The Discriminant Power of Simultaneous Monitoring of Spontaneous Electroencephalogram and Evoked Potentials as a Predictor of Different Clinical States of General Anesthesia

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Spontaneous or evoked electrical brain activity is increasingly used to monitor general anesthesia. Previous studies investigated the variables from spontaneous electroencephalogram (EEG), acoustic (AEP), or somatosensory evoked potentials (SSEP). But, by monitoring them separately, the available information from simultaneous gathering could be missed. We investigated whether the combination of simultaneous information from EEG, AEP, and SSEP shows a more discriminant power to differentiate between anesthesia states than from information derived from each measurement alone. Therefore, we assessed changes of 30 EEG, 21 SSEP, and 29 AEP variables recorded from 59 patients during four clinical states of general anesthesia: “awake,” “light anesthesia,” “surgical anesthesia,” and “deep surgical anesthesia.” The single and combined discriminant powers of EEG, AEP, and SSEP variables as predictors of these states were investigated by discriminant analysis. EEG variables showed a higher discriminant power than AEP or SSEP variables: 85%, 46%, and 32% correctly classified cases, respectively. The frequency of correctly classified cases increased to 90% and 91% with information from EEG/AEP and EEG/AEP/SSEP, respectively. Thus, future anesthesia monitoring should consider combined information simultaneously distributed on different electrophysiological measurements, rather than single variables or their combination from EEG or AEP or SSEP.

(Anesth Analg 2006;103:894–901)

Measuring electrical brain activity in an attempt to prevent inadequate anesthesia states such as responsiveness to surgical stimuli and awareness is still a difficult challenge. This is evident when considering the wide variety of electrophysiological variables described in the literature. Frequency and time domain derivations of the electroencephalogram (EEG) have been involved for more than two decades in monitoring anesthesia (1). Processed auditory evoked potentials (AEP) have been proposed as a potential method for the detection of intraoperative awareness (2,3).

Recently, a factor analysis (6) performed on several variables extracted from EEG, AEP, and SSEP has shown that 80% of their observed variance during general anesthesia could be best explained by 13 factors, i.e., the observed variance could not be projected on a single dimension. Interestingly, none of the derived factors combined information from EEG, AEP, and SSEP. Considering the linear independence of the derived factors, it may be reasonable to assume that each of the three electrophysiological measurements represents a different aspect of electrical brain activity changes associated with general anesthesia (6).

The monitoring techniques and devices aim at the quantification of the complex EEG changes during general anesthesia via numerical indices derived from EEG or AEP or SSEP. Comparative investigation on the potential monitoring value of these measurements revealed their individual limited potential use as indicators of “depth of anesthesia” (7–9). This approach may not detect valuable information simultaneously distributed on different aspects of neuronal...
processing, such as EEG, AEP, and SSEP. As it has
developed evident that anesthesia can be caused by
different mechanisms (10,11), a multidimensional,
rather than one-dimensional, monitoring framework
is more likely to reliably represent changes in the
electrical brain activity of a patient during general
anesthesia. Therefore, this study was designed to
investigate whether combined information from these
electrophysiological measurements shows more dis-
criminant power to differentiate between different
clinical states of general anesthesia than information
derived from each measurement alone. Also, it has
been suggested that the evaluation of the discriminant
power of potential indicators of anesthetic effect
should be performed on more consecutive clinical
end-points of observed anesthesia, rather than only
between conscious versus unconscious or awake ver-
sus deep anesthesia (12). Thus, we assessed single or
combined changes of EEG, AEP, and SSEP recorded
during four observed anesthesia states from awake to
deep general anesthesia and quantified their contribu-
tion to the separation of these states.

