An Algorithm for Assessing Intraoperative Mean Arterial Pressure Lability

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Background: Intraoperative blood pressure lability may be related to risk factors, hypovolemia, light anesthesia, and morbid outcomes, but the measurements of lability in previous studies have been limited by imprecise and infrequent data collection methods. Computerized intraoperative data acquisition systems have provided an opportunity to readdress the issue of intraoperative blood pressure lability with more abundant and precise data. This study sought to derive and validate an algorithm (expert system) to measure mean arterial pressure (MAP) lability.

Methods: Two hundred thirty-nine computerized anesthesia records were reviewed retrospectively. Three anesthesiologists separately rated MAP as very stable, average, or very labile. The parameters of a computer algorithm that measured the change of median MAP between consecutive 2-min epochs were optimized to achieve the best possible agreement among the anesthesiologists. The algorithm was then validated on 229 additional anesthesia records.

Results: The proportion of consecutive 2-min epochs in which the absolute value of the fractional change of median MAP exceeded 0.06 (i.e., 6%) correlated strongly with the anesthesiologists' ratings ($r = 0.78$, $P < 0.0001$). The optimal sensitivity and specificity of the algorithm for detecting MAP lability were 98% and 59%, respectively.

Conclusions: One potential application of expert systems to anesthesia practice is a "smart alarm" to detect blood pressure lability. It may also provide a better tool to assess the relation between lability and outcome than has been available previously. (Key words: Blood pressure. Computers: expert systems monitoring. Hemodynamic. Surgery, cardiac: coronary artery bypass grafting.)

A large body of literature addresses the topic of intraoperative hemodynamic lability. Issues that have been examined include preoperative risk factors such as treated and untreated hypertension of varying severity, vascular disease, advanced age, and reduced blood volume.1-3 Measurements of intraoperative blood pressure lability in these studies, however, have been limited to intraoperative blood pressure nadir, steady-state pre- and postoperative measurements, and blood pressure greater and less than defined limits of normal for given intervals.1-4

Although the influence of intraoperative blood pressure lability on morbid outcomes such as stroke and myocardial infarction is controversial,1-3 the presence of lability alerts the clinician to potentially deleterious conditions, such as hypovolemia, inadequate depth of anesthesia, and the potential for cardiovascular complications. Hemodynamic lability is assessed in a subjective manner by anesthesiologists observing trends on a hemodynamic monitor display or handwritten anesthesia record. This assessment is impaired by imperfect vigilance and competing duties in the operating room. The programmable alarms of current hemodynamic monitoring systems are limited to comparing instantaneous hemodynamics with upper and lower numeric limits. Extreme blood pressure lability, however, may exist within "normal" hemodynamic parameters, such as when the mean arterial pressure (MAP) swings rapidly between 110 and 60 mmHg.

The advent of computerized intraoperative data acquisition systems provides an opportunity to address the issue of intraoperative blood pressure lability with more abundant and precise data. Medical expert systems are computer programs that assist in the diagnosis and management of various medical problems. Although they have been used in certain medical specialties as diagnostic aids, their use in anesthesia practice has been limited. One potential application of expert systems to anesthesia practice is the detection of blood pressure lability. This investigation derived and validated a math-

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Mean arterial pressure lability algorithm

mathematical method for the quantitative description of hemodynamic lability using data taken from computerized anesthesia records.

Methods

The protocol was institutionally approved and exempt from informed consent as a retrospective investigation. Four hundred sixty-eight computerized anesthesia records (CompuRecord; Anesthesia Recording, Inc., Pittsburgh, PA) of sequential patients undergoing coronary artery bypass graft surgery between January and December 1995 were printed. All physiologic data had been automatically recorded on the computerized anesthesia record. The MAP was derived from indwelling arterial catheters, electronic transducers, and Hewlett-Packard Component Monitoring Systems (Waltham, MA) and was recorded every 15 s during operation. The printed anesthesia record represented the MAP as an “x” on a grid every 2 min, each printed value corresponding to the mean of eight 15-s samples. The ordinate of the graph represented the blood pressure range from 0–250 mmHg, with a resolution of 3.5 mmHg.

