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Published in:
Journal of Clinical Neurophysiology

DOI:
10.1097/WNP.0000000000000498

Publication date:
2018

ORIGINAL RESEARCH

Influence of the Montage of Stimulation Electrodes for Intraoperative Neuromonitoring During Orthopedic Spine Surgery

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Purpose: In transcranial electrical stimulation, induced motor evoked potentials (MEPs) are influenced by the montage of stimulation electrodes. Differences are to be examined between coronal and sagittal stimulation.

Methods: Forty-five patients with idiopathic scoliosis were included. Coronal and sagittal montages were obtained by electrode placement at C3C4 and Cz'F using large contact electrodes. Corkscrew and short needle electrodes were additionally placed at C3C4 in five patients. Voltage motor thresholds ($MT_{voltage}$) and MEP amplitudes at 2 times $MT_{voltage}$ ($MEP_{2MTvoltage}$) were obtained of upper and lower extremity muscles. Differences of $MT_{voltage}$ and $MEP_{2MTvoltage}$ at Cz'F and C3C4 and between electrodes were analyzed.

Results: $MEP_{2MTvoltage}$ benefits from coronal positioning. Correlations between $MT_{voltage}$ and impedance were not significant for large electrodes at Cz'F, very low for C3C4, and high for short needles or corkscrew electrodes. $MT_{voltage}$ of short needles and corkscrews was up to 200% higher compared with $MT_{voltage}$ of long needles. $MT_{current}$ is increased by 20% to 30% and 2% to 10% for the arm and leg muscles, respectively.

Conclusions: Biphasic stimulation at C3C4 is advised when constant voltage stimulation is used to monitor the spinal cord during orthopedic spine surgery. $MT_{voltage}$ of corkscrew and small needle electrodes are highly sensitive to electrode impedances.

Key Words: Electrode montage, TcMEP, TESMEP, TES, Threshold, Intraoperative neuromonitoring, Transcranial electrical stimulation.

(J Clin Neurophysiol 2018;35: 419–425)

During orthopedic spine surgery, the integrity of the spinal cord can be monitored using motor evoked potentials (MEPs) elicited by transcranial electrical stimulation (TES). Stimulation electrodes placed in the scalp stimulate axons of the cortex and corticospinal tract of the brain. The evoked action potentials in the corticospinal tract are conducted along the spinal cord, intermediated by motor neurons and neuromuscular junctions before elicitation of muscle MEPs (mMEP). Stimulation variables affecting the amplitude, morphology, and latency of the mMEP have to be optimized.[1,2] One of these variables is the position of the stimulation electrodes in the scalp.

The charge necessary to generate an MEP depends on the 3-dimensional profile of the electric fields in the brain and on the specific location of axons in the motor tract and cortex that project on the recorded muscle groups. Because different structures in the brain have different electrical conductivities, the current flow depends on the anatomy of the traversed structures, such as the scalp, skull/vertebrae, brain, and cerebrospinal fluid (CSF). Different positions of the electrodes result in different pathways along which the currents travel.

Few studies have examined the effects of the positioning of the stimulus electrodes. The optimal electrode position for monophasic current stimulation has the highest elicitability and lowest threshold for C3C4 and C4C3[3] or C3Cz and C4Cz[4] when using a 0.5-ms pulse width. The electrode pairs refer to anode and cathode, respectively. It is suggested that "the cross scalp position achieved a more distributed and possibly deeper stimulating current across the scalp, as opposed to the more focal midline stimulating position."[4] Tomio et al. created 3D head models to visualize the electric field in the brain after transcranial stimulation. They found the stimulation at Cz-inion to have the lowest motor threshold for the lower extremity, compared with Cz'F, C1C2, and C3C4. Lowest thresholds for the upper extremity were found when using C3C4. Tomio explained these results by the orientation of the electric field in relation to the pyramidal tract.[5]

Additionally, the flow of the current depends on the size of both the active and the "return" electrode.[6–10] Previous studies used constant current stimulation and relatively long pulse widths of 200 to 500 μs. Constant current stimulation is known to be less sensitive to local electrode impedances compared to constant voltage stimulation, although it is more sensitive to shunting effects from the scalp. In addition, several (electro-) physiologic differences may exist between voltage and current stimulation. These differences between voltage and current stimulation and longer and shorter pulse widths may become apparent in different optimal placement of stimulation electrodes.