METHODS
Anesthetic Technique
With the appropriate ethics committee approval and
informed consent from patients, the electrophysiological
data of 59 patients (30 women; 29 men; 45 ± 13 yr; 171 ±
10 cm; 75 ± 16 kg; mean ± sd) from three university
hospitals enrolled in a prospective multicenter study
were analyzed. Patients with ASA physical status >2
or indication for rapid sequence induction, pregnancy,
recent administration of central nervous system-
affecting drugs, or neurological or psychiatric diseases
were excluded from this investigation. The general an-
esthetic procedure was performed by the attending
anesthesiologist in accordance with the daily clinical
practice of the corresponding institution. An IV cannula
was placed, and infusion of lactated Ringer’s solution
was started before induction of anesthesia. After admin-
istration of oxygen via a facemask and administration of
remifentanil (0.5 μg · kg⁻¹ · min⁻¹), alfentanil (20–40
μg/kg), or fentanyl (2–4 μg/kg), anesthesia was in-
duced with either propofol (1–1.5 mg/kg) or thiopen-
tal (5 mg/kg). Tracheal intubation was performed
after muscle relaxation with atracurium besilat (0.6
mg/kg). Normoxemia and normocapnia were main-
tained by mechanical ventilation of the lungs with a
mixture of oxygen in air for the rest of the surgical
procedure. Repetitive application of opioid doses and
the amount of administered propofol or isoflurane or
sevoflurane was left to the discretion of the attending
anesthesiologist and was guided by clinically observ-
ing the patient. At the end of the surgical procedure,
the administration of anesthetics was ended. As soon
as the patients had regained adequate consciousness,
they were tracheally extubated, disconnected from the
monitoring devices, and transferred to the anesthetic
recovery room.

Neuromonitoring
The signal acquisition was performed with a spe-
cially adapted four-channel recording system (Neuro-
screen, Viasys Healthcare, Hoechberg, Germany and
EEG “Infinity POD,” Draeger Medical Systems, Dan-
vers, MA). Ag/AgCl EEG electrodes were placed at
F1, F2, M2, P3’, and Fz (reference) with Fp1 as ground
(10–20 international system). Before recording, the
skin was prepared to maintain impedances <5 kΩ.
The sampling frequency of raw signals was 4 kHz.
SSEP stimuli of 100 μs duration were applied to the
right median nerve via an electrode on the right wrist,
with a frequency of 3–3.098 Hz. Stimulus intensity was
chosen 20% greater than the motor threshold as deter-
dined before the induction of anesthesia. AEP stimuli
were rarefaction clicks of 100 μs duration and 90 dB
(SPL). They were presented binaurally 9.3 times per
second via shielded earphones (Viasys Healthcare,
Hoechberg, Germany). Each SSEP epoch consisted of
306 stimuli, each AEP epoch of 1000 stimuli. The
stimulus modalities, i.e., no stimuli for EEG, AEP
stimuli, or SSEP stimuli, were sequentially applied for
1.7 min and evenly distributed. The order of the
stimulus modality was randomly generated for nine
intervals. This ordered sequence was constantly re-
peated before and during anesthesia.

Data Selection
We extracted 80 variables for the discriminant
function analysis: 30 EEG, 21 SSEP, and 29 AEP (Table
1). Preferably, EEG, AEP, and SSEP should be mea-
sured simultaneously. As this is not possible, we
defined parameter collections as tightened variable
values extracted from sequential recordings of these
stimulus modalities. They were considered as simulta-
neously recorded if 1) no artifacts were detected; 2)
EEG, AEP, and SSEP were recorded in close temporal
succession; 3) no bolus doses of anesthetics were given
within a minimum of 2.5 min preceding the recording
period; 4) only constant anesthetic infusion or concen-
trations of volatile anesthetics were applied within a
minimum of 2.5 min preceding the recording period;
5) there were no prominent surgical stimuli; and 6)
hemodynamic values were unchanged. Therefore, a
parameter collection consists of a group of 30 EEG, 21
SSEP, and 29 AEP variable values extracted from such
a “stable anesthesia period.”