Anesthesiologists’ Clinical Assessment of Blood Pressure Lability

Three experienced anesthesiologists reviewed the printed anesthesia records of each patient for the pre-cardiopulmonary bypass (pre-CPB) period. These evaluators each rated the lability of MAP using a three-point scale: 1 was assigned to records that were interpreted as having minimal lability (very stable); 2 was assigned to records that were interpreted as having average lability; and 3 was assigned to records that were interpreted as having markedly labile MAP. The evaluators were instructed to ignore the absolute values of the MAP data points and to rate only the degree of lability. A patient with a constant MAP of 35 mmHg, therefore, would have been rated as very stable for the purpose of this analysis. In addition, if there were periods of stability and lability, the evaluators were instructed to rate the blood pressure lability according to the condition that predominated. Each of the evaluators was blinded to the ratings of the others. A fourth experienced anesthesiologist reviewed all of the ratings and identified the three instances in which ratings differed by more than one grade (i.e., any time that a 1 and a 3 were assigned to the same anesthesia record). These evaluations were resubmitted to the evaluators to correct the errors.

The three anesthesiologists’ ratings for each chart were summed to obtain a combined rating such that the final score for each anesthesia record ranged from 3 (when each reviewer evaluated the pre-CPB MAP as minimally labile) through 9 (when each reviewer evaluated the MAP as very labile). Although the combined rating cannot be considered a gold standard because of the subjective nature of the assessments, we used it as a benchmark for clinical assessment of blood pressure lability. We defined a case as having a clinically labile MAP in the pre-CPB period as any record in which two or three of three evaluators rated the MAP as unstable (i.e., records with a combined rating of 8 or 9).

Derivation of an Algorithm for Assessing Blood Pressure Lability

The algorithm for quantifying lability of MAP for the pre-CPB period was developed using the 239 computerized anesthesia records for the first half of 1995 as follows:

1. The instantaneous MAP data collected by the computer every 15 s was used, not the printed anesthesia record used for the clinical assessments. The median MAP was calculated for consecutive blocks of eight MAP measurements, constituting 2 min. The median was used instead of the mean to eliminate artifactual data more completely (e.g., arterial line flushes).
2. The rate of MAP change from each 2-min median MAP to the next one was calculated using the following formula:

\[ |FCM| = \frac{|MAP_{x+1} - MAP_x|}{MAP_x} \]

where MAP\(_x\) is the initial median MAP, MAP\(_{x+1}\) is the subsequent median MAP, and the result of the equation (absolute value of the fractional change in median MAP) was abbreviated as |FCM|. This process is illustrated in table 1.
3. We hypothesized that the set of |FCM| values in the pre-CPB period could be transformed mathematically into an MAP lability index. We found that an effective means of transforming the |FCM| data was to calculate the proportion of |FCM| values that exceeded some threshold value. The proportion would then be the lability index. For example, if we set the threshold at 0.20, and found that 80% of the |FCM| values were greater than 0.20, the lability index would be 0.80, and this would represent a

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Table 1. Illustration of the Initial Steps of the Algorithm

<table>
<thead>
<tr>
<th>MAP</th>
<th>Very Stable MAP</th>
<th>Labile MAP</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>15-s Intervals</td>
<td>2-min Median</td>
</tr>
<tr>
<td>84</td>
<td>100</td>
<td></td>
</tr>
<tr>
<td>84</td>
<td>100</td>
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<tr>
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<tr>
<td>86</td>
<td>91</td>
<td></td>
</tr>
<tr>
<td>86</td>
<td>88</td>
<td></td>
</tr>
<tr>
<td>83</td>
<td>85.5</td>
<td>0.01</td>
</tr>
<tr>
<td>83</td>
<td>79</td>
<td></td>
</tr>
<tr>
<td>86</td>
<td>72</td>
<td></td>
</tr>
<tr>
<td>85</td>
<td>72</td>
<td></td>
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<td>86</td>
<td>71</td>
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<td>85</td>
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<td>84</td>
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<td>85</td>
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<td>78</td>
<td>75</td>
<td></td>
</tr>
<tr>
<td>86</td>
<td>85.5</td>
<td>0.00</td>
</tr>
</tbody>
</table>

