Acoustic monitoring of intraoperative neuromuscular block

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Standard methods for accurate intraoperative measurement of neuromuscular block are either expensive or inconvenient and are not used widely. We have evaluated a new method of monitoring neuromuscular block using a low-frequency microphone. The method is based on the phenomenon of low-frequency sound emission by contracting skeletal muscle. Acoustic monitoring (MIC) with an air-coupled microphone was used to evaluate intraoperative neuromuscular block in 25 anaesthetized patients. The MIC recorded the response of the adductor pollicis muscle to supramaximal electrical stimulation of the ulnar nerve with train-of-four stimuli. The ratios of the first response (T1) to control (Tc) were used for evaluation. Data obtained from the MIC were compared with simultaneous recordings, from the same hand, of mechanomyography (FDT), electromyography (EMG) and accelerography (ACC).

Throughout the operative procedure, T1/Tc ratios of the acoustic method correlated with the three reference devices: FDT, 12 patients, 262 data sets, \( r=0.86 \), bias (\%MIC–\%FDT) = mean –5.3 (SD 19.6)%; EMG, 18 patients, 490 data sets, \( r=0.85 \), bias (\%MIC–\%EMG) = –0.39 (20.29)%; and ACC, 13 patients, 328 data sets, \( r=0.91 \), bias (\%MIC–\%ACC) = –3.0 (15.6)%.

We conclude that monitoring intraoperative neuromuscular block by a microphone which transduces low-frequency muscle sounds is clinically feasible.

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Incomplete recovery from intraoperative neuromuscular block has been documented in several studies.1–3 Although it is difficult to separate the role of residual paralysis from that of residual anaesthetic effect or the effects of surgery, significant morbidity and mortality have been ascribed to postoperative respiratory failure and unrecognized residual paralysis.4–6 Thus accurate intraoperative monitoring of neuromuscular block is of considerable clinical importance.

The standard technique of assessing neuromuscular block in the operating room is by measuring the ratio of the fourth to the first twitch of the train-of-four (TOF) in response to supramaximal electrical stimuli, delivered at 0.5-s intervals to a peripheral motor nerve.7 Three devices are currently available for accurate measurement and recording of muscular contraction. Mechanomyography (FDT), based on a force-displacement transducer, is technically difficult to apply in the clinical setting. Electromyography (EMG) is a device that measures electrical muscle activity and has been shown to display inconsistent findings or drug-specific responses.8 9 Accelerography (ACC) measures the acceleration of the thumb and is associated with as yet unexplained differences from the existing standard devices.10 These devices are used infrequently in routine clinical anaesthesia, probably because of high costs and inconvenience. Subjective assessment of TOF fade by visual or tactile means is probably the technique used most commonly although it has been shown repeatedly to be inaccurate and insensitive.11 12

The need for a more easily applied, yet accurate, method of quantifying the degree of motor block motivated us to evaluate an acoustic approach to clinical monitoring of neuromuscular transmission. It is based on the previously established finding that contraction of skeletal muscle generates intrinsic low-frequency sounds.13–15 These acoustic waves propagate to the skin, generating pressure waves which can be recorded by a low-frequency micro-
phone. The amplitude of the acoustic signal has been shown to be proportional to the degree of muscle contraction and thus it can be used as a non-invasive technique to quantify the development of force in human muscle.\(^\text{16}\) We have evaluated the performance of a low-frequency microphone (MIC) in monitoring intraoperative muscular function and compared its performance with that of FDT, EMG and ACC.

**Patients and methods**

We studied 25 patients (aged 20–78 (median 57) yr; 14 females, 11 males) undergoing abdominal or orthopaedic surgery after obtaining approval from the Institutional Ethics Committee and patient consent. All patients were free of neuromuscular, renal or hepatic disease and were not receiving drugs that may alter neuromuscular function other than neuromuscular blocking drugs and anaesthetic agents. Premedication comprised morphine 0.1 mg kg\(^{-1}\) i.m. and/or neuromuscular blocking drugs and anaesthetic agents. The neuromuscular blocking drug. At the end of the procedure, induction with thiopental and before injection of the neuromuscular blocking drug (T1/ TC), was calculated. Intraoperative neuromuscular block was achieved by administration of tubocurarine 0.4 mg kg\(^{-1}\) (n=15), atracurium 0.4 mg kg\(^{-1}\) (n=8) or succinylcholine 1 mg kg\(^{-1}\) (n=2). Additional doses of non-depolarizing neuromuscular blocking drug were administered during surgery as needed. Neuromuscular monitoring began after induction with thiopental and before injection of the neuromuscular blocking drug. At the end of the procedure, neuromuscular block was antagonized with neostigmine 2.5–5 mg and atropine 1.2 mg i.v.