For further analysis, parameter collections were
selected from four defined stages of the clinical course
of anesthesia: A1, “awake” during last 10 min before
induction of anesthesia; A2, “light anesthesia” be-
tween 2.5 min after tracheal intubation and 2.5 min
before surgical incision, containing no EEG suppres-
sion (13) or induced movements caused by diagnostic
or patient transfer procedures; A3, “surgical anesthe-
sia” between 2.5 min after surgical incision and 2.5
Table 1. Electroencephalogram (EEG), Auditory Evoked Potentials (AEP), Somatosensory Evoked Potentials (SSEP) Variables

<table>
<thead>
<tr>
<th>Parameter Definition</th>
<th>Parameter Definition</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>EEG epoch</strong> Mean absolute amplitude</td>
<td><strong>AEP wavelet coefficients</strong></td>
</tr>
<tr>
<td>SdAmp Standard deviation of amplitudes</td>
<td>L5_P0r Ratio of sum of squared coeff level 5 packet 0</td>
</tr>
<tr>
<td>SkwAmp Skewness of histogram of amplitudes</td>
<td>L5_P1r Ratio of sum of squared coeff level 5 packet 1</td>
</tr>
<tr>
<td>KurtAmp Kurtosis of histogram of amplitudes</td>
<td>L5_P2r Ratio of sum of squared coeff level 5 packet 2</td>
</tr>
<tr>
<td>SEF25 Frequency below which 25% of total power resides</td>
<td>L5_P3r Ratio of sum of squared coeff level 5 packet 3</td>
</tr>
<tr>
<td>SEF50 Frequency below which 50% of total power resides</td>
<td>L5_P4r Ratio of sum of squared coeff level 5 packet 4</td>
</tr>
<tr>
<td>SEF75 Frequency below which 75% of total power resides</td>
<td>L5_P5r Ratio of sum of squared coeff level 5 packet 5</td>
</tr>
<tr>
<td>SEF90 Frequency below which 90% of total power resides</td>
<td>L5_P6r Ratio of sum of squared coeff level 5 packet 6</td>
</tr>
<tr>
<td>SEF95 Ratio of sum of squared coeff level 5 packet 0 to sum of all squared coeff power</td>
<td>L5_P7r Ratio of sum of squared coeff level 5 packet 7</td>
</tr>
<tr>
<td>Abs05_2 Power in band 0.5–2.0 Hz</td>
<td>L5_P8r Ratio of sum of squared coeff level 5 packet 8</td>
</tr>
<tr>
<td>Abs2_5 Power in band 2.0–5.0 Hz</td>
<td>L5_P9r Ratio of sum of squared coeff level 5 packet 9</td>
</tr>
<tr>
<td>Abs5_8 Power in band 5.0–8.0 Hz</td>
<td>L5_P9r Ratio of sum of squared coeff level 5 packet 9</td>
</tr>
<tr>
<td>Abs8_13 Power in band 8.0–13.0 Hz</td>
<td>L5_P9r Ratio of sum of squared coeff level 5 packet 9</td>
</tr>
<tr>
<td>Abs13_20 Power in band 13.0–20.0 Hz</td>
<td>L5_P9r Ratio of sum of squared coeff level 5 packet 9</td>
</tr>
<tr>
<td>Abs20_26 Power in band 20.0–26.0 Hz</td>
<td>L5_P9r Ratio of sum of squared coeff level 5 packet 9</td>
</tr>
<tr>
<td>Abs26_32 Power in band 26.0–32.0 Hz</td>
<td>L5_P9r Ratio of sum of squared coeff level 5 packet 9</td>
</tr>
<tr>
<td>Rel05_2 Ratio of power in band 0.5–2.0 Hz to total power</td>
<td>L5_P9r Ratio of sum of squared coeff level 5 packet 9</td>
</tr>
<tr>
<td>Rel2_5 Ratio of power in band 2.0–5.0 Hz to total power</td>
<td>L5_P9r Ratio of sum of squared coeff level 5 packet 9</td>
</tr>
<tr>
<td>Rel5_8 Ratio of power in band 5.0–8.0 Hz to total power</td>
<td>L5_P9r Ratio of sum of squared coeff level 5 packet 9</td>
</tr>
<tr>
<td>Rel8_13 Ratio of power in band 8.0–13.0 Hz to total power</td>
<td>L5_P9r Ratio of sum of squared coeff level 5 packet 9</td>
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<tr>
<td>Rel13_20 Ratio of power in band 13.0–20.0 Hz to total power</td>
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<tr>
<td>Rel20_26 Ratio of power in band 20.0–26.0 Hz to total power</td>
<td>L5_P9r Ratio of sum of squared coeff level 5 packet 9</td>
</tr>
<tr>
<td>Rel26_32 Ratio of power in band 26.0–32.0 Hz to total power</td>
<td>L5_P9r Ratio of sum of squared coeff level 5 packet 9</td>
</tr>
<tr>
<td>SpecEnt Spectral entropy</td>
<td>L5_P9r Ratio of sum of squared coeff level 5 packet 9</td>
</tr>
<tr>
<td>SymbEnt Symbolic entropy</td>
<td>L5_P9r Ratio of sum of squared coeff level 5 packet 9</td>
</tr>
<tr>
<td>ApEnt1 Approximate entropy</td>
<td>L5_P10r Ratio of sum of squared coeff level 5 packet 10</td>
</tr>
<tr>
<td>ApEnt2 Approximate entropy</td>
<td>L5_P10r Ratio of sum of squared coeff level 5 packet 10</td>
</tr>
<tr>
<td>BispV Integral under bispectrum 0.5–2.0 Hz</td>
<td>L5_P10r Ratio of sum of squared coeff level 5 packet 10</td>
</tr>
<tr>
<td>AbsBispV Volume under bispectrum 0.5–32.0 Hz</td>
<td>L5_P10r Ratio of sum of squared coeff level 5 packet 10</td>
</tr>
<tr>
<td>Bic Integral under bicoherence 0.5–2.0 Hz</td>
<td>L5_P10r Ratio of sum of squared coeff level 5 packet 10</td>
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SSEP wavelet coefficients

<table>
<thead>
<tr>
<th>Parameter Definition</th>
<th>Parameter Definition</th>
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<tr>
<td>L4P1 Sum of squared coeff level 4 packet 1</td>
<td></td>
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<tr>
<td>L3P1 Sum of squared coeff level 3 packet 1</td>
<td></td>
</tr>
<tr>
<td>L2P1 Sum of squared coeff level 2 packet 1</td>
<td></td>
</tr>
<tr>
<td>L5P0 Sum of squared coeff level 5 packet 0</td>
<td></td>
</tr>
<tr>
<td>L5P1 Sum of squared coeff level 5 packet 1</td>
<td></td>
</tr>
<tr>
<td>L5P2 Sum of squared coeff level 5 packet 2</td>
<td></td>
</tr>
<tr>
<td>L5P3 Sum of squared coeff level 5 packet 3</td>
<td></td>
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<tr>
<td>L5P4 Sum of squared coeff level 5 packet 4</td>
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<tr>
<td>L5P5 Sum of squared coeff level 5 packet 5</td>
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<tr>
<td>L5P6 Sum of squared coeff level 5 packet 6</td>
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<tr>
<td>L5P7 Sum of squared coeff level 5 packet 7</td>
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<tr>
<td>L5P8 Sum of squared coeff level 5 packet 8</td>
<td></td>
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<tr>
<td>L5P9 Sum of squared coeff level 5 packet 9</td>
<td></td>
</tr>
<tr>
<td>L5P10 Sum of squared coeff level 5 packet 10</td>
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</tr>
<tr>
<td>L5P11 Sum of squared coeff level 5 packet 11</td>
<td></td>
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<tr>
<td>L5P12 Sum of squared coeff level 5 packet 12</td>
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<td>L5P13 Sum of squared coeff level 5 packet 13</td>
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<td>L5P14 Sum of squared coeff level 5 packet 14</td>
<td></td>
</tr>
<tr>
<td>L5P15 Sum of squared coeff level 5 packet 15</td>
<td></td>
</tr>
<tr>
<td>L2P2 Sum of squared coeff level 2 packet 2</td>
<td></td>
</tr>
<tr>
<td>L2P3 Sum of squared coeff level 2 packet 3</td>
<td></td>
</tr>
</tbody>
</table>