MAP = mean arterial pressure; |FCM| = fractional change in median MAP.

very labile MAP. To maximize the sensitivity and specificity of this index, we tested a wide range of potential threshold values (0.03–0.25). For each potential threshold, Pearson’s correlation coefficient was calculated for the association of lability index and the anesthesiologists’ combined rating. The threshold for |FCM| that yielded the highest correlation coefficient was selected as the best test algorithm for predicting MAP lability (i.e., threshold = 0.06, r = 0.691; table 2). In this manner, the computer algorithm for the quantitative assessment of MAP lability (lability index) was:

\[
\text{Lability index} = \frac{|\text{FCM}|}{0.06}
\]

Validation of the Algorithm for Assessing Blood Pressure Lability

The algorithm was validated on a separate data set of 229 computerized anesthesia records (from the second half of 1995) that also had combined ratings by the three cardiac anesthesiologists. The Pearson’s correlation coefficient for the lability index (proportion of |FCM| > 0.06) compared with the combined ratings of the anesthesiologists was calculated. A receiver-operator characteristic curve was plotted to determine the ability of the algorithm to distinguish records with clinically labile MAP (combined rating scores 8 and 9) from those with average and very stable MAP (combined rating scores 3–7).

The statistical methods included Pearson’s correlation coefficient and receiver-operator characteristic curves graphs of sensitivity versus [1 – specificity], as described previously. Agreement among the anesthesiologists’ ratings was analyzed using two-way analysis of variance to calculate the intraclass correlation coefficient. A two-tailed probability value less than 0.05 was considered significant.

Results

In the first half of 1995 (algorithm development data set), there was a range of 19–118 (median, 61) 2-min epochs in the pre-CPB period of the 239 coronary artery bypass graft cases. The agreement in evaluations of lability among anesthesiologists is described by the intraclass correlation coefficient (R) of 0.60. In the second half of 1995 (algorithm validation data set) there was a range of 48–209 (median, 79) 2-min epochs in the pre-CPB period of the 229 coronary artery bypass graft cases. The graph of combined anesthesiologists’ ratings versus the lability index (proportion |FCM| > 0.06) for the validation data is presented in figure 1 (r = 0.78, P < 0.0001).

The ability of the algorithm to distinguish the clinicians’ evaluations of labile (combined ratings 8 and 9)
from average and very stable MAP (combined rating 3–7) trends is presented in table 3. The lability index
criterion that best differentiated the labile patients from
average or stable patients was 0.30 (i.e., when median
MAP changed by at least 6% from one 2-min interval to
the next in more than 30% of the intervals before CPB).
This is further demonstrated in the receiver-operator
characteristic curve in figure 2. The line that connects
the data points yields an integral of 0.909 (perfect test
= 1.000; useless test = 0.500).

Discussion

This study shows that a computer algorithm can mea-
sure blood pressure lability in a manner that correlates
strongly with anesthesiologists’ assessments based on
review of anesthesia records. The development of this
algorithm was predicated on finding a method that re-
sulted in the greatest possible agreement with clinicians

who specifically sought to quantify the degree of MAP
lability in a relatively controlled clinical scenario: before
CPB in patients undergoing coronary artery bypass graft
surgery.

Most of the correlation coefficient values presented
in table 2 are similar. This implies that selection of any
threshold values between 0.03 and 0.10 for the lability
index probably would have produced similar results.
However, we chose the 0.06 threshold because it
yielded the highest correlation coefficient.

Despite our initial expectations, preliminary work
(data not shown) showed that standard measures of
mathematical variability, such as standard deviation,
variance, and fast Fourier transformation–derived pa-
rameters (i.e., spectral edge and power at various fre-
quencies) did not correlate with the anesthesiologists’
assessments of MAP.