The objective of this study was to evaluate the motor evoked potentials in all extremities induced by transcranial voltage stimulation using pulse widths of 100 μs by comparing sagittal and coronal placed stimulation electrodes during orthopedic spine surgery. To be able to extrapolate the results to a setting using a different kind of stimulation electrodes and to current

The authors have no funding or conflicts of interest to disclose.
All authors contributed in a meaningful way to the preparation of the manuscript.
Poster presentation: 5th ISIN congress, Rio de Janeiro, Brazil, November 12, 2015.
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ISSN: 0736-0258/18/3505-0419
DOI 10.1097/WNP.0000000000000498

stimulation, the different effects of these electrodes on the TES-voltage titration curve are analyzed.

METHODS

Forty-five neurologically healthy patients (mean age 17.4 ± 7.9 years, 38 female and 7 male) diagnosed with idiopathic scoliosis were retrospectively included in the study. The patients underwent posterior instrumented correction for thoracic and lumbar level scoliosis.

The study was performed following all the guidelines for experimental investigation with human subjects required by the institutions. Voltage—mMEP-amplitude curves were obtained of both electrode montages, and the optimum stimulation parameters were defined for each patient separately.[11]

Anesthesia Management

All patients were sedated by total intravenous anesthesia using propofol (maximum of 8 $mg \cdot kg^{-1} \cdot hour^{-1}$), remifentanil (maximum of 0.5 $\mu g \cdot kg^{-1} \cdot minute^{-1}$), and ketamine (2.5 $\mu g \cdot kg^{-1} \cdot minute^{-1}$). Muscle relaxants were not used. During induction of anesthesia, a bolus of propofol and remifentanil was given. Minimally 30 minutes after induction, $MT_{voltage}$ was measured. To maintain adequate spinal cord blood flow, the mean arterial blood pressure (MAP) had to be at least 60 mm Hg. Normothermia was maintained using a warming blanket.

Stimulator

The voltage stimulator of the IONM system (Neuro-guard; JS-center, Bedum, the Netherlands) was used in the clinical procedure for parameter optimization before mMEP monitoring. A bandpass filter was used with a passband from 50 Hz until 2500 Hz (3-dB cutoff level). Positioning of the electrodes was performed in compliance with the standardized 10 to 20 system. Cz' was defined in the midline at 1 cm occipital from the central location of Cz. Two stimulating needle electrodes (Rochester, ref 016393, length 37 mm, diameter 26ga, uncoated) were inserted at Cz' in the opposite direction toward both ears, resulting in an about 6- to 7-cm long cylindrical stimulating surface between C1 and C2. One half of a cautery ground plate electrode over the forehead was used as F (cathode: 3M ref 9160F) (impedance 172 ± 27 Ω). For C3C4, two needle electrodes were used (impedance 299 ± 60 Ω). The center of the electrodes was placed at C3 and C4, 7 cm laterally to Cz on the line between Cz and the earlobes. Input impedances of these electrodes were checked and maintained below 460 Ω.[12] When stimulating Cz'F, a monophasic pulse was applied, where Cz' was used as the anode and F as the cathode. When stimulating C3C4, a biphasic pulse was used to obtain bilateral symmetric mMEPs.

To test the differences between the motor thresholds using different kinds of stimulating electrodes, in addition in five patients, small needle electrodes (stainless steel, 13 mm, 27ga, Medtronic) and corkscrews (stainless steel, Medtronic, DME2002) were placed with their geometric centers of contact surfaces spaced within about 6 mm from the used long needle electrodes at C3C4. The centers of the conducting surfaces were located at C3 and C4.

