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CLINICAL ARTICLE

Electromyographic assessment of condylar screw placement during occipitocervical fusion

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OBJECTIVE This is a retrospective study of a series of occipitocervical fusion procedures with condylar screw fixation in which the authors investigated the utility of electromyography (EMG, free-running and triggered) as a reliable tool in assessing the positioning of condylar screws. This series consisted of 197 patients between 15 and 60 years of age who presented with craniocervical instability, and who were treated between October 2014 and December 2017.

METHODS Intraoperative free-running EMG was observed at the placement of condylar screws, as well as at realigning of the spine. After placement the condylar screws were stimulated electrically, and the thresholds were recorded. CT scans were obtained intraoperatively soon after screw stimulation, and the results were analyzed by the surgeon in real time. Free-running EMG results and triggered EMG thresholds were tabulated, and the minimum acceptable threshold was established.

RESULTS Intraoperative free-running EMG and triggered EMG were able to correlate alerts with condylar screw placement accurately. A triggered EMG threshold of 2.7 mA was found to be a minimum acceptable threshold. A combination criterion of free-running EMG and triggered EMG alerts was found to enable accurate assessment of condylar screw positioning and placement.

CONCLUSIONS Intraoperative free-running EMG and triggered EMG were both found to be invaluable utilities in assessing the placement and positioning of condylar screws. Stimulation thresholds below 2.7 mA correlated with a superior or anterior condylar breach. Thresholds in the 2.7-mA to 9.0-mA range were generally acceptable but warranted additional inspection by the surgeon. Threshold values above 9.0 mA corresponded with solid condylar screw placement.

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KEYWORDS electromyography; intraoperative neuromonitoring; condylar screws; craniocervical instability; occipitocervical fusion; triggered EMG; cervical

Craniocervical instability (CCI) is a condition with potentially life-threatening consequences. CCI may manifest as disabling pain, cranial nerve (CN) dysfunction, paralysis, or even sudden death.[1–4] There are acute and chronic causes of CCI. Examples of acute CCI include traumatic dislocation of the atlantooccipital joint and complex fractures of the atlas and axis. Chronic causes include rheumatoid arthritis, infections, tumors, and congenital malformation.[2,3,5]

Surgical treatments such as occipitocervical (OC) fusion require a thorough understanding of the complex anatomy of essential bony and soft-tissue elements.[6–10] The neighboring hypoglossal nerve is at risk. On its superior border is the jugular tubercle. The jugular foramen lies superolaterally, and the sigmoid sinus lies laterally. Inferior to the hypoglossal canal is the occipital condyle.[11–14] The first OC fusions reported in the literature were described in 1910 by Pilcher.[15] Since then, the OC fusion techniques have evolved, ranging from cable wires with rods to modern constructs based on screw fixation. Recently, Uribe and colleagues introduced condylar screw fixation as a rescue technique for OC fusions when a craniectomy limits the number of available fixation points on the occipital squama.[16–18] Malpositioned condylar screws can cause injury to the hypoglossal nerve in proximity. An injured hypoglossal nerve causes tongue protrusive deviation to the ipsilateral side of the injury. The tongue may also atrophy, leading to difficulties with mastication, swallowing, and speaking.

ABBREVIATIONS CCI = craniocervical instability; CMAP = compound muscle action potential; CN = cranial nerve; CoMEP = corticobulbar MEP; EMG = electromyography; IONM = intraoperative neurophysiological monitoring; MAT = minimum acceptable threshold; MEP = motor evoked potential; OC = occipitocervical; SSEP = somatosensory evoked potential.

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Intraoperative neurophysiological monitoring (IONM) with motor evoked potentials (MEPs), somatosensory evoked potentials (SSEPs), and electromyography (EMG) is a powerful tool to reduce the risk of injury to neural structures during complex spine surgeries.[19–24] IONM has been widely used for procedures related to CCI.[25–28]

Free-running and triggered EMG have been used to assess the integrity of lumbar, thoracic pedicle, and cervical lateral mass screws.[21,29–31] Given the location of the hypoglossal canal right above the occipital condyles,[5] a significant risk of the procedure is direct damage of the hypoglossal nerve during insertion of the screws through the occipital condyle. Thus, monitoring of the hypoglossal nerve has been recommended for OC fixation.[32] Uribe and colleagues in their single case report used EMG while placing screws.[17] However, no detailed IONM description and systematic assessment reports are available for these procedures to date. We used both spontaneous and triggered EMG to assess condylar screw placement and integrity of the condyles during all stages of the OC fusion procedure.

This paper is the first systematic analysis of the use of EMG for placement of condylar screws. We provide the following: 1) warning criteria of possible condylar wall breach, and 2) criteria to evaluate the safety of condylar screw placement. The study presents data analyses from 197 patients, with a conclusion that IONM is an indispensable component to ensure positive outcomes of OC fusion with condylar screw fixation.

Methods

This study covers 197 OC fusion surgeries in patients between 15 and 60 years of age. Surgeries were performed at various Long Island, New York, hospitals. IONM was performed in all procedures. Our institutional review board approved the study.

Each patient was met in the preoperative holding area. A brief history of the present illness was documented. Informed consent for IONM was obