Journal of Clinical Monitoring and Computing (2019) 33:1097–1103
https://doi.org/10.1007/s10877-018-00244-1

ORIGINAL RESEARCH

The fundamental contribution of the electromyogram to a high bispectral index: a postoperative observational study

Kazuko Hayashi[1] · **Teiji Sawa**[2]

Received: 31 August 2018 / Accepted: 22 December 2018 / Published online: 3 January 2019

Abstract

The electromyogram (EMG) activity has been reported to falsely increase BIS. Conversely, EMG seems necessary to constitute the high BIS indicative of an awake condition, and may play a fundamental role in calculating BIS, rather than distorting the appropriate BIS. However, exactly how EMG is associated with a high BIS remains unclear. We intended to clarify the respective contributions of EMG and various electroencephalogram (EEG) parameters to high BIS. In 79 courses of anaesthesia, BIS monitor-derived EMG parameters (EMGLOW), and other processed EEG parameters [SEF95 (spectral edge frequency 95%), SynchFastSlow (bispectral parameter), BetaRatio (frequency parameter), total power subtypes in five frequency range], were obtained simultaneously with BIS, every 3 s. These EEG parameters were used for receiver operating characteristic (ROC) analysis of detecting three BIS levels (BIS > 80, BIS > 70, and BIS > 60) to assess their diagnosabilities. A total of 218,418 data points derived from 79 cases were used for analysis. Area under the ROC curve (AUC) was calculated and optimal cut-off (threshold) was determined by Youden index. As the results, for detecting BIS > 80, the AUC of EMGLOW was 0.975 [0.974–0.977] (mean [95% confidence interval]), significantly higher than any other processed EEG parameters such as BetaRatio (0.832 [0.828–0.835]), SEF95 (0.821 [0.817–0.826]) and SynchFastSlow (0.769 [0.764–0.774]) ($p < 0.05$ each). The threshold of EMGLOW for detecting BIS > 80 was 35.7 dB, with high sensitivity (92.5%) and high specificity (96.5%). Our results suggest EMG contributes considerably to the diagnosis of high BIS, and is particularly essential for determining BIS > 80.

Keywords Bispectral index · Electromyogram · Awareness · Anaesthesia depth · Monitoring

1 Introduction

The frequency of electromyogram (EMG) is distributed widely, i.e. 0–300 Hz range, and broadly overlaps EEG frequency range [1–3]. Bispectral index (BIS) also uses the EEG signals overlapping EMG in frequency, for analysis of EEG. For example, 30–47 Hz component of the BetaRatio, one of BIS-subcomponents, typically associated with awake or light levels of anaesthesia, overlaps the same frequency of EMG [4–7]. EMG activity is therefore inherent in the calculation of the BIS, as Dahaba reviewed [4]. It is natural that the EMG is expected to be closely related to a rise in BIS [8–16].

Actually, EMG activity has been reported to falsely increase BIS, and the reliability of BIS should therefore be carefully considered in the absence of muscle relaxants [15]. Conversely, EMG seems necessary to constitute the high BIS indicative of an awake condition, because neuromuscular block alone was found to cause low BIS suggestive of deep sedation and/or anaesthesia in conscious subjects [17–20]. For a paralyzed individual under neuromuscular blockade, BIS may be an unreliable indicator of awareness. EMG thus has the possibility to play a fundamental role in the BIS calculation, rather than distorting otherwise appropriate BIS values. However, how EMG is associated with high BIS score regarded as reflecting light anaesthesia is not apparent.

We hypothesized that the EMG is essential in constituting high BIS, rather than interfering with BIS. The present study intended to clarify the respective contributions of

✉ Kazuko Hayashi
zukko@koto.kpu-m.ac.jp

[1] Department of Anesthesiology, Kyoto Chubu Medical Center, Yagi Ueno 25, Nantan, Kyoto 629-0917, Japan

[2] Department of Anesthesiology and Critical Care, Kyoto Prefectural University of Medicine, Kyoto, Japan

EMG and various electroencephalogram (EEG) parameters to high BIS using a receiver operating characteristic (ROC) analysis, to examine what causes the high BIS predicting shallow anaesthesia.

2 Methods

This postoperative observational study was approved by the Institutional Review Board for Human Experiments at Kyoto Chubu Medical Center, Kyoto, Japan. Written, informed consent for analysing and publishing their EEGs for this investigation was obtained from all patients. We enrolled all adult (> 18 years old) patients scheduled for general anaesthesia in Kyoto Chubu Medical Center from November 2017 to April 2018 who we were scheduled for anaesthesia. Cases monitored by motor evoked potentials were excluded. We were able to analyze data from 79 general anaesthesia patients (40 men, 39 women; mean age, 54.6 ± 21.2 years; range 18–91 years). Eight patients underwent propofol sedation and spinal anaesthesia, and no muscle relaxant was administered. All other patients received sevoflurane and remifentanil/fentanyl anaesthesia with rocuronium for muscle relaxation. Sugammadex was used for complete antagonism of muscle relaxation at the end of surgery.

A BIS Quatro sensor was mounted on the forehead and connected to a BIS VISTA monitor (Medtronic, Minneapolis, USA). BIS recordings were started after verifying that electrode impedance was < 5 kΩ. Throughout the period of anaesthesia, we obtained all BIS-derived data (processed EEG parameters and related data including raw EEG) output from the BIS VISTA monitor using our online computer system developed by us (EEG analyzer f-PIS monitor; see "Appendix"), with packet transmissions via the serial port. Frontal EMG was available as "EMGLOW" (absolute power in the 70–110 Hz range, value in decibel (dB) with respect to 0.0001 μV^2), calculated by the BIS monitor. A measure of the absolute total power (TP) in the wide frequency range from 0.5 to 30.0 Hz (in dB with respect to 0.0001 μV^2), was derived from the BIS monitor calculation, and was termed "TOTPOW". Other EEG variables collected from the BIS monitor were 95% spectral edge frequency (SEF95, the frequency at which 95% of TP lies below) and signal quality index (SQI, the percentage of good epochs within the last 120 epochs). These values were obtained as averages of the preceding 1 min of EEG data.

In this EEG collection and analyzer system, raw EEG signals from the BIS monitor were collected at a sampling rate of 128 Hz. Continuously, data from the preceding 8-s epoch were bandpass-filtered (0.5–50 Hz), and each epoch was applied to a Blackman window function, followed by fast Fourier transform (FFT) for power spectrum analysis and bispectral analysis, by the similar method described in the previous articles [5–7, 21–26]. Briefly, the bispectrum was calculated, using the following equations, where the epochs were overlapped and summed in 1 min [21–26];

$$\text{Bispectrum}: B(f_1, f_2) = \left| \sum_{i=1}^{L} X_i(f_1) X_i(f_2) X_i^*(f_1 + f_2) \right|$$

The subscript i refers to the epoch number; $X_i(f_1)$: complex value calculated by Fourier transformation of the i-th epoch; $X_i^*(f_1 + f_2)$: conjugate of $X_i(f_1 + f_2)$. SynchFastSlow (SFS), log10 [bispectral power (40–47 Hz)/bispectral power (0.5–47 Hz)], was calculated as a logarithm of the ratio of the sum of the bispectrum activity in the space of 40–47 Hz to the sum of the bispectrum activity in the space of 0.5–47 Hz [6, 7]. BetaRatio, log10 [spectral power (30–47 Hz)/spectral power (11–20 Hz)], was calculated as a logarithm of the ratio of the sum of spectral power in the 30–47 Hz to that in the 11–20 Hz, where the power spectra were averaged in 1 min. In order to calculate SynchFastSlow and BetaRatio, we used the equations and descriptions written in the previous articles [5–7, 21, 22], and referred to the privately communicated information with Aspect Medical Systems (Natick, Massachusetts, USA) concerning the Serial Port Technical Specification (Copyright 2004, Aspect Medical Systems), although the precise detailed method for calculation of BetaRatio and SynchFastSlow remained unclear.

This EEG analyzer also allows frequency-based analyses using multiple bandpass finite impulse response (FIR) filters (transitional width, 0.25 Hz), and total powers of the various frequency ranges can be respectively calculated from the filtered EEG. This enabled estimation of the effect of the different frequency components of EEG on BIS values. Four kinds of TP from filtered EEG were then obtained: TP1 as TP < 11.0 Hz; TP2 as TP at 11.0–20.0 Hz, TP3 as TP at 20.0–30.0 Hz and TP4 as TP at 30.0–50.0 Hz. Finally, all these EEG variables from the BIS monitor were logged every 3 s for postoperative analysis. Among the obtained data, we used points for which SQI was > 50% for analysis, because this indicates good signal quality and reliable values. As a result, a total of 218,418 data points were applied for ROC analysis.