Study Paradigm

Measurements started with a TES-voltage curve using long needle electrodes. The voltage was increased while keeping all other TES parameters unchanged. Initial settings were interpulse interval (ipi) = 1.1 ms, number of pulses (n) = 5 per train. The pulse width (pw) for monophasic stimulation and each phase of a biphasic pulse was 100 μs (total duration of a biphasic pulse was 200 μs). The voltage was increased in predefined steps starting at 0 V. Subsequently from 25 to 50 V, the voltage was increased in steps of 5 V, from 50 to 150 V in steps of 10 V and from 150 to 250 in steps of 25 V.

Recording of Muscle MEPs

In each patient, mMEPs were measured over the muscle belly of four muscles using two bipolar Ag/AgCl surface monitoring electrodes (3M). The mMEPs in the musculus abductor pollicis brevis (apb), musculus tibialis anterior (ta), and musculus quadriceps rectus femoris (quad) were bilaterally monitored in all patients. Additionally, depending on the level of the spondylodesis, the musculus rectus abdominis (ra) was bilaterally assessed for a thoracic fusion trajectory down to L2 or the musculus gastrocnemius (gas) when fusion extended to levels below L2.

Analysis

The voltage motor threshold ($MT_{voltage}$) of each muscle was defined as the first appearance of the mMEP in the voltage/mMEP-amplitude curve. The peak-to-peak amplitudes of the mMEP of all muscles at 2 times $MT_{voltage}$ were measured ($MEP_{2MTvoltage}$).

Because constant voltage stimulation was used, the voltage provided by the stimulator (Vset) was not equal to the voltage at the tip of the stimulating needles (V_{TES}), which depended on the total electrode impedance. Formula 1 was used to calculate V_{TES}, where $R_{int} = 68\ \Omega$, being the internal resistance of the circuitry including the stimulator at the TES electrodes. The measured impedance between the TES electrodes was impTES. V_{TES} was used for the analysis.

$$V_{TES} = V_{set} \times impTES/(impTES + R_{int}) \qquad 1$$

Statistical analysis was performed using the MANOVA, in which the independent variables were "electrode position" (Cz'F or C3C4), "muscle" where the mMEP was recorded (apb, ta, ra, gas, or quad), and the "side" of the limb (left or right). Dependent variables were $MT_{voltage}$ and $MEP_{2MTvoltage}$. The significance level was $P < 0.05$. To further analyze statistical differences found in the independent variables of the MANOVA, an ANOVA was used for post hoc analysis, using the Bonferroni correction.

To analyze differences between electrodes, correlations between impedance and $MT_{voltage}$ and impedance and $MEP_{2MTvoltage}$ were tested using the Pearson correlation coefficient. $P < 0.05$ was considered significant.

RESULTS

Cz'F versus C3C4

Tables 1 and 2 summarize the descriptives of $MT_{voltage}$ and $MEP_{2MTvoltage}$, respectively, of the muscles for each electrode position and each side.

TABLE 1. Descriptives of $MT_{voltage}$ of the Muscles for Each Electrode Position and Each Side (Mean ± SD)

	$MT_{voltage}$ apb (V)	$MT_{voltage}$ ta (V)	$MT_{voltage}$ quad (V)	$MT_{voltage}$ ra (V)	$MT_{voltage}$ gas (V)
CzF left extremities	70.7 ± 18.4	60.0 ± 16.2	70.2 ± 25.6	70.9 ± 25.4	59.6 ± 14.5
C3C4 left extremities	50.6 ± 26.4	72.6 ± 31.3	78.3 ± 36.0	78.5 ± 33.8	73.8 ± 25.7
CzF right extremities	117 ± 45.2	84.3 ± 33.3	89.1 ± 33.6	99.4 ± 41.1	82.8 ± 34.9
C3C4 right extremities	50.4 ± 21.3	75.6 ± 34.9	76.1 ± 35.4	73.8 ± 25.7	82.8 ± 34.9

The p-p plot showed the data to be right skewed, a log transformation of the data did not change this distribution. The skewness was not caused by outliers or by one of the included muscles. Because the samples are quite large and the MANOVA is not very sensitive to violations of multivariate normality when not caused by outliers, we decided to use the MANOVA.

