with less than 15 minutes. In comparison 11% of those without MAPs ≤70 mmHg had complications. The sensitivity of a MAP less than 70 mmHg for more than 10 minutes was 30% and the specificity was 82%. Figure 6 shows the complication rates according to whether patients had intraoperative pressures of ≤70 mmHg. Within the MAP strata for 20-mmHg changes, an intraoperative MAP of ≤70 mmHg made a noticeable difference only among those patients who had decreases in MAP of ≥20 mmHg for more than 1 hour: in this group 15% of those with less than 14 minutes and 33% of the patients with more than 15 minutes of MAPs ≤70 mmHg had complications, almost two to four times the rate among patients without MAPs ≤70 mmHg. Logistic regression revealed that patients who had MAPs less than 70 mmHg did not have increased complications on the whole; within the strata of patients with 5 to 59 minutes of ≥20-mmHg decreases, an absolute MAP less than 70 mmHg did not achieve significance ($p = 0.12$).

Elevated pressures also were evaluated. For example patients who had intraoperative MAPs ≥120 mmHg for varying durations were evaluated. Patients without such pressures had a 25% complication rate; those with less than 10 minutes had a 19% rate, and those with more than 10 minutes had 22% complication rate. The sensitivity of 120 mmHg for more than 10 minutes was 31%, the specificity was 69%, and the positive predictive value was 21%. Logistic regression confirmed that the use of 120 mmHg did not add prognostic information.

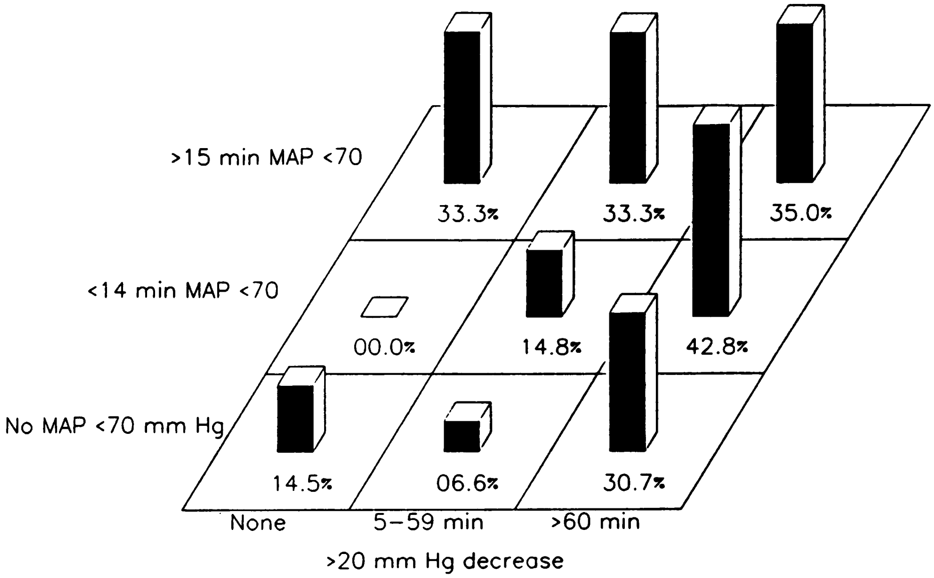
Discussion

The methods used by different studies to characterize the intraoperative hemodynamics vary widely, which impairs our ability to compare the results of the studies. For example percentage changes in the systolic pressure or MAP or absolute changes in intraoperative pressure have been used to define intraoperative hypertension or hypotension.[1-10] This is the first paper to systematically explore the issue of how intraoperative changes in blood pressure should be measured to optimally predict postoperative complications. The purpose of this study was to provide a framework and an initial starting point to standardize the method by which we characterize the intraoperative hemodynamic course. Clearly these findings must be tested and confirmed or refuted by other investigators.

The true-positive rate or sensitivity is the percentage of patients with cardiac or renal complications who had the specified changes in intraoperative blood pressure; if all patients who had complications had the specified changes, the sensitivity would be 100%. The false-positive rate is the percentage of patients without cardiac or renal complications who had the specified changes in intraoperative blood pressure. If none of the patients without the specified changes in blood pressure had complications, the false-positive rate would be 0%. An optimal definition of intraoperative changes in blood pressure in identifying patients with postoperative complications would have a true-positive rate of 100% and a false-positive rate of 0%. In Figure 7 the true-positive rate for identifying patients with complications is plotted against the false-positive rate. The points on the graph represent the true-positive and false-positive rates for different definitions of intraoperative changes in blood pressure. Because none achieve the ideal