With the aim of conducting ROC analysis of high BIS regarded as reflecting conditions of light anaesthesia, we applied three settings for distinguishing BIS outcome: (1) awakening level of BIS > 80 vs. BIS ≤ 80; (2) super-light anaesthesia of BIS > 70 vs. BIS ≤ 70; and (3) moderate to light anaesthesia of BIS > 60 vs. BIS ≤ 60. For deep anaesthesia level, (4) BIS < 40 vs. BIS ≥ 40 was additionally examined. Finally, nine parameters (SynchFastSlow, BetaRatio, SEF95, EMGLOW, TOTPOW, and the TP subtypes TP1, TP2, TP3, and TP4) were used for ROC analysis concerning the four BIS settings to assess the ability to diagnose

BIS. Area under the ROC curve (AUC) was shown with a 95% confidence interval (95% CI), and the appropriate threshold (cut-off point) was determined using the Youden index, and the sensitivity and specificity of the cut-off point were calculated. ROC curve analysis was examined using predictive analysis software (IBM SPSS Statistics version 25.0, SPSS, Tokyo, Japan). Statistical procedures concerning sample size and power computation for ROC curves was performed by "power.roc.test" [27] using the pROC library in R (version 3.4.2; R Core Team, 2017, Austria, http://www.R-project.org/).

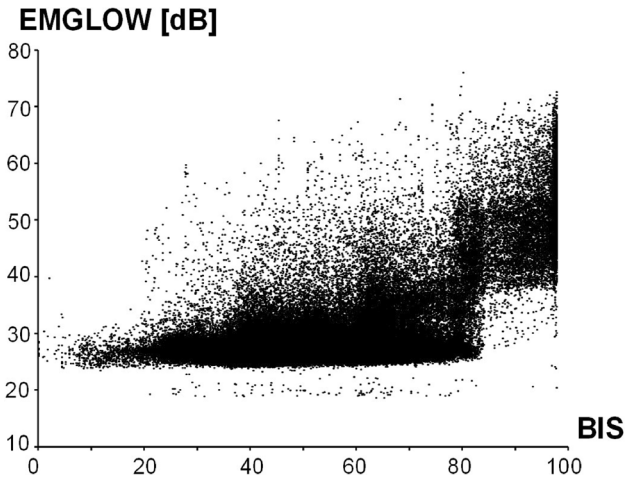

Fig. 1 The relationships between BIS and EMGLOW, simultaneously obtained from BIS monitors, are described in 218,418 points

3 Results

When the power calculation for the two paired ROC curves was examined between EMGLOW and any EEG parameter for predicting BIS > 80, the number of obtained data points (total, 218,418 points) was sufficient to meet the requirements for statistical significance (0.05) and test power (0.95). The relationship between the pair of BIS and EMGLOW, for the total of 218,418 points, obtained at the same time from BIS monitors, is described in Fig. 1. The area where BIS was larger than about 80 attracted our attention. If EMGLOW did not exceed around 35 dB, BIS generally did not reach more than 80. This suggests that EMGLOW may play a role in BIS calculation.

Figure 2 shows diagnosability results for ROC curves when the diagnostic procedure was set to one of the EEG parameters (EMGLOW, SEF95, SynchFastSlow (SFS), BetaRatio (RBR), TOTPOW, TP1, TP2, TP3, or TP4) and when the outcome (evaluation of the predictive value) was set to one of the diagnostic results (BIS > 80, > 70, > 60, or < 40). The summary of EEG parameters (EMGLOW, SEF95, SynchFastSlow, BetaRatio, TOTPOW, TP1, TP2, TP3, and