One of the major limitations in performing this study
was the lack of a gold standard to measure hemody-
namic lability. The interobserver agreement among the
anesthesiologists was relatively poor ($R_1 = 0.60$),
de spite our use of a three-point ordinal scale. A more
elaborate (four- or five-point) scale of increasing lability
would not have improved the precision of the cli ni-
cians’ assessments of lability. The relatively frequent
disagreements between anesthesiologists’ ratings of
pre-CPB MAP lability reflect the indistinct nature of the
variable being measured. It is a clinical bench mark,
therefore, and not a gold standard per se.

The results of the study might have been more impres-
sive if only portions of the pre-CPB period that were
markedly stable or unstable were tested or if “syn-
thetic” cases representing various extremes were pre-
sented to the experienced anesthesiologists for rating.
For example, if the analysis compared only the anesthe-
sia records in which two or three of the observers con-
curred that the MAP trend was very stable (combined

<table>
<thead>
<tr>
<th>Correlation coefficient</th>
<th>0.03</th>
<th>0.04</th>
<th>0.05</th>
<th>0.06</th>
<th>0.07</th>
<th>0.10</th>
<th>0.15</th>
<th>0.20</th>
<th>0.25</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0.655</td>
<td>0.669</td>
<td>0.685</td>
<td>0.691</td>
<td>0.684</td>
<td>0.650</td>
<td>0.589</td>
<td>0.508</td>
<td>0.395</td>
</tr>
</tbody>
</table>

*The Pearson’s correlation coefficient was calculated for the association of each potential lability index threshold value for fractional change in median MAP (|FCM|) and anesthesiologists’ combined rating. The threshold for |FCM| that yielded the highest correlation coefficient was selected as the lability index test
algorithm.
†Highest correlation coefficient.
Table 3. Relationship between Lability Index and Detection of Labile MAP

<table>
<thead>
<tr>
<th>Lability Index Criterion</th>
<th>Stable and Average MAP (rated 3–7) (false positives)</th>
<th>Labile MAP (rated 8–9) (true positives)</th>
<th>Sensitivity</th>
<th>1 – Specificity</th>
</tr>
</thead>
<tbody>
<tr>
<td>&gt;0.70</td>
<td>0</td>
<td>1</td>
<td>0.02</td>
<td>0</td>
</tr>
<tr>
<td>&gt;0.60</td>
<td>0</td>
<td>3</td>
<td>0.06</td>
<td>0</td>
</tr>
<tr>
<td>&gt;0.50</td>
<td>1</td>
<td>18</td>
<td>0.36</td>
<td>0.01</td>
</tr>
<tr>
<td>&gt;0.40</td>
<td>20</td>
<td>37</td>
<td>0.74</td>
<td>0.11</td>
</tr>
<tr>
<td>&gt;0.35</td>
<td>43</td>
<td>45</td>
<td>0.9</td>
<td>0.24</td>
</tr>
<tr>
<td>&gt;0.30</td>
<td>73</td>
<td>49</td>
<td>0.98</td>
<td>0.41</td>
</tr>
<tr>
<td>&gt;0.25</td>
<td>107</td>
<td>49</td>
<td>0.98</td>
<td>0.60</td>
</tr>
<tr>
<td>&gt;0.20</td>
<td>147</td>
<td>50</td>
<td>1.00</td>
<td>0.82</td>
</tr>
<tr>
<td>&gt;0.10</td>
<td>173</td>
<td>50</td>
<td>1.00</td>
<td>0.97</td>
</tr>
<tr>
<td>&gt;0.00</td>
<td>179</td>
<td>50</td>
<td>1.00</td>
<td>1.00</td>
</tr>
</tbody>
</table>

MAP = mean arterial pressure.

rating 3 and 4) versus records in which the trend was very labile (combined ratings 8 and 9), the receiver-operator characteristic curve yields an integral of 0.992 (i.e., a nearly perfect test in which the curve is nearly coincident with the vertical and horizontal axes). This approach, however, would not be applicable to any real-life situations. We believe that a more useful approach was to classify actual cases and complete with artifact, varying duration of pre-CPB period, and including the complete spectrum of hemodynamic lability.

