Phonomyography of the corrugator supercilii muscle: signal characteristics, best recording site and comparison with acceleromyography

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Background. This study investigated the acoustic signal characteristics and best recording site of phonomyography at the corrugator supercilii muscle and compared phonomyography with acceleromyography.

Methods. In 12 patients (group I), after induction of anaesthesia and insertion of a laryngeal mask, a microphone (frequency range 2.5 Hz to 10 kHz) was placed on six different areas on the forehead and the peak-to-peak response after single-twitch stimulation of the facial nerve was measured. The microphone was placed where the response was largest and mivacurium 0.2 mg kg⁻¹ was administered. Fast Fourier transformation was applied to all signals to determine peak frequencies and the power–frequency relationship at different stages of neuromuscular block. In an additional 15 patients (group II), the same microphone and an acceleromyographic probe were placed above the middle portion of the left and right eyebrows respectively. Onset and offset of neuromuscular block were determined after mivacurium 0.2 mg kg⁻¹.

Results. In all seven women and all five men in group I, the best response was obtained just above the middle portion of the eyebrow. Peak frequency was 4.1 (± 0.9) Hz without neuromuscular block and did not change significantly during onset and offset of neuromuscular block. Ninety per cent of the total signal power was below 40 Hz. In group II, mean onset time and maximum effect measured were 104 (20) s and 76 (10)% respectively using acceleromyography and 134 (30) s and 92 (4)% using phonomyography (P < 0.04). Mean time to reach 25, 75 and 90% of control was 9.5 (2.8), 14 (5.1) and 15.1 (5.3) min respectively using acceleromyography and 6.9 (2.8), 12.5 (5.9) and 13.6 (4.9) min using phonomyography (P < 0.04). Bland-Altman testing revealed significant bias (precision) for onset time, maximum effect and time to reach 25% of control (acceleromyography minus phonomyography) at −30 (38) s, −16 (11)% and 2.6 (2.8) min respectively.

Conclusions. Phonomyography can be used to determine neuromuscular block at the corrugator supercilii muscle. In comparison with acceleromyography, phonomyography tends to measure a longer onset with more pronounced maximum effect and shorter recovery of neuromuscular block.

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The contraction of skeletal muscles generates intrinsic low-frequency sounds,¹ which can be used to monitor neuromuscular block.² ³ The corrugator supercilii muscle is a small muscle under the medial portion of the eyebrow.⁴
where onset and offset of neuromuscular block are shorter and less intense than in the adductor pollicis muscle. The time course of neuromuscular block is similar at the corrugator supercilii muscle and at the larynx.5 6

This study was designed to establish the optimal site for acoustic signal recording of the corrugator supercilii muscle and to analyse the signal using Fourier transformation. Phonomyography was then used to determine onset and offset of neuromuscular block at the corrugator supercilii muscle after mivacurium and to compare it with acceleromyography.

**Patients and methods**

We obtained institutional ethics committee approval and informed consent from all patients. Twenty-seven patients (ASA physical status 1–3) undergoing elective general surgery were included. Pregnant women, patients with neuromuscular, hepatic or renal disease and patients receiving medications known to interact with neuromuscular blocking drugs were excluded. Anaesthesia was induced with propofol 1–2.5 mg kg⁻¹ and remifentanil 0.1–0.5 μg kg⁻¹ min⁻¹. After loss of consciousness, a laryngeal mask was inserted. Anaesthesia was maintained with 1–1.5 minimum alveolar concentration (MAC) sevoflurane in a breathing gas mixture of 30% oxygen in air, and remifentanil 0.05–0.25 μg kg⁻¹ min⁻¹. Minute ventilation was set to maintain $P_{E'CO_2}$ at 3.5–4.5 kPa.

**Phonomyography**

Stimulation of the motor branches of the facial nerve supplying the corrugator supercilii muscle was performed using two Ag/AgCl electrodes (diameter 3.5 cm) (Safelead; Grass Instruments, Astro-Med, West Warwick, USA) at both temporal areas in group I ($n=12$) and the unilateral temporal area in group II ($n=15$). A constant-current stimulator (Innervator; Fisher and Paykel Healthcare, Auckland, New Zealand) generated single-twitch square pulses of 0.2 ms with a current intensity of 20 mA (single twitch 0.1 Hz, train-of-four stimulation once every minute). A small microphone (diameter 1.6 cm; frequency response 2.5 Hz to 5 kHz, signal output 20–40 mV into 1 MΩ (Model 1010, Grass Instruments, Astro-Med, Rhode Island, USA) was taped above the eyebrow for recording the evoked responses of the corrugator supercilii muscle. The microphone signal was amplified and bandpass-filtered between 0.5 and 1000 Hz using an AC/DC amplifier (Model 7P122, Grass Instruments, Astra-Med).

**Acceleromyography**

In 15 patients (group II), two Ag/AgCl electrodes were placed on the right temporal area to stimulate the motor branches of the right facial nerve supplying the corrugator supercilii muscle. They were connected to a TOF watch SX (Organon Instruments, Boxtel, Netherlands) for single-twitch (0.1 Hz) and train-of-four stimulation (once every minute). The acceleromyographic probe of the TOF watch SX was taped above the right medial eyebrow as the microphone on the left side (Fig. 1). Maximum sensitivity of the TOF watch SX was set for all patients.