Statistics

From selected parameter collections, we formed seven sets of predictors with variables from 1) SSEP or 2) AEP or 3) EEG; 4) EEG + SSEP or 5) EEG + AEP or 6) SSEP + AEP; 7) EEG + SSEP + AEP. The stepwise discriminant function analysis (SPSS DISCRIM, Version 11.5.1, SPSS, Chicago, IL) was performed on the data matrix of parameter collections (rows) variables (columns). Before running the analysis, the data matrix was screened for presence of multivariate outliers. As a criterion for the exclusion of parameter collection (mentioned further as “case”) from analysis, we used the Mahalanobis distance at $P < 0.001$, evaluated as $\chi^2$.
with degrees of freedom equal to the number of variables (14). Multicollinearity and singularity in the data matrix were avoided by using a stepwise selection of each variable as predictor of group membership with the default settings of SPSS DISCRIM. The prediction of group membership was evaluated through cross-validation as classification procedure, where each case was classified with discriminant functions derived from all other cases. Significant differences between overall classification results obtained with different sets of predictors were identified with the two-sided SPSS McNemar test for pair-wise comparison at $P < 0.05$.

**RESULTS**

Thirty-six of the 59 patients were premedicated with midazolam. Twenty-five patients received total IV anesthesia with propofol and remifentanil or alfentanil. Thirty-four patients were anesthetized with isoflurane or sevoflurane combined with fentanyl or alfentanil. More than 90% of the patients underwent general or orthopedic surgery, with 20% having major abdominal surgery. Figure 1 illustrates typical changes of the original SSEP, EEG, and AEP in a representative patient during the four anesthesia states.

Table 2 and Figure 2 summarize the classification results of the calculated discriminant functions with SSEP, AEP, and EEG variables as predictors of membership in four anesthesia states. They suggest more discriminant power of AEP than SSEP variables, but less than EEG variables. Remarkably, combined information from EEG and AEP variables discriminates better between observed anesthesia states than does the EEG variables alone: 90% correctly classified cases compared with 83%, respectively. This finding was supported by combinations of either AEP or EEG with SSEP variables (predictor sets 4 and 5, respectively). In both cases, the calculated discriminant functions were determined by changes of either AEP or EEG variables alone, showing no significant contribution of SSEP variables. Therefore, the classification results obtained with these discriminant functions found no consideration for further interpretation. The combined information from EEG, AEP, and SSEP variables discriminates best between the observed anesthesia states: 91% correctly classified cases.

**Detailed Results of Discriminant Function Analysis**

The obtained data matrix for the discriminant function analysis comprised 161 cases (36 from A1, 43 from A2, 40 from A3, and 42 from A4) for 30 EEG, 21 SSEP, and 29 AEP variables (Appendix, available online).

With predictor set 1, 17 of 161 cases were deleted as multivariate outliers. The calculated discriminant functions were determined mainly by two variables representing low and medium frequency ranges: L5_P2 and L5_P0. As with SSEP variables, they represent low and medium frequency ranges. Figure 3A shows no relevant changes of the variables between A2 and A3, which led to a high frequency of false classified cases in these groups.

Evaluating predictor set 2, 25 cases were removed as multivariate outliers. The significant discriminant functions were mainly determined by L5_P2, L5_P8, and L5_P0. As with SSEP variables, they represent low and medium frequency ranges. Figure 3B shows no relevant changes of the variables between A2 and A3, which led to a high frequency of false classified cases in these groups.
Using predictor set 3, 17 of 161 cases were excluded as multivariate outliers. The variables loading on the calculated discriminant functions showed two distinct trend changes during anesthesia states: 1) an increase from A1 to A2 followed by a subsequent decrease during A3 and A4, and 2) a consecutive decrease through the anesthesia states (Fig. 3C). The first trend can be explained by ocular and eyelid artifacts in the frontal EEG (13), and by biphasic behavior of some spectral quantities during the induction of anesthesia (15). Low-voltage EEG was present during A1 and A4 and agreed with other investigations (7). The variables following this trend such as SpecEnt and SEF75 separated best between A1/A4 and A2/A3. The second trend in variable changes was best represented by ApEnt1 and SEF90 and discriminated best between A1/A2 and A3/A4, in combination with SpecEnt and KurtAmp. Finally, SEF90, Abs20_26, and SpecEnt distinguished between A1/A3 and A2/A4.