There was a significant main effect for "electrode position" ($F(2,693) = 8.1$; $P < 0.0005$; $\lambda = 0.98$), for "muscle" $F(8,1386) = 29.9$; $P < 0.0005$; $\lambda = 0.73$), and for "side" ($F(2,693) = 19.7$; $P < 0.0005$; $\lambda = 0.95$). Post hoc analyses showed that the significant differences between both electrode positions were caused by a lower $MT_{voltage}$ at C3C4 (70.1 ± 33.4 V) compared with Cz'F (81.2 ± 34.9 V) ($P < 0.0005$). The $MEP_{2MTvoltage}$ also differed significantly ($P = 0.020$), where the $MEP_{2MTvoltage}$ at C3C4 (689 ± 707 μV) was significantly higher compared with $MEP_{2MTvoltage}$ at Cz'F (572 ± 631 μV).

Interaction effects were found between electrode and side ($F(2,693) = 17.7$; $P < 0.0005$; $\lambda = 0.95$) and between electrode and muscle ($F(8,1386) = 8.4$; $P < 0.0005$; $\lambda = 0.91$). The interaction effects were only significant for $MT_{voltage}$ (electrode × side: $P < 0.0005$, and electrode × muscle: $P < 0.0005$).

The interaction effects between electrode and side were further tested post hoc using an ANOVA. A difference of $MT_{voltage}$ between the left side (66.7 ± 21.1 V) and the right side (95.7 ± 39.7 V) was found when using the Cz'F montage.

The interaction effect between muscle and electrode for $MT_{voltage}$ can be explained by differences at apb, where $MT_{voltage}$ at the apb was higher using Cz'F compared with using C3C4 ($MT_{voltage}$ at Cz'F: 93.6 ± 42.0, $MT_{voltage}$ at C3C4: 50.5 ± 23.7) (Fig. 1).

To determine the effects of the apb on the results of $MT_{voltage}$, post hoc tests were done using an ANOVA with the apb excluded. The significant differences were found between the electrodes ($P = 0.94$) or muscles ($P = 0.16$). The significant difference of $MT_{voltage}$ between both sides was still present ($P = 0.00$), and also the significant interaction between side and electrode still existed.

When only the leg muscles were considered, and the apb was excluded, post hoc analysis using an ANOVA still showed a significant difference between C3C4 (479 ± 476 μV) and Cz'F (394 ± 409 μV) ($P = 0.028$) for $MEP_{2MTvoltage}$.

Electrode Types

The electrode impedances were used to convert $MT_{voltage}$ into estimates of current motor threshold ($MT_{current}$) values. Impedances of large needles were significantly lower compared with both corkscrews and small needles ($P < 0.000$). Impedances of corkscrews were significantly lower compared with small needles ($P = 0.023$). The descriptives are given in Table 3. The impedances of Cz'F were lower compared with C3C4. According to the Pearson correlation, a significant weak correlation ($P = 0.006$) of $r = 0.402$ was found between the impedance at C3C4 and $MT_{voltage}$. A nonsignificant very low correlation was found between impedance and $MT_{voltage}$ for CzF ($r = 0.106$, $P = 0.49$) (Fig. 2).

To better determine the effect of the impedances on the differences of $MT_{voltage}$, MT_{curent} was calculated (Table 3). To express the sensitivity of MTs to the specific electrode impedance, the differences of $MT_{voltage}$ and $MT_{current}$ between the electrodes are given as percentages relative to $MT_{voltage}$ and $MT_{current}$ of the large needles ($\Delta MT_{voltage}LN$ and $\Delta MT_{current}LN$). Highest MT sensitivities were found for voltage stimulation: $\Delta MT_{voltage}LN = 130\%$ for apb and 189% to 200% for ta muscles and marked lower sensitivities for current stimulation with $\Delta MT_{current}LN = 20\%$ to 30% for abp muscles and 2.1% to 9.5% for ta muscles. The highest values applied to corkscrew electrodes (Fig. 3).