**Part I**

**Mapping and Fourier analysis**

Twelve patients were included in the first part of the study. The forehead was divided into six areas (Fig. 1A). After stimulation of the facial nerve with single-twitch impulses at 20 mA and 0.1 Hz, the microphone was placed consecutively at areas 1–6, starting medially at area 1 and...
ending at area 6, more distant to the eyebrow. This mapping
was used to determine the site of maximal evoked responses
of the corrugator supercilii muscle. Signals were recorded
and the microphone was placed at the area where the
maximal response was found. After supramaximal stimula-
tion for at least 3 min (20 mA, single-twitch 0.2 ms, 0.1 Hz;
train-of-four stimulation every minute), mivacurium
0.2 mg kg\(^{-1}\) was injected within 5 s in a fast-flowing
infusion of Ringer’s lactate. Phonomyographic monitoring
was maintained until train-of-four responses reached a T4/
T1 ratio of at least 1 or showed no increase for 15 min.

**Signal processing and analysis**
The signals were sampled continuously at 1000 Hz using the
Polyview software package (Astra-Med), digitized, and
stored on a portable microcomputer. The single-twitch
phonomyography signal was measured peak-to-peak and
processed using Fourier transformation to determine the
peak frequency and the power–frequency relationship of the
signal at control stimulation and (at the best recording site)
throughout the period of neuromuscular block. Fast Fourier
analysis was used to calculate the power under various
frequency cut-offs relative to the total power of the
frequency domain under 500 Hz. The cut-offs were 10,
20, 30, 40, 50, 100, 200, 300 and 400 Hz.

**Statistical analysis**
Patient data and all pharmacodynamic variables are pre-
sented as the mean and standard deviation. One-way
analysis of variance (ANOVA) was used to define signifi-
cant differences in signal amplitude among the six areas of
mapping. One-way analysis of variance (ANOVA) was also
used to determine significant differences between the mean
peak frequencies in relation to onset and offset of
neuromuscular block, when the first decrease in the control
amplitude was detected (lag time), at 50% block (onset 50),
maximum blockade and 25, 75 and 90% recovery. \(P<0.05\)
was considered to show a statistically significant difference.
Statistical analysis was performed using a commercial
software package (Statview; SAA Institute, Cary, NC,
USA).

**Part II**

**Comparison between acceleromyography and
phonomyography**
Fifteen patients were included in this part of the study. After
induction of anaesthesia, insertion of the laryngeal mask and
application of the acceleromyography and phonomyogra-
phy monitoring devices at the optimal recording site
determined in part I, supramaximal stimulation (20 mA,
single-twitch 0.2 ms, 0.1 Hz; train-of-four stimulation every
minute) was initiated and after at least 3 min mivacurium
0.2 mg kg\(^{-1}\) was injected within 5 s in a fast-flowing
infusion of Ringer’s lactate solution. Onset and recovery of
neuromuscular block were determined by phonomyography
and acceleromyography. Monitoring was maintained until
train-of-four responses reached a T4/T1 ratio of at least 1 or
showed no increase for 15 min.

**Statistical analysis**
Group size was chosen to achieve a power of more than 0.9,
based on calculation of an expected difference in the mean
onset time of 20% and a standard deviation of 20% of the
mean. Patient data and all pharmacodynamic variables are
presented as mean and standard deviation. Pharmacody-
namic data were compared between phonomyography
and acceleromyography using the paired \(t\)-test; \(P<0.05\)
was considered to show a statistically significant difference. The
extent to which the two methods were in agreement was
tested by the method of Bland-Altman. \(P<0.05\) was
regarded as showing a statistically significant difference.
Statistical analysis was performed with Statview.

**Results**

**Part I**
The mean age of the seven women and five men was 53
(38–78) yr and the mean weight was 71 (19) kg.

**Mapping**
In all patients, the maximum evoked response of the
corrugator supercilii muscle was obtained in area 2 (Fig.
1B), with a mean maximum amplitude of 2.37 (SD 0.67) mV
at a mean peak frequency of 4.13 (0.9) Hz. All other areas
provided signals which were significantly smaller (\(P<0.01\))
but had the same biphasic shape and mean peak frequencies.
In all patients, a signal from the contralateral corrugator
supercilii muscle could be detected at a mean amplitude of
0.8 (0.6) mV; the shape of the acoustic signal was inverted
and its amplitude was 34% of the signal of the ipsilateral
corrugator supercilii.

**Fourier transformation**
The peak frequencies were in the ranges of 2.5 and 5 Hz.
Analysis in the frequency domain showed that signal
recording up to 40 Hz detected 90% of the total signal
power. In three of 12 patients, the microphone recorded
acoustic signals at the same frequency as the patient’s pulse
at a mean amplitude of 0.1 (0.02) mV and a peak frequency
of 3.4 (0.3) Hz, as a monophasic signal. Train-of-four-
evoked stimulation phonomyographic signals showed an
equal height for all four twitches at a mean duration of 2.03
(0.06) s before injection of mivacurium followed by typical
fade.