With predictor set 5, 19 of 161 cases were excluded as multivariate outliers. The higher discriminant power of the calculated discriminant functions (Fig. 2) compared with functions determined by EEG, AEP, or SSEP variables was partly due to three AEP variables:

**Table 2. Cross-Validated Classification Statistics**

<table>
<thead>
<tr>
<th>Predictor</th>
<th>Group</th>
<th>A1</th>
<th>A2</th>
<th>A3</th>
<th>A4</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>SSEP</td>
<td>A1</td>
<td>16</td>
<td>5</td>
<td>20</td>
<td>1</td>
<td>27</td>
</tr>
<tr>
<td></td>
<td>A2</td>
<td>1</td>
<td>10</td>
<td>21</td>
<td>6</td>
<td>38</td>
</tr>
<tr>
<td></td>
<td>A3</td>
<td>1</td>
<td>2</td>
<td>15</td>
<td>1</td>
<td>37</td>
</tr>
<tr>
<td>AEP</td>
<td>A4</td>
<td>2</td>
<td>0</td>
<td>7</td>
<td>21</td>
<td>34</td>
</tr>
<tr>
<td>EEG</td>
<td>A1</td>
<td>23</td>
<td>0</td>
<td>1</td>
<td>4</td>
<td>27</td>
</tr>
<tr>
<td></td>
<td>A2</td>
<td>0</td>
<td>27</td>
<td>11</td>
<td>0</td>
<td>38</td>
</tr>
<tr>
<td></td>
<td>A3</td>
<td>0</td>
<td>6</td>
<td>31</td>
<td>1</td>
<td>38</td>
</tr>
<tr>
<td>EEG + AEP</td>
<td>A4</td>
<td>2</td>
<td>0</td>
<td>0</td>
<td>39</td>
<td>41</td>
</tr>
<tr>
<td>Original group membership</td>
<td>EEG + SSEP + AEP</td>
<td>22</td>
<td>0</td>
<td>1</td>
<td>4</td>
<td>27</td>
</tr>
</tbody>
</table>

Eeg, electroencephalogram; AEP, auditory evoked potentials; SSEP, somatosensory evoked potentials.
L5_P11, L5_P2, and L5_P5. They led to a better separation between A1/A2 and A3 and represent changes in low, medium, and high frequency ranges of AEP.

The predictor set 7 comprised all variables. After exclusion of 15 of 161 cases as multivariate outliers, the calculated discriminant functions showed the highest frequency of correctly classified cases (91%). The additional content in discriminant power when compared with predictor set 5 was partly due to the SSEP variable L5P0. This introduced a better separation of A2 and A4, but a lower identification of A1 and A3.

DISCUSSION

In this study, we investigated whether the combination of simultaneous monitoring of EEG, AEP, and SSEP adds substantial information to the monitoring of each measurement separately. Therefore, we quantified the single and combined discriminant powers of these measurements as predictors of four levels of general anesthesia.

The chosen levels of anesthesia were defined as a partition of the anesthetic continuum used in daily clinical practice: “awake” (A1), “light anesthesia” (A2), “surgical anesthesia” (A3), and “deep surgical anesthesia” (A4). A1 is clinically different from the other levels. As a consequence of the study design, A4 is also different from the other levels. A difference between anesthesia before skin incision (A2) and during surgery (A3) can be assumed, as clinically experienced anesthesiologists were chosen for this study. To reduce hemodynamic suppression before skin incision, the anesthetic level may be reduced, whereas during surgery, anesthetic and analgesic concentrations will be increased. The effect of increased drug concentrations may, in part, be reduced by surgical stimuli. As no reliable additional parameters that separate A2 from A3 are available, a difference between these levels cannot be guaranteed, but may only be deducted from clinical implications.

Different anesthetics may cause different patterns in EEG and evoked potentials during clinically similar anesthesia levels (16). This may have neurophysiological relevance, but for monitoring, clinical anesthesia parameter changes should correlate as closely as possible with different levels of observed anesthesia and ideally show no anesthetic drug specificity (12). With respect to this important particularity of monitoring parameters, the anesthetic technique was left to the discretion of the attending anesthesiologist and was varied among patients.