a. ≥ 20 mm Hg increase = 0 -14 min

Number of patients per group		
3	18	20
2	27	7
55	30	13



b. ≥ 20 mm Hg increase = ≥ 15

Number of patients per group		
3	27	24
7	41	32
85	47	13

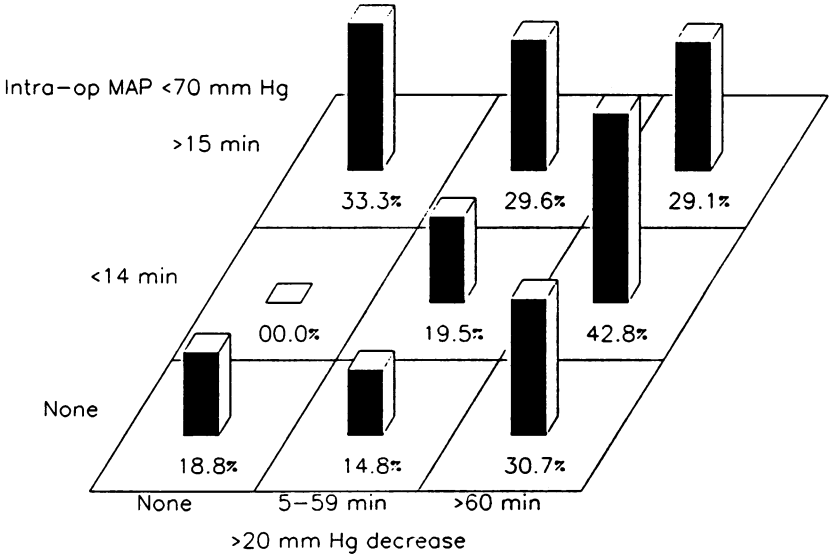


FIG. 6a and b. Postoperative complications according to duration of 20-mmHg changes in MAP and the duration of intraoperative MAP ≤70 mmHg.

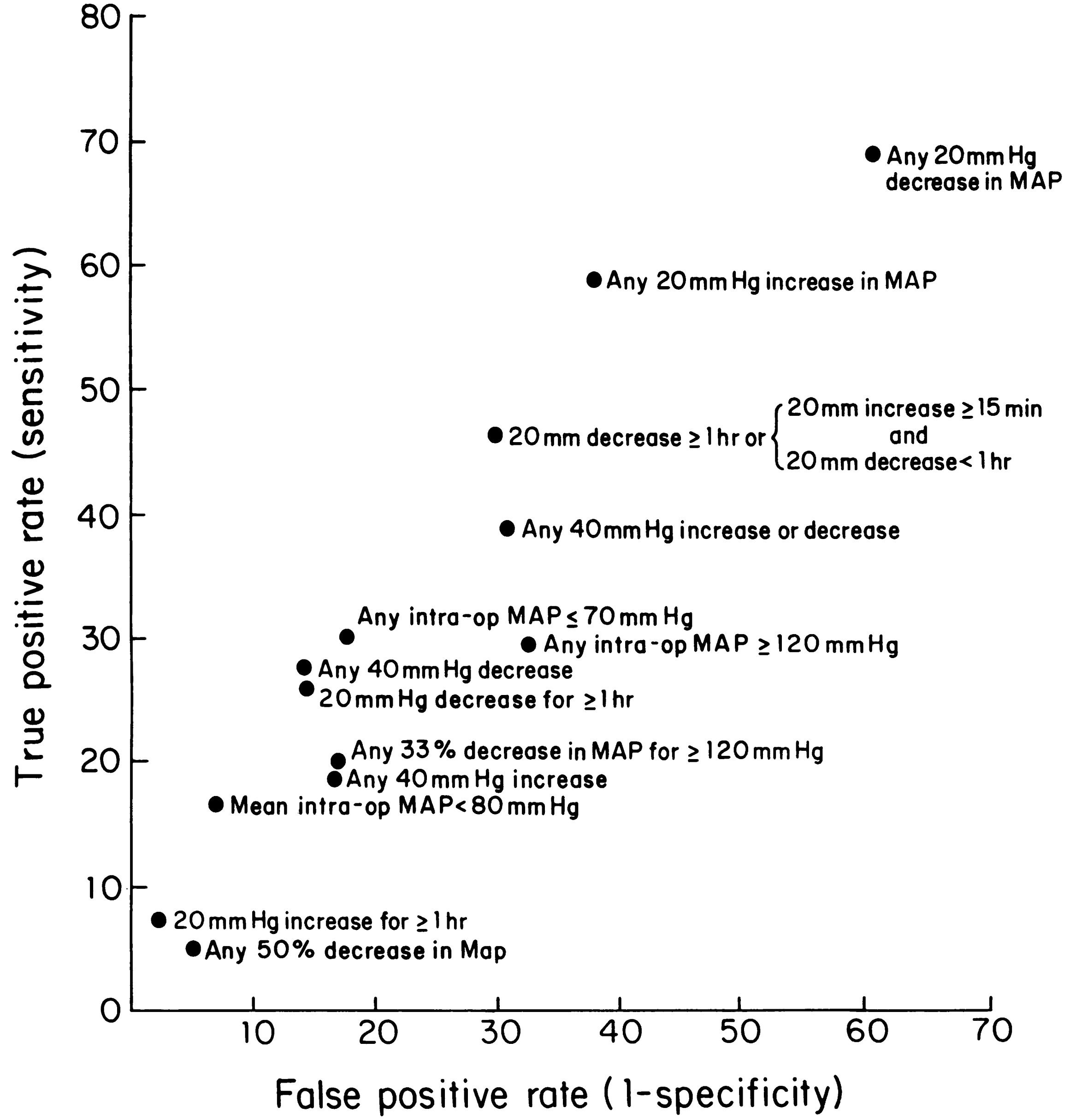


FIG. 7. Receiver operating characteristic curve for different definitions of intraoperative hypotension and hypertension.

of 100% true positive and 0% false positive, the optimal definition is that which maximizes the true-positive while minimizing the false-positive rate. Generally the optimal cutoff is delineated by the point with highest true-positive value before the points begin to curve to the right. In this figure the 20-mmHg differences were the optimal points.