Neuromuscular transmission was assessed by stimulating the ulnar nerve at the wrist with supramaximal TOF stimuli (50–70 mA). The stimuli and the control response were obtained using a commercially available Relaxograph NMT-100 (Datex, Instrumentarium Corp., Helsinki, Finland) which was the source of the stimuli for all four recording devices. The fully supinated hand was strapped and fixed to a supporting board and the thumb was preloaded with a weight of 150 g. Measurements of muscular contraction of the adductor pollicis muscle were obtained simultaneously using three of the following four devices: MIC, ACC, FDT and EMG (hypothenar muscles) (Fig. 1). For technical reasons, ACC and FDT could not be applied simultaneously.

Acoustic signals were obtained by an air-coupled microphone (Mennen-Medical phonocardiogram, 319–001). The MIC, with an overall bandpass of 2–1500 Hz, was secured tightly to the thenar muscles by a ribbon belt (Fig. 1). Power spectrum analysis of the acoustic signal contained major components at approximately 60 and 100 Hz (Matlab version 5.2, Mathworks Inc., USA). The MIC within-patient coefficient of variation for pre-block data was 3.9% (single twitch recordings, compared with 3.5%, 3.4% and 2.9% for ACC, FDT and EMG, respectively). The evoked mechanical response of the muscle was quantified by a force-displacement transducer (Grass FDT-10) or an accelerograph transducer (Grass SPA1) and the signals were passed through a Grass model 7PIE low level pre-amplifier. Electromyography was obtained via standard surface electrodes placed on the hypothenar muscles and connected to a Datex Relaxograph (bandpass filter of 60–400 Hz).

Signals from the three measuring devices and the stimulating signal were recorded continuously on a Nihon Kohden RMG-5104 tape recorder for later analysis. Recording was discontinued during periods of noisy orthopaedic manipulations. The stored data (four channels: MIC, EMG, stimulating current and FDT or ACC) were converted from analogue to digital signals at a sampling rate of 1001 Hz (AT-CODAS card, version 5.43, DataQ), a rate which allows adequate signal description below a certain frequency (compliant with the Nyquist sampling theory). Because of technical difficulties, parts of the data could not be analysed. The final number of patient data sets for comparisons of MIC with FDT, ACC and EMG were 13, 12 and 18, respectively (data sets for each subject consisted of at least 10–15 measurements).

The data obtained from the MIC were analysed using the amplitude of the response and the root mean square of the amplitude response. Both methods yielded comparable results \(r=0.99, n=144, P<0.01\). Accordingly, the amplitude of the MIC responses was used for comparisons with data obtained using the other devices. Data processing consisted of calculating the amplitude response of the first deflection from baseline for the MIC, FDT and ACC signals and the area under the curve for the EMG signal. The ratio of the first response (T1) to the control response (T_C), obtained in each patient before administration of a neuromuscular blocking drug (T1/ T_C), was calculated.

Data are presented as mean (SD) T1/ T_C ratios. Statistical analysis was performed using scatter diagrams, the Mann–Whitney rank sum test, correlation coefficients \(r\) and bias plots \(r^{2}=0.99, n=144, P<0.01\). Accordingly, the amplitude of the MIC responses was used for comparisons with data obtained using the other devices. Data processing consisted of calculating the amplitude response of the first deflection from baseline for the MIC, FDT and ACC signals and the area under the curve for the EMG signal. The ratio of the first response (T1) to the control response (T_C), obtained in each patient before administration of a neuromuscular blocking drug (T1/ T_C), was calculated.

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**Results**

A sample recording of the waveforms generated by the different measuring devices, except for the ACC, is shown in Figure 2. The acoustic signal showed a multiphasic waveform, crossing the baseline several times and then decaying to it, as described previously.\(^\text{13–15}\) The initial EMG response followed the electrical stimulating signal by 3.6
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Before administration of the neuromuscular blocking drug, all four MIC responses were equal in amplitude (Fig. 3A). After injection of the non-depolarizing neuromuscular blocking drug, a gradual decrease in the MIC response to TOF stimulation was observed, resulting in a decrease in T1/Tc and T4/T1 ratio (Fig. 3B). The shape of the microphone-generated wave did not change with varying degrees of neuromuscular block induced by depolarizing or non-depolarizing drugs.

Scatter plots of the T1/Tc ratios for the MIC compared with the other three devices (Fig. 4A, B, C; Table 1) showed a statistically significant correlation for all comparisons ($P<0.001$). Bias plots and the differences between the various devices are summarized in Table 1 and Figure 4D.

E. F. The linear slopes, intercept and bias of MIC were closest to the EMG.

When data were analysed for final recovery of T1/Tc ratios after antagonism of neuromuscular block (Table 2), the plateau of recovery with the microphone was closer to the FDT and ACC than to the EMG. The EMG results demonstrated significantly slower recovery of T1/Tc ratios compared with the MIC ($P<0.05$, Mann–Whitney test).