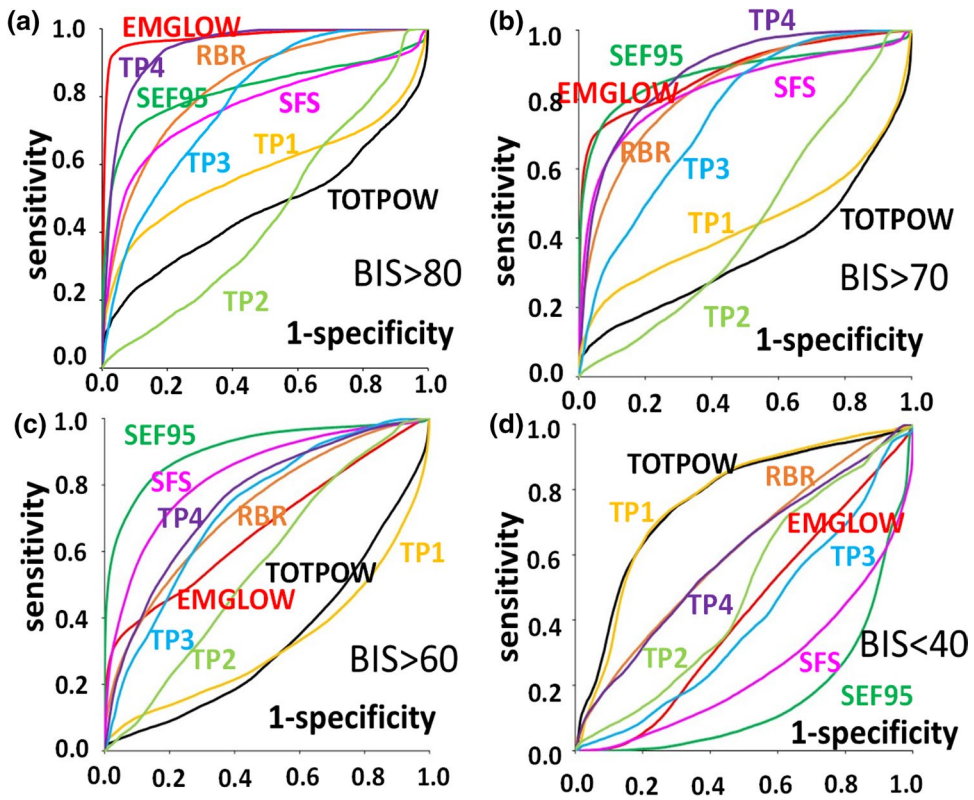

Fig. 2 Diagnosability results for ROC curves when the diagnostic procedure was set to one of the EEG parameters [EMGLOW, SEF95, SynchFastSlow (SFS), BetaRatio(RBR), TOTPOW, TP1, TP2, TP3, or TP4] and when the outcome (evaluation of the predictive value) was set to one of the diagnostic results (BIS > 80, >70, > 60, or < 40), are shown. **a** BIS > 80, **b** BIS > 70, **c** BIS > 60, **d** BIS < 40. EMGLOW (red line); RBR, BetaRatio (orange); SEF95 (green); SFS, SynchFastSlow (pink); TOTPOW, total power of 0.5–30.0 Hz (black); TP1, total power of < 11 Hz (yellow); TP2, total power of 11–20 Hz (light green); TP3, total power of 20–30 Hz (blue); TP4, total power of 30–50 Hz (purple)

TP4), when BIS was divided by criterion (80, 70, 60, and 40) into two groups, is shown in Table 1. Area under the ROC curve (AUC), threshold (cut-off) as determined by Youden index, and sensitivity and specificity at the cut-off are shown in Table 2. The threshold for EMGLOW to distinguish BIS > 80 was 35.7 dB, showing high sensitivity (92.5%) and high specificity (96.5%). TP4 (total power at 30–50 Hz) also showed high sensitivity (91.0%) and high specificity (83.8%) for detecting BIS > 80 at a threshold of 49.2 dB. For detecting the anaesthesia level of BIS > 70, EMGLOW, TP4, SEF95, BetaRatio, and SynchFastSlow all showed a high AUC, larger than 0.8. In particular, EMGLOW again showed the high specificity (94.3%) at the threshold of 31.8 dB. The best parameter for predicting the anaesthesia level of BIS > 60 was SEF95. The AUC was 0.908 (0.907–0.910) at the threshold of 17.2 Hz, with high sensitivity (81.1%) and high specificity (86.1%). However, the highest specificity was obtained using EMGLOW (94.8%). For detecting the deep anaesthesia level of BIS < 40, TP1 and TOTPOW were effective, but the above-mentioned parameters of EMGLOW, TP4, SEF95, BetaRatio, and SynchFastSlow did not contribute.

The results of the ROC curves previously described in Fig. 2 are summarized by the EEG parameters of EMGLOW, BetaRatio (RBR), SEF95, and SynchFastSlow (SFS), respectively, in Fig. 3. Concerning EMGLOW, high specificity was again obvious throughout the results at BIS > 60, BIS > 70, and BIS > 80. BetaRatio showed better ability for detecting the higher BIS level of BIS > 70 and BIS > 80, rather than BIS > 60. SEF95 and SynchFastSlow contributed to diagnosis with the relatively low BIS criterion of BIS > 60 rather than BIS > 80. Furthermore, SynchFastSlow was found to show a stable ability to judge BIS at a wide level of light anaesthesia, with BIS > 60, BIS > 70, and BIS > 80, similar to SEF95.

4 Discussion

The present study showed that EMGLOW distinguishes the state of BIS > 80 with quite high sensitivity and high specificity. For the prediction of BIS > 70, EMGLOW has high sensitivity, similar to processed EEG parameters such as BetaRatio, SEF95 and SynchFastSlow. Moreover, the specificity is higher (low false-positive rate) than other parameters. The BIS during light anaesthesia is statistically produced using a complex proprietary algorithm from combined subcomponents, such as the frequency-domain BetaRatio and bispectral-domain SynchFastSlow, whereas EMG has been reported as not included among these subcomponents [5, 17, 28]. Therefore, the strong diagnosability of EMGLOW for high BIS level found in this study is noteworthy, indicating that a high BIS score is tightly correlated with EMG, and that EMG has the possibility of participating in the constitution of BIS, via pathway other than the described BIS subcomponents. Although it is natural that EMG influence the BIS calculation because EMG contaminates EEG in the frequency range of BIS subcomponents, the present study presents the likelihood that BIS monitor uses another parameter like EMGLOW for the calculation of BIS index in most high BIS level. Indeed, EMG activity conspicuously influenced high BIS (> 80) through EMGLOW (70–110 Hz) by the threshold of 35.7 dB, with extremely high sensitivity and specificity, which is the different frequency area not reflected in BIS subcomponents.