The potential utility of the lability index algorithm in an expert system (“smart alarm”) is an important issue and one that cannot yet be answered. Ultimately, an ideal monitor of lability would alert clinicians to the need for intervention by differentiating patients with excessive blood pressure lability from those with average or minimal lability. Therefore we sought a means to discriminate between these groups (i.e., excessive lability versus the remaining patients) using a system that would yield optimal sensitivity and specificity. Using a receiver-operator characteristic curve and the data presented in table 3, the optimal criterion for determining the labile group appears to be 0.30. Thus our definition of clinically significant MAP lability is a patient with more than 6% changes in median MAP in either direction for at least 30% of the consecutive 2-min epochs analyzed (sensitivity = 0.98, specificity = 0.59).

The algorithm reported in the current study has only been validated for intraoperative pre-CPB MAP in patients having myocardial revascularization surgery and may not be applicable to patients having other types of surgery. Further, the three anesthesiologists who rated the degree of MAP lability are all from the same institution, performing the same type of anesthetic, and may have similar views of lability. This could have biased the results of the study in favor of better intraobserver agreement. Another limitation was that the anesthesiologists were presented with mean values for MAP, whereas the algorithm resulted in better smoothing by analyzing median MAP data. It is also possible that other hemodynamic parameters, such as heart rate, systolic and diastolic arterial pressure, and cardiac filling pressures, may require different algorithms. Another limitation of the study is that only patients with intraarterial catheters were studied. The sparser data collection with noninvasive blood pressure measurement was not addressed in the current study.

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Artifacts due to intraarterial catheter flushing, arterial blood sampling, and sudden movements of pressure tubing interfered with our preliminary attempts to devise an algorithm that distinguished hemodynamic lability. These are problematic because they are indistinguishable mathematically from blood pressure lability. It is possible to filter the raw data to improve the signal-to-noise ratio by calculating the median of the MAP for every 2-min epoch. This is demonstrated by the fact that the correlation coefficients for the lability index and the combined ratings were markedly lower when raw 15-s data were used (data not shown). Although there is little material published in this area, several of the current commercial computerized anesthesia recordkeeping systems use median data processing for artifact rejection (personal oral communication, Chester A. Phillips III, M.D., Anesthesia Recording, Inc., Pittsburgh, PA).

Another possible computerized approach to the problem of differentiating labile from nonlabile blood pressure is the use of a neural network. The validity of this approach has been shown in various applications.\(^6\) The most important task for getting optimal results from a neural network system is "training" the system to recognize all possible patterns of lability and stability. The disadvantage of this technique lies in the inability of the programmer(s) to adjust the numeric values assigned to the various "nodes" that constitute the neural network. In practical terms, this may produce unpredictable results when the neural network is confronted with an example that it was not trained to handle. In contrast, the algorithmic approach used in the current study is classified as a rule-based system, in which the parameters can be adjusted to get optimal results.

Fuzzy logic is another technique that is suited to the analysis of blood pressure lability. It allows the classification of categories, such as lability, with degrees of certainty. However, we were interested in generating a more quantitative descriptor of hemodynamic lability.

An important question that arises is the utility of this algorithm as a research or clinical tool. A study of this size has insufficient power to determine whether lability is an independent predictor or surrogate marker of mortality, morbidity, or hemodynamic decompensation, because the incidence of these events is relatively rare, even in patients having coronary artery bypass graft surgery. Hemodynamic (MAP) lability also may be an indicator of light anesthesia, but this will be difficult to establish because of an absence of valid and reliable measures of depth of anesthesia. The utility of the algorithm, therefore, lies in the ability of a computerized system to retrospectively or prospectively analyze thousands of anesthesia records with absolute vigilance and with sensitivity and specificity that compare favorably with human observers. Future investigations should reveal whether MAP lability is associated with death, complications, or hemodynamic decompensation.

References