DISCUSSION

The results of this study show that both electrode montages Cz'F and C3C4 are effective for the induction of an mMEP in all muscles measured. However, the amplitude of the $MEP_{2MTvoltage}$ benefits from coronal positioning of the electrodes on the head.

TABLE 2. Descriptives of the MEP Amplitude at 2 Times $MT_{voltage}$ ($MEP_{2MTvoltage}$) of the Muscles for Each Electrode Position and Each Side (Mean ± SD)

	$MEP_{2MTvoltage}$ apb (μV)	$MEP_{2MTvoltage}$ ta (μV)	$MEP_{2MTvoltage}$ quad (μV)	$MEP_{2MTvoltage}$ ra (μV)	$MEP_{2MTvoltage}$ gas (μV)
CzF left extremities	987 ± 791	539 ± 483	330 ± 284	405 ± 730	304 ± 258
C3C4 left extremities	1,226 ± 898	595 ± 494	404 ± 327	450 ± 800	345 ± 253
CzF right extremities	1,224 ± 895	472 ± 266	368 ± 390	2,952 ± 419	294 ± 168
C3C4 right extremities	1,400 ± 889	673 ± 430	435 ± 418	327 ± 553	326 ± 554

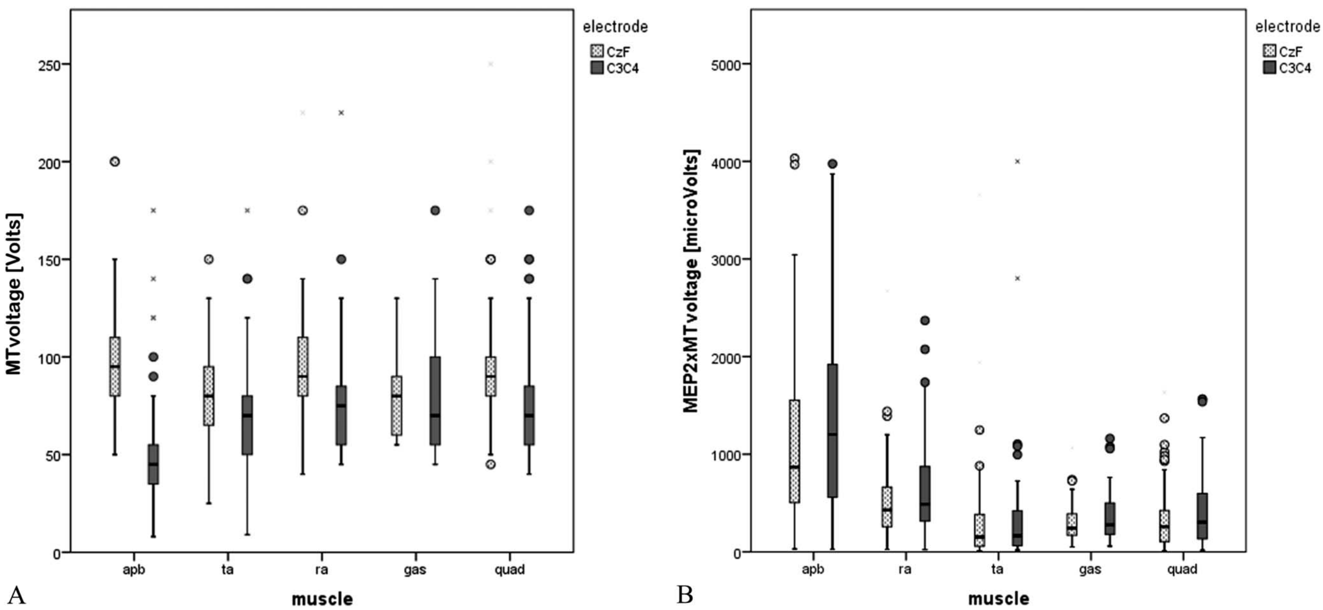

FIG. 1. Boxplots of the MTvoltage (A) and MEP-amplitude (B) at 2 times MTvoltage of bilateral muscle groups. The boxplot shows Q1 to Q3 of the values, with the horizontal line as the Median. The whiskers show the lowest and highest, non-extreme values. The squares are the outliers. All measurements were done using only a single train. Some values are rather low, in these patients a double train had to be used during the surgery. MTvoltage is the true voltage at the electrodes, obtained after correction for the internal resistance according to Formula 1. MEP, motor evoked potential; MT, motor threshold.