There were several basic findings. First it is important to consider the intraoperative MAPs in relation to the patient's preoperative blood pressure. Strategies that examined absolute intraoperative MAPS, whether the overall MAP or a given threshold value, without reference to the patient's preoperative pressures had a much lower predictive ability than when the changes from preoperative MAPs to intraoperative MAPs were evaluated. Nonetheless, when intraoperative MAPs decreased to less than 70 mmHg, complication rates increased, although the differences were not significant.

Second the use of mean difference in intraoperative pressures from preoperative levels would hide the risk in patients who had intraoperative hypotension and hypertension.

Third patients with greater intraoperative changes in MAP (*i.e.*, more than 40 mmHg) did not have higher complication rates once the duration of the 20-mmHg or

20% changes were taken into account. However most of the larger changes occurred in the setting of ≥60 minutes of ≥20-mmHg decreases or ≥15 minutes of ≥20-mmHg increases.

Fourth two intraoperative hemodynamic patterns were associated with significantly increased postoperative cardiac and renal complications: (1) ≥20-mmHg decreases lasting more than 1 hour, and (2) ≥20-mmHg increases lasting 15 minutes or more and those with decreases of more than 5 minutes but less than 1 hour. The results were nearly identical if changes were defined as 20 mmHg or 20%; in most circumstances the use of 20-mmHg changes, which is much simpler to calculate, may be preferable.

While 20 mmHg may seem like a relatively minor change in intraoperative MAP, this magnitude of change had been hypothesized to be important at the beginning of the study. The reasons for the choice of this cutoff arise from the physiology of autoregulation of regional circulations[28,30] and the impact of anesthesia and surgery on autoregulation.[31] In the coronary and renal circulations, for example, autoregulation preserves perfusion at relatively constant levels despite changes in the systemic pressure within the upper and lower limits for autoregulation.[28,30,31] Below the lower autoregulatory limit, blood flow suddenly decreases, resulting in ischemia; above the upper limit, blood flow suddenly more than doubles, resulting in a local hypermia.[28,30,32,33] Therefore, in coronary and renal circulations, autoregulation preserves perfusion when systemic pressures are within 20 to 30 mmHg of the patient's usual systemic pressure.[30,32,33] The absolute autoregulatory limits are altered in hypertensive patients, partly as a result of structural changes in the vessel wall, and generally are higher and narrower than in normotensive patients.[34] Nonetheless, while the actual limits change, the autoregulatory range remains about 20 to 30 mmHg around the patient's usual MAP. Narrowing of the coronary arteries also may increase the lower limit of autoregulation because the ability to vasodilate in response to increased demands is structurally limited. In summary there is a physiologic basis for the selection of the 20-mmHg change from preoperative levels.

The population in this study consisted mainly of hypertensive and diabetic patients. Thus the extent to which these findings can be generalized to normotensive patients cannot be defined precisely. However the severity of hypertension was not a predictor of postoperative cardiac or renal complications. Diabetes *per se* was a risk factor only for postoperative CHF, and not for renal or ischemic complications. In Goldman's study 29% of the patients undergoing elective noncardiac surgery were hypertensive.[35] In the worst case, this study would have absolutely no applicability to normotensive patients but would apply to the 25% to 35% of patients undergoing elective noncardiac surgery who have hypertension. However it is likely that the sensitivity and specificity of the 20-mmHg changes would be similar in the hypertensive and normotensive population, but that the predictive values would change substantially in a lower-risk population with a lower complication rate.

In this study 25% to 30% of the eligible patients were enrolled. In a previous study of randomized trials, an average of 50% of the patients who met the eligibility criteria were entered into the trials.[36] The critical issue for the validity of the study is the extent to which the results in these patients represented all eligible hypertensive and diabetic patients. It might be helpful to compare the postoperative complications in the two groups; however the surveillance strategy that we used for study patients was more extensive than that used in routine patient care and undoubtedly led to the detection of more postoperative complications in the study group than in patients who were not enrolled. Therefore a comparison of the outcomes may not be as helpful as it appears.

In this paper MAPs were evaluated in relation to postoperative complications. Systolic and diastolic pressures were not evaluated separately, nor were they compared to MAP. Consequently no inferences can be made about the value of the use of the MAP in contrast to systolic/diastolic pressures.

Clearly the issue of how to define optimally intraoperative hemodynamic patterns that place patients at risk for postoperative complications requires further study. The specific results of this study may be confirmed, refuted, or modified by subsequent investigations, but we hope the analytic framework will be useful to others who are faced with the problem of trying to characterize intraoperative hemodynamics.

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