Among the empirically used EEG subparameters for BIS score, BetaRatio has been shown to provide a sensitive indicator of the transition between consciousness and unconsciousness in subjects and is reported to largely determine the BIS in the 60–100 range [5, 6, 29, 30]. SynchFastSlow can also predict the awake or anaesthetized state, but is not superior to the analogous power spectral

Table 1 The summary of EEG parameters, when BIS was divided by criterion (80, 70, 60, and 40) into two groups, is shown, as mean (standard deviation)

	BIS > 80	BIS ≤ 80	BIS > 70	BIS ≤ 70	BIS > 60	BIS ≤ 60
n	15,471	202,947	26,637	191,781	71,810	146,608
BIS	91.7 (6.3)	51.1 (12.2)	84.5 (9.9)	49.8 (11.1)	71.4 (11.9)	45.5 (9.1)
EMGLOW (dB)	47.9 (8.4)	27.6 (3.5)	41.1 (11.2)	27.3 (3.0)	32.8 (9.8)	27.1 (2.6)
RBR	− 0.39 (0.29)	− 0.78 (0.29)	− 0.41 (0.29)	− 0.80 (0.28)	− 0.58 (0.30)	− 0.84 (0.27)
SEF95 (Hz)	22.0 (5.7)	15.7 (3.6)	22.0 (4.8)	15.3 (3.3)	20.0 (3.7)	14.3 (2.7)
SFS	− 1.85 (0.46)	− 2.24 (0.31)	− 1.82 (0.41)	2.27 (0.28)	− 1.96 (0.32)	− 2.34 (0.26)
TOTPOW (dB)	60.8 (6.1)	60.4 (3.5)	59.4 (5.3)	60.5 (3.4)	59.2 (3.8)	61.0 (3.5)
TP1 (dB)	71.5 (7.6)	68.8 (4.0)	69.1 (6.9)	69.0 (3.9)	67.7 (5.1)	69.7 (3.8)
TP2 (dB)	57.8 (4.7)	58.2 (4.9)	57.7 (4.4)	58.3 (5.0)	58.9 (4.3)	57.9 (5.1)
TP3 (dB)	55.4 (4.6)	50.0 (4.9)	54.5 (4.7)	49.8 (4.9)	53.1 (4.6)	49.1 (4.8)
TP4 (dB)	57.3 (5.9)	45.4 (4.6)	54.1 (6.6)	45.2 (4.5)	49.6 (6.3)	44.6 (4.4)

RBR BetaRatio, *SFS* SyncFastSlow, *TOTPOW* total power in 0.5–30.0 Hz, *TP1* total power in < 11 Hz, *TP2* total power in 11–20 Hz, *TP3* total power in 20–30 Hz, *TP4* total power in 30–50 Hz

Table 2 Area under the ROC curve (AUC), threshold, sensitivity and specificity at the threshold, are shown

	AUC (95% CI)	Threshold	Sensitivity	Specificity
BIS > 80				
EMGLOW	0.975 (0.974–0.977)	35.7 (dB)	92.5 (%)	96.5 (%)
RBR	0.832 (0.828–0.835)*	−0.568	72.9	77.6
SEF95	0.821 (0.817–0.826)*	20.1 (Hz)	70.8	89.4
SFS	0.769 (0.764–0.774)*	−1.974	64.0	84.1
TP3	0.784 (0.781–0.788)*	50.8 (dB)	82.9	58.6
TP4	0.943 (0.942–0.944)*	49.2 (dB)	91.0	83.8
BIS > 70				
EMGLOW	0.880 (0.877–0.883)	31.8 (dB)	70.6	94.3
RBR	0.833 (0.831–0.836)*	−0.583	71.8	78.5
SEF95	0.876(0.873–0.879)	19.7 (Hz)	75.5	90.7
SFS	0.830 (0.827–0.834)*	−2.007	70.8	84.7
TP3	0.755 (0.752–0.758)*	49.6 (dB)	85.9	52.5
TP4	0.878 (0.876–0.880)	48.6 (dB)	76.5	82.1
BIS > 60				
EMGLOW	0.670 (0.668–0.673)	30.9 (dB)	34.6	94.8
RBR	0.729 (0.727–0.731)*	−0.696	63.5	69.0
SEF95	0.908 (0.907–0.910)*	17.2 (Hz)	81.1	86.1
SFS	0.832 (0.830–0.834)*	−2.164	75.0	77.1
TP3	0.730 (0.728–0.732)*	49.9 (dB)	74.2	61.9
TP4	0.758 (0.756–0.761)*	45.0 (dB)	76.2	63.5