The increased mMEP amplitudes of leg muscles for C3C4 compared with Cz'F montages might be the result of the coronal direction of the electrical field, which more or less agrees with the initial course of corticospinal axonal fibers, whereas the course of the electrical field from Cz'F is effectively perpendicular to these axon orientations. In addition, the electrical fields may exert differences in motor facilitation that modulate muscle MEP amplitudes. Axons better depolarize at parallel directions of currents at condensed gradients of electrical fields and curvatures in their course. This is supported by modeling studies calculating the current flow in 3D head models by rendering the axonal courses from dti-mri's and TMS studies in which, in contrast to anterior-posterior directions, latero-medial induction currents are able to produce d-waves.[13–15] Moreover, axons show in TMS-induced electrical fields increased excitability at bendings of axons.[5,16,17]

Relation Between Electrode Type and Transcranial Motor Threshold

To minimize the influence of the impedance on $MT_{voltage}$, we originally choose to use large needle electrodes. We earlier reported the absence of a significant correlation between $MT_{voltage}$ and impedance for Cz'F montages.[12] This is confirmed by this study for Cz'F (172 ± 27 Ω); however, a small but significant correlation was found for C3C4 (299 ± 60 Ω).

In contrast to the large needles, there is a significant high correlation of $MT_{voltage}$ and impedance of corkscrew and small needle electrodes. Two factors controlling the sensitivity of $MT_{voltage}$ to impedance are the contact surface and shape of the electrode. Although $MT_{current}$ is known to be sensitive to differences between electrode types, the geometric shape of the electrode contacts may introduce differences in MTs that applies to both $MT_{voltage}$ and $MT_{current}$. The long contact lengths of the large needle electrodes define wider electrical fields departing from the electrodes compared with small needle and corkscrew electrodes. There will probably be loss of spatial resolution away from the electrodes. Compared with large electrodes, $MT_{current}$ of corkscrew and small needle electrodes is respectively 33% and 20% higher for the apb and for TA 10% and 2%. The larger increases at the apb may be explained by less spatial dispersion at the relatively small distance between electrode and origin of apb bound corticospinal axons. When using transcranial direct current stimulation (tDCS), models have found a spatial extension of the stimulated area when using larger stimulation and reference electrodes.[6,10] Bikson et al.[8] support the larger overlap of cortical areas by using large electrodes. Additionally, large distances between the stimulation electrodes at Cz'F and C3C4 result in deep penetration of the electrical field.[18] The deep penetration causes the current to be more sensitive to the conductivity of the traversed structures such as gray matter, white matter, and CSF.[19] This theory is maintained when the results of the supramaximal mMEPs in this study are considered. When higher voltages are used to receive supramaximal mMEPs, the stimulation will penetrate deeply into the brain and the traversed structures will have a higher impact on the results compared with electrode differences.

It is noted that $MT_{current}$ in this study is estimated based on small signal electrode impedances. These may differ from the actual quotient for stimulation voltages and currents and may

TABLE 3. Impedance, $MT_{voltage}$, and MEP_{amp} of Long Needle Electrodes, Corkscrews and Small Needle Electrodes of the apb and the ta ($n = 5$ Patients and 2 Muscle Groups)

	Imp (Ω)	$MT_{voltage}$ apb (V), $\Delta MT_{voltage}LN$ (%)	$MT_{current}$ apb (mA) $\Delta MT_{current}LN$ (%)	$MT_{voltage}$ ta (V), $\Delta MT_{voltage}LN$ (%)	$MT_{current}$ ta (mA), $\Delta MT_{current}LN$ (%)	MEP_{amp} apb (μV)	MEP_{amp} ta (μV)
C3C4 large needles	245 ± 19	30 ± 6.6	123, —	46 ± 5.0, —	188, —	794 ± 438	1,043 ± 1,156
C3C4 Corkscrew	423 ± 36	69 ± 14, +130%	163, +33%	87 ± 18, +89%	206, 9.5%	656 ± 457	1,108 ± 1,377
C3C4 Small needles	477 ± 70	69 ± 15, +130%	147, +20%	92 ± 13, +100%	192, 2.1%	605 ± 467	915 ± 1,181