After complete neuromuscular block, recovery to a T4/T1
ratio of \(\leq 1\) and a height of T1 between 80–120% of control
was reached in all patients.

**Part II**
The mean age of eight women and seven men was 51
(35–79) yr and mean weight was 67 (13) kg. In seven of the
15 patients, time to reach 25% of control twitch height could not be determined by acceleromyography because the maximum effect was less than 75%. Table 1 shows the values for onset and offset of neuromuscular block measured by acceleromyography and phonomyography. There was no significant difference between lag time and the time to reach a 50% decrease in control twitch height between the two methods. The onset time was significantly longer, the maximum effect more pronounced and recovery from neuromuscular block faster when determined by phonomyography in comparison with acceleromyography. Bland-Altman calculations showed significant systematic bias and wide limits of agreements for all pharmacodynamic variables (Fig. 2). Bias, precision and limits of agreement for all variables are presented in Table 2.

**Discussion**

Phonomyography is a quantitative and sensitive monitor of neuromuscular block of the corrugator supercilii muscle. Low-frequency signals can be obtained and clearly distinguished after single-twitch or train-of-four stimulation, and the signal frequency is stable, reproducible and independent of block. Mapping the forehead revealed that the optimal area for recording the acoustic responses of the corrugator supercilii muscle lies not directly over the muscle but more laterally, just above the eyebrow (area 2 in Fig. 1). Peak frequencies were within a narrow range between 2.5 and 5 Hz and did not change significantly throughout the study period; 90% of the signal power can be recorded if the upper frequency of recording is limited to 40 Hz.

The pharmacodynamic data determined using acceleromyography and phonomyography cannot be used interchangeably and differed most significantly in the maximum effect, onset time and time to reach 25% recovery from block (acceleromyography vs phonomyography: 76 vs 92%, 104 vs 134 s and 9.5 vs 6.9 min). With acceleromyography, one obtains a shorter onset time (bias ±30 s), with less maximum effect (bias ±16%), and a longer offset of neuromuscular block (bias for time to reach 25% of control, +2.5 min).

The location of the best recording areas reflects muscle anatomy. It follows the contraction line of vertical frowning from the medial aspect just above the eyebrow (area 1) to the lateral distal site (area 4). The sensitivity of the microphone is such that even in the area where the signal...
response was weakest (area 5). 27% of the maximal signal height could still be recorded. Even acoustic signals from the opposite corrugator supercilii muscle could be recorded, and these reached 34% of the maximal signal height of the same side. It could, however, be easily identified in all patients because of the opposite direction of the signal.

Barry and colleagues have shown that high-pass filtering of the signals at 30 Hz effectively removes artefacts due to motion. According to our frequency domain analysis, however, filtering the signals above 30 Hz would mean that 16% of the signal power would be lost.

The peak frequencies measured for the corrugator supercilii muscle differ substantially from the peak frequencies of other muscles and from signals derived from either voluntary contraction or tetanic stimulation, which are usually in the range of 25 Hz. The acoustic waveform is generated by lateral muscle oscillations. The frequency of these oscillations should correspond to the resonant frequency of the muscle. This explains why different muscles produce acoustic signals with varying resonant frequencies and therefore varying peak frequencies. Different forms of stimulation (e.g. tetanic vs single-twitch stimulation) mobilize different numbers of muscle fibres and generate different forms of contraction of the whole muscle, with different resonant frequencies.

Acceleromyography is the only method which has been used to measure neuromuscular block in the corrugator supercilii muscle. Originally, the acceleromyography probes were designed for use at the adductor pollicis muscle. The acceleration created by the contraction of the corrugator supercilii muscle is much smaller than that of the adductor pollicis muscle, with only minimal displacement of the acceleromyographic probe. The TOF watch SX provides a greater range of sensitivity than the TOF guard (Organon Instruments) to suit different muscles. Maximum sensitivity was set for all patients to ensure the detection of even small values of acceleration. In no patient, however, was a maximum effect greater than 90% block detected using the TOF watch SX. In seven of the 15 patients, time to reach 25% of control could not be detected using acceleromyography because the maximum effect was less than 75% of control. Phonomyography seems to be advantageous for small muscles, such as the corrugator supercilii muscle and the orbicularis oculi muscle, where little kinetic energy is created, because it is based on the measurement of sound generated not by the movement of an effector organ but the muscle contraction itself, i.e. the lateral movement of the muscle fibres.

In conclusion, phonomyography can be used to determine the onset and offset of neuromuscular blockade at the corrugator supercilii muscle. The best position for microphone positioning is in the middle of an area between the medial frontal line and the lateral part of the forehead, just above the eyebrow. Phonomyography and acceleromyography cannot be used interchangeably to determine neuromuscular block at the corrugator supercilii muscle. Acceleromyography demonstrates shorter onset time with lesser maximum effect and longer recovery from block in comparison with phonomyography.

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