*Statistical significance (0.05) and test power (0.95), when compared with EMGLOW, in two paired ROC curves power calculation test

parameter [30]. Our results show that EEG parameters SEF95, BetaRatio, SynchFastSlow, and TP4, as well as EMGLOW, effectively detect BIS > 70. Although our results thus did not contradict previous reports [30], these findings add important information on the contribution of EMG to previous reports concerning BIS formation. Clinically, we sometimes meet the scene where BIS is increased, and we are wondering how we should interpret this. Our finding presents a fact that BIS is unlikely to increase when muscle relaxants are used. In that case, BIS seldom rises beyond 80, even if the patient is awake. An increase of the BIS value around 70 may result from both effects of EEG and EMG on BIS subcomponents. How EMG contributes to high BIS around 70 may vary, depending on the presence or absence of muscle relaxants, depending on the dosing of hypnotic agents and depending on individual factors such as the age. Our study demonstrates the importance of recognizing that EMG activity contributes considerably to high BIS values.

The best performance for detection of awareness was reportedly achieved by the higher-frequency components (> 30 Hz) of the monitored EEG [29–31]. In the present study, we therefore used TP in various frequency ranges as the subject of examination for ROC analysis, in addition to the well-known EEG parameters and EMGLOW. The present results showed that total power in the 30–50 Hz frequency range (TP4) shows good performance for detecting a high BIS of > 80, next to the EMGLOW parameter. Our result was again compatible with previous research emphasizing the importance of higher-frequency components in the detection of awareness, although our target was BIS values, not

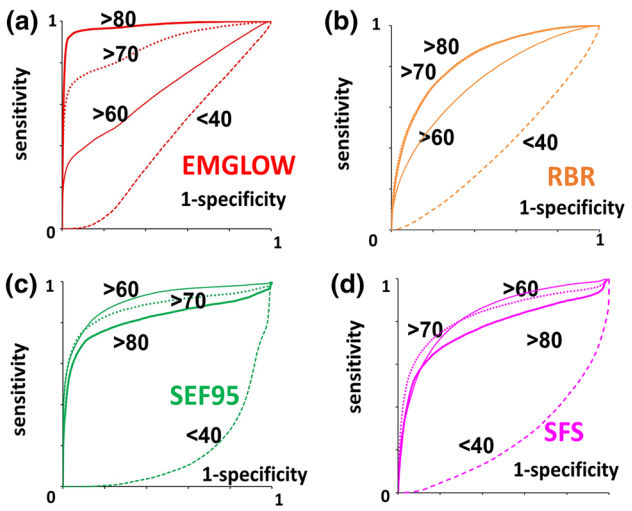

Fig. 3 The results of the ROC curves are summarized by the EEG parameters of **a** EMGLOW, **b** RBR (Beta Ratio), **c** SEF95 and **d** SFS (SynchFastSlow), respectively. Bold line, BIS > 80; dotted line, BIS > 70; thin line, BIS > 60; dashed line, BIS < 40

detection of awareness. The origin of the observed higher-frequency EEG such as 30–50 Hz frequency components was unclear, because the frequency of the EEG generally overlaps that of the EMG in the wide frequency area, again. However, EMG power considerably surpasses EEG power in such high-frequency areas. In fact, at frequencies > 20 Hz, the EMG of an awake subject is reported to be between 6- and 100-times greater than their EEG [17], and EMG from the scalp was greatest at 20–30 Hz frontally and at 40–80 Hz temporally [2, 3]. We therefore think that TP4 is also primarily derived from EMG, although the high-frequency components of true EEG, such as γ and β waves, may be increased under conditions of light anaesthesia.

The present study used ROC analysis as a statistical measure enabling quantitative evaluation between the diagnostic procedure (EEG parameters) and diagnostic outcome (BIS). The key advantages are the independence from scale units and the lack of need for assumptions on distribution patterns [32–35]. Concerning the selection of BIS criteria, we selected three stages of BIS (that is, BIS > 80, BIS > 70, and BIS > 60) for light anaesthesia level, and selected BIS < 40 for deep anaesthesia level. Values > 80 reportedly indicate that the patient is awake, values between 60 and 80 indicate a sedation level such that the patient may respond purposefully to stimulus, and values between 40 and 60 are thought to reflect a level of unconsciousness suitable for surgery [17]. We therefore considered that our application of graded BIS criteria (BIS > 60, >70, > 80) was suitable for appropriate staging of light anaesthesia in this study, although this selection remains somewhat arbitrary.