The data are indicated as mean ± SD. $\Delta MT_{voltage}LN$ or $\Delta MT_{current}LN$ are the differences of the mean $MT_{voltage}$ or $MT_{current}$ with MTs of the large needle electrodes. $MT_{current}$ is estimated by division of mean $MT_{voltage}$ by mean electrode impedances.

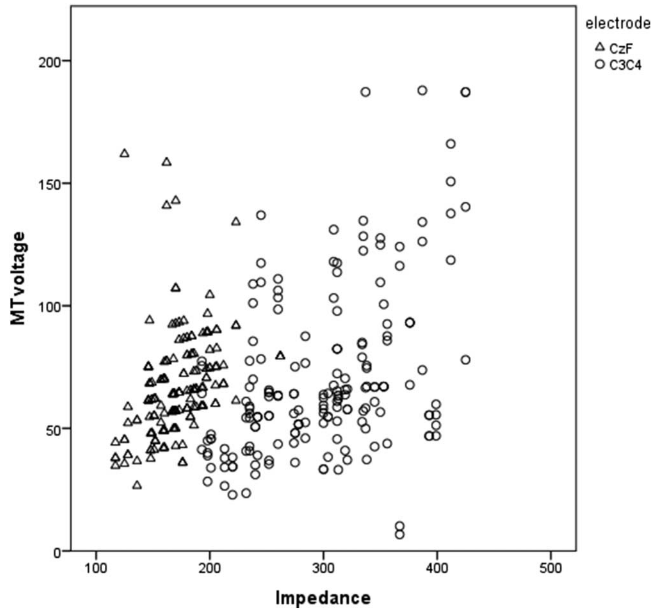

FIG. 2. Scatterplot of the relation between MTvoltage and impedance for electrode position. Every dot reflects one muscle in one patient. MT, motor threshold.

render the absolute values of $MT_{current}$ inaccurate. This is of minor importance when $MT_{current}$ values are compared with each other.

Other biasing factors in this study are a negative bias from the pulse width of 100 μs compared with 50 and 75 μs of most transcranial voltage stimulators and higher MTs from MEPs because of the higher background noise of surface electrodes

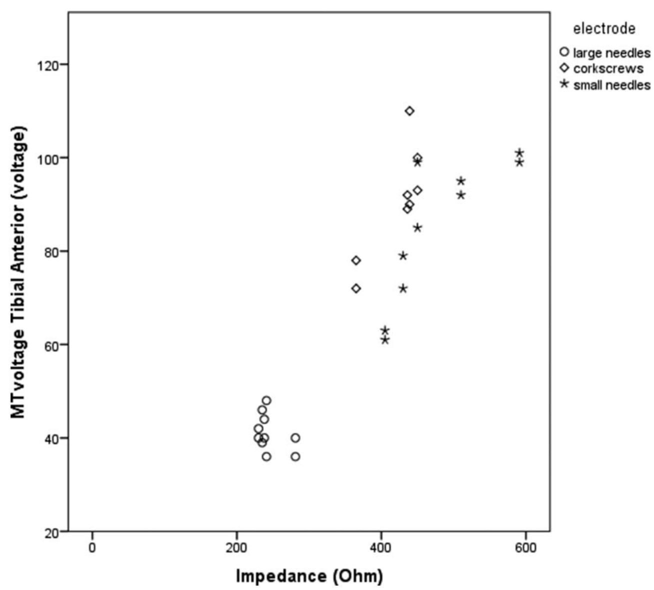

FIG. 3. Scatterplot of the relation between MTvoltage and impedance for electrode type. Every dot reflects one muscle in one patient. MT, motor threshold.

compared with needle electrodes. However, these biasing factors are not essential when comparing MTs because these apply to both electrode montages and shall not change the outcomes of the study.