Discussion

We have demonstrated that acoustic monitoring of neuromuscular activity during anaesthesia correlated closely with monitoring by FDT, EMG and ACC. In our study, a new method based on recording muscle sound with a low-frequency microphone was used to monitor intraoperative neuromuscular block in anaesthetized patients. MIC data agreed well (from $-5\%$ to $-3\%$, $r=0.8–0.9$) with data
Table 1 Statistical comparison of the microphone vs simultaneously obtained mechanomyographical (FDT), electromyographical (EMG) and accelerographical (ACC) ratios of the first response (T1) to the control response (Tc) of the adductor pollicis muscle (T1/Tc). n=Number of data sets. SEE=Standard error of the estimate (units are percentage of supramaximal evoked twitch).

<table>
<thead>
<tr>
<th></th>
<th>FDT (n=262)</th>
<th>EMG (n=490)</th>
<th>ACC (n=328)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Correlation coefficient</td>
<td>0.862</td>
<td>0.847</td>
<td>0.906</td>
</tr>
<tr>
<td>Linear regression data</td>
<td>Slope 0.94</td>
<td>0.98</td>
<td>1.08</td>
</tr>
<tr>
<td></td>
<td>Y intercept</td>
<td>-1.43</td>
<td>0.67</td>
</tr>
<tr>
<td></td>
<td>SEE</td>
<td>19.50</td>
<td>20.31</td>
</tr>
<tr>
<td>Bias (%)</td>
<td>-5.31</td>
<td>-0.39</td>
<td>-3.04</td>
</tr>
<tr>
<td>Precision (%)</td>
<td>19.58</td>
<td>20.29</td>
<td>15.65</td>
</tr>
</tbody>
</table>

Table 2 Comparison of recovery plateau of T1/Tc ratio after antagonism of neuromuscular block. Recovery (from 40–60 s) was compared between the accelerometer and microphone, EMG and microphone, and the force transducer and microphone. Data are mean (SEM).

<table>
<thead>
<tr>
<th>Method of assessment</th>
<th>Recovery of T1/Tc ratios (%)</th>
<th>Patients</th>
<th>P (Mann Whitney)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Accelerator</td>
<td>84.4 (2.8)</td>
<td>8</td>
<td>ns</td>
</tr>
<tr>
<td>Microphone</td>
<td>97.1 (1.8)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>EMG</td>
<td>74.8 (8.5)</td>
<td>7</td>
<td>&lt; 0.05</td>
</tr>
<tr>
<td>Microphone</td>
<td>98.5 (5.9)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Force transducer</td>
<td>100.8 (2.9)</td>
<td>6</td>
<td>ns</td>
</tr>
<tr>
<td>Microphone</td>
<td>91.7 (5.0)</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

obtained from the reference devices, yielding 16–20% precision (Table 1).

The acoustic signals recorded by the MIC were probably derived from movement of muscles during contraction, primarily by transverse resonant vibrations of the fibrils. It is hypothesized that during muscular contraction, a stepwise change in muscle length causes a gradual increase in muscle width, generating brief shock waves, detectable as discrete sound bursts. Sound wave propagation is influenced by the muscle environment, elasticity, variation in tissue densities and the distance to the recording device. Characteristics of the microphone and amplification system also influence the final signal.

Acoustic monitoring (MIC) demonstrated comparable correlations with the mechanically based monitors (FDT and ACC) and with the EMG on overall recordings. While a good correlation has been reported between ACC measurement and FDT, the EMG responses may deviate significantly from a mechanical device. Our limited results during recovery from neuromuscular block showed basal drift of the EMG (Table 2). The values indicate discrepancies between MIC and the other methods available, especially with the EMG, with results closest, but not identical, to the FDT and ACC. The data should be evaluated further and supported by additional studies in more patients before final conclusions can be drawn. It is not surprising that there was some discrepancy between measuring devices which are based on transducing different physical phenomena: kinetic energy (FDT and ACC), electrical activity (EMG) and acoustic energy (MIC). For example, onset times of the different evoked signals, after electrical stimulation of the ulnar nerve, varied between 3.6 (0.3) and 13.2 (1.9) ms, emphasizing the difference between various recording systems.

In the clinical and research setting, the adductor pollicis muscle is the most commonly used muscle for intraoperative monitoring of neuromuscular function. It is the most convenient site for both tactile evaluation and application of recording devices, such as the FDT and ACC. However,
various studies have found significant discrepancies between onset time and extent of block between the adductor pollicis and other more central muscles, such as the diaphragm,21 masseter22 and laryngeal muscles.23 As a topic for future investigation, acoustic monitoring may lend itself more easily than other devices to monitoring central muscles.

In summary, we have tested the clinical usefulness of an additional technique for monitoring intraoperative neuromuscular function in 25 anaesthetized patients. The device is based on transducing muscle sounds with a microphone. The clinical performance of this acoustic monitor was comparable with that of mechanomyography, electromyography and accelerography and further exploration is indicated.

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