Because the present research was a postoperative observation study, the time course of anaesthesia and/or the timing of muscle relaxant antagonism were not unified. This indicates the relationship between brain anaesthesia level and EMG varies between cases. We consider this a limitation of the study, but possibly reflective of the general real clinical setting, where BIS is monitored. Our aim was to examine the comprehensive relationship between BIS and EMG under clinical conditions. Another limitation is the calculation method of BetaRatio and SynchFastSlow, in this study. Although we calculated these BIS-subcomponents based on previous research [4–7, 21–26], the precise algorithm used for calculation in the BIS monitor has not been opened. Therefore, our parameters, BetaRatio and SynchFastSlow, may not necessarily agree to those calculated in BIS monitor, which could cause some errors in our results concerning BetaRatio and SynchFastSlow.

In summary, EMG contributes considerably to the diagnosis of high BIS, and is particularly essential to determine a high BIS score > 80.

Funding This work was partly supported by a Grant-in-Aid for Scientific Research (C) from the Japan Society for the Promotion of Science (JSPS KAKENHI No. 15K10518), Tokyo, Japan.

Compliance with ethical standards

Conflict of interest The authors declare that they have no conflict of interest.

Appendix

EEG analyzer f-PIS monitor

The EEG analyzer f-PIS monitor (Fourier-analysis-coordinated Poincare-plot Integrated Score monitor) is an electroencephalogram analyzer for anaesthesia depth, developed by one of our co-authors (T. Sawa). Briefly, using the JAVA Apache Commons Math library for arithmetic functions and the JAVA Swing library for GUI, he developed an online system that enables transmission and various analyses of EEG packets from the BIS monitor. In the system, frequency analysis with multiple FIR-filters is available, as well as bispectral analysis and power spectral analysis from captured EEG. "Processing 3" supported by JAVA was used to develop this system. He compiled the program codes with a JAVA virtual machine and created a standalone application software named "EEG analyzer f-PIS monitor" (Version 45_SR, 46_SR) [36].

References

1. Whitham EM, Pope KJ, Fitzgibbon SP, et al. Scalp electrical recording during paralysis: quantitative evidence that EEG frequencies above 20 Hz are contaminated by EMG. Clin Neurophysiol. 2007;118:1877–8.
2. Goncharova II, McFarland DJ, Vaughan TM, Wolpaw JR. EMG contamination of EEG: spectral and topographical characteristics. Clin Neurophysiol. 2003;114:1580–93.
3. Kamata K, Aho AJ, Hagihira S, Yli-Hankala A, Jantti V. Frequency band of EMG in anaesthesia monitoring. Br J Anaesth. 2011;107:822–3.
4. Dahaba AA. Different conditions that could result in the bispectral index indicating an incorrect hypnotic state. Anesth Analg. 2005;101:765–73.
5. Rampil IJ. A primer for EEG signal processing in anesthesia. Anesthesiology. 1998;89:980–1002.
6. Morimoto Y, Hagihira S, Koizumi Y, Ishida K, Matsumoto M, Sakabe T. The relationship between bispectral index and electroencephalographic parameters during isoflurane anesthesia. Anesth Analg. 2004;98:1336–40.
7. Sleigh JW, Steyn-Ross DA, Steyn-Ross ML, Williams ML, Smith P. Comparison of changes in electroencephalographic measures during induction of general anesthesia: influence of the gamma frequency band and electromyogram signal. Br J Anaesth. 2001;86:50–8.
8. Dahaba AA, Bornemann H, Hopfgartner E, et al. Effect of sugammadex or neostigmine neuromuscular block reversal on bispectral index monitoring of propofol/remifentanil anaesthesia. Br J Anaesth. 2012;108:602–6.