A surprising finding is the higher $MT_{voltage}$ at the right side using Cz'F (Table 1). Asymmetry is also observed when using C3Cz or C4Cz stimulation,[3] whereas an opposite asymmetry was found using TMS.[20] Previous studies show a higher percentage of right-handedness making a training effect to be unlikely.[21–23] Asymmetric distribution, anatomy, and course of ipsilateral and contralateral pyramidal fibers exposing left-right differences of the pyramidal tract and cortical areas might explain this asymmetry. A reason why $MT_{voltage}$ shows left-right asymmetry for Cz'F, whereas symmetry is preserved for C3C4 montages, may be that the orientation of the electrical field at Cz'F is least optimal for corticospinal axonal orientations at their origin in the corona radiata. Asymmetries in the course of the leg bound axons in the deep midline region may then become apparent.

Because large needle electrodes and a bovie pad are applied in only a few centers, commonly used stimulation electrodes such as corkscrews and small needle electrodes are also considered in this study. Comparing the Cz'F and C3C4 montages, C3C4 seems to be the optimal stimulation site. The different pulse waves—monophasic at Cz'F and biphasic at C3C4— are both optimal choices for generation of symmetrical MEPs. Cz' is a location in the midline between symmetrical located cortical spinal tracts. Monophasic and biphasic stimulation at Cz' are identical because first-phase biphasic anodal stimulation already activates both corticospinal tracts bilaterally, whereas the second cathodal phase is redundant. For symmetrical MEPs at C3C4, biphasic stimulation is essential because only axons at anodal sides will be activated. When, during the first phase, C3 is assigned as anode, the left corticospinal axons will be activated, whereas after this phase, C4 becomes the anode, activating the corticospinal tract of the right hemisphere.

Clinically, when the stimulation voltage, and thus the stimulus depth, is limited, biphasic stimulation is recommended when using C3C4 because according to Table 1 and Szelenyi et al.,[3] the MEP responses are found to be more symmetrical compared with Cz'F. At higher intensities, the near threshold asymmetric responses from Cz'F become symmetrical when all corticospinal axons become activated at deeper locations. Physiologically, the effect of the biphasic stimulus is not completely understood. Influences of conditioning effects from the first to the second phase are not considered in this study. Ukegawa found a higher success rate for inducing an mMEP in the biceps brachii when using biphasic stimulation at C3C4 compared with monophasic stimulation at C3C4 or C4C3. This difference might be the result of the facilitatory effect of the first part of the pulse on the second part when using biphasic stimulation.[24] Ipsilateral activation of the pyramidal tract is demonstrated by studies using monophasic stimulation of C3Cz and C4Cz and finding a bilateral mMEP[3,4,24] and might be induced by transcallosal conduction or by stimulation of deep white matter motor tracts. In adults, however, transcallosal connections usually have inhibiting effects.

This study included only patients with idiopathic scoliosis who were elder than 9 years. The results of our study may not pertain to other patient groups with compromised motor functions, affected neuroanatomic dimensions and location because of tumors, altered tissue compartments, and specific conductances that modify electrical stimulation fields as in hydrocephalus. MTs may also deviate in very young children younger than 4 years with a developing pyramidal system and neural connectivity. Motor thresholds are then usually increased and are found to decrease until adolescence.[20,25–28]

For example, in cerebral palsy (CP), corticospinal connections may be reduced or absent. MT's may be over 3-fold increased to activate the spinal bound motor tracts on the brain stem level including the supportive system.[29]

In conclusion, during orthopedic spine surgery, the use of biphasic stimulation at C3C4 is recommended to obtain symmetric high-amplitude mMEPs because no additional features are expected for sagittal oriented TES electrode montages.

Most prominent differences between stimulation electrodes can be found in the upper extremity, in which large, low impedance stimulation electrodes have lowest voltage motor thresholds by which voltage stimulation characteristics are best preserved.

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