The highest discriminant power to distinguish between the observed anesthesia states when using SSEP or AEP or EEG as predictors was achieved with variables extracted from EEG. Figure 3C illustrates the assessed changes in these variables, which showed a sufficient difference to reliably discriminate between awake and light anesthesia, surgical anesthesia and deep surgical anesthesia. Assuming no linear correlation between the calculated discriminant functions, variables like spectral entropy, absolute power 20–26 Hz and 26–32 Hz, SEF90, and approximate entropy were most effective in discriminating between these anesthesia states. These findings agree with the results of other investigations (7,17,18). The monitoring value of single EEG variables seems to be limited, because each of them represents <35% relative discriminant power on each discriminant function (see Table A1 of the Appendix, available online at www.anesthesia-analgesia.org). This could explain the higher predictive value for different anesthesia states achieved with combined, rather than single, variables of EEG (19).

Further, our results showed no relevant contribution of the bicoherence variable Bic to separate the defined anesthesia states and agree with earlier investigations concerning its practical value for monitoring clinical
anesthesia (20,21). In this context, the relative discriminant power achieved by the bispectrum variable AbsBisV seems to rely on energy changes in frequency components of the power spectrum, rather than in their phase relationships.

The discriminant power of AEP variables was significantly lower than that of EEG variables, because of smaller changes between light and surgical anesthesia. As the reliable representation of different anesthesia states remains an important goal of clinical monitoring (12), the practical value of AEP variables alone seems limited. These findings could explain their promising results as predictors for consciousness versus unconsciousness (3) and their lower value as an indicator of anesthetic effect compared with EEG quantities (22).

SSEP variables showed the lowest discriminant power compared with variables from AEP or EEG. Because of small changes in these variables, the calculated discriminant functions could not distinguish between all observed anesthesia states. This may, in part, reflect the definition of anesthetic levels used in the present study. The different levels may mainly reflect the hypnotic component, whereas the analgesic component was poorly controlled or targeted. Generally, the term “anesthetic level” is hard to define. It is unclear to what extent each of the components—amnesia, hypnosis, and antinociception—must be present to induce and maintain “general anesthesia.” As the clinical definition used in the present study may mainly reflect hypnotic and amnesic components, it is not surprising that SSEP variables as a potential indicator of antinociception (23,24) do not consistently reflect the “level of anesthesia.”

Combined information from EEG and AEP variables showed significantly more discriminant power to distinguish between the defined anesthesia states compared with information extracted from EEG or AEP or SSEP. The increase in discriminant power was due to the combination of spectral and entropy quantities of EEG with low, medium, and high frequency ranges of AEP. The achieved classification results point out a higher resolution between awake and different levels of anesthesia, and represent the additional information content delivered by AEP variables. No statistically significant improvement to these results could be obtained with combined information from EEG, AEP, and SSEP variables as predictors. Also, discriminant functions were calculated with variables from either EEG or AEP when these were combined with SSEP variables.

We conclude that variables from EEG show more discriminant power to identify different anesthesia states compared with variables from AEP or SSEP. This result, however, may not be due to the characteristics of the underlying signal (i.e., AEP or SSEP) alone, but may also reflect the characteristics of the applied signal analysis. Wavelet coefficients, the results of AEP and SSEP processing, reflect only a very little detail of the underlying signal. It cannot be excluded that additional processing of wavelet coefficients (e.g., construction of a parameter combined from several wavelet coefficients) would have resulted in a more reliable classification of the clinical states. As indicated by the calculated discriminant functions, the monitoring value of combined variables seems to be higher than for each variable alone, even if they partly include redundant information, as with some quantities of the power spectrum of EEG. Our findings showed that combined information extracted from EEG and AEP gives a higher representation of different clinical states of general anesthesia than the information extracted from EEG alone. Thus, future anesthesia monitoring should consider information distributed on different electrophysiological measurements, rather than single quantities or their combinations out of EEG or AEP or SSEP.

ACKNOWLEDGMENTS

We thank Dr. James Blunk for the helpful discussion and Draeger Medical Systems, Danvers, MA, for the technical support.

REFERENCES