9. Aho AJ, Kamata K, Yli-Hankala A, Lyytikäinen LP, Kulkas A, Jäntti V. Elevated BIS and entropy values after sugammadex or neostigmine: an electroencephalographic or electromyographic phenomenon? Acta Anaesthesiol Scand. 2012;56:465–73.
10. Russell IF. The ability of bispectral index to detect intraoperative wakefulness during total intravenous anaesthesia compared with the isolated forearm technique. Anaesthesia. 2013;68:502–11.
11. Andrzejowski JC, Carroll TA. Inappropriate elevation of bispectral index and disruption of neurosurgery after irrigation induced facial nerve irritation. Br J Anaesth. 2007;99:750–1.
12. Liu N, Chazot T, Huybrechts I, Law-Koune J-D, Barvais L, Fischler M. The influence of a muscle relaxant bolus on bispectral and Datex-Ohmeda entropy values during propofol remifentanil induced loss of consciousness. Anesth Analg. 2005;101:1713–8.
13. Vivien B, Di Maria S, Ouattara A, Langeron O, Coriat P, Riou B. Overestimation of Bispectral Index in sedated intensive care unit patients revealed by administration of muscle relaxant. Anesthesiology. 2003;99:9–17.
14. Panousis P, Heller AR, Burghardt M, Bleyl JU, Koch T. The effects of electromyographic activity on the accuracy of the Narcotrend® monitor compared with the Bispectral Index during combined anaesthesia. Anaesthesia. 2007;62:868–74.
15. Bruhn J, Bouillon TW, Shafer SL. Electromyographic activity falsely elevates the bispectral index. Anesthesiology. 2000;92:1485–7.
16. Vasella FC, Frascarolo P, Spahn DR, Magnusson L. Antagonism of neuromuscular blockade but not muscle relaxation affects depth of anaesthesia. Br J Anaesth. 2005;94:742–7.
17. Schuller PJ, Newell S, Strickland PA, Barry JJ. Response of bispectral index to neuromuscular block in awake volunteers. Br J Anaesth. 2015;115(1):i95–103.
18. Messner M, Beese U, Romstock J, Dinkel M, Tschaikowsky K. The bispectral index declines during neuromuscular block in fully awake persons. Anesth Analg. 2003;97:488–91.
19. Chakrabarti D, Surve RM, Bs D, Masapu D. Intraoperative aberrant bispectral index values due to facial nerve monitoring. J Clin Anesth. 2017;37:61–2.
20. Hayashi K. Inappropriately low bispectral index of the elderly during emergence from sevoflurane anesthesia. J Clin Anesth. 2016;34:279–81.
21. Sigl JC, Chamoun NG. An introduction to bispectral analysis for the electroencephalogram. J Clin Monit Comput. 1994;10:392–404.
22. Hagihira S, Takashina M, Mori T, Mashimo T, Yoshiya I. Practical issues in bispectral analysis of electroencephalographic signals. Anesth Analg. 2001;93:966–70.
23. Araki R, Hayashi K, Sawa T. Dopamine D2-receptor antagonist droperidol deepens sevoflurane anesthesia. Anesthesiology 2018;128:754–63.
24. Hayashi K, Mukai N, Sawa T. Simultaneous bicoherence analysis of occipital and frontal electroencephalograms in awake and anesthetized subjects. Clin Neurophysiol. 2014;125:194–201.
25. Hayashi K, Sawa T, Matsuura M. Anesthesia depth-dependent features of electroencephalographic bicoherence spectrum during sevoflurane anesthesia. Anesthesiology. 2008;108:841–50.
26. Hayashi K, Tsuda N, Sawa T, Hagihira S. Ketamine increases the frequency of electroencephalographic bicoherence peak on the alpha spindle area induced with propofol. Br J Anaesth. 2007;99:389–95.
27. Obuchowski NA, McClish DK. Sample size determination for diagnostic accuracy studies involving binormal ROC curve indices. Stat Med. 1997;16:1529–42.
28. Johansen JW, Sebel PS. Development and clinical application of electroencephalographic bispectrum monitoring. Anesthesiology. 2000;93:1336–44.
29. Miller A, Sleigh JW, Barnard J, Steyn-Ross DA. Does bispectral analysis of the electroencephalogram add anything but complexity? Br J Anaesth. 2004;92:8–13.
30. Schneider G, Schöniger S, Kochs E. Does bispectral analysis add anything but complexity? BIS sub-components may be superior to BIS for detection of awareness. Br J Anaesth. 2004;93:596–7.
31. Dressler O, Schneider G, Stockmanns G, Kochs EF. Awareness and the EEG power spectrum: analysis of frequencies. Br J Anaesth. 2004;93:806–9.
32. Zand F, Hadavi SM, Chohedri A, Sabetian P. Survey on the adequacy of depth of anaesthesia with bispectral index and isolated forearm technique in elective Caesarean section under general anaesthesia with sevoflurane. Br J Anaesth. 2014;112:871–8.
33. Jordan D, Steiner M, Kochs EF, Schneider G. A program for computing the prediction probability and the related receiver operating characteristic graph. Anesth Analg. 2010;111:1416–21.
34. Hino M, Mihara T, Miyazaki S, et al. Development and validation of a risk scale for emergence agitation after general anesthesia in Children: a prospective observational study. Anesth Analg. 2017;125:550–55.
35. Mathews DM, Clark L, Johansen J, Matute E, Seshagiri CV. Increases in electroencephalogram and electromyogram variability are associated with an increased incidence of intraoperative somatic response. Anesth Analg. 2012;114:759–70.
36. Sawa T, EEG analyzer f-PIS monitor. http://anesth-kpum.org/blog_ts/?p=559, (Ver.46_SR) and p = 373, (Ver.45_SR). Accessed 6 Dec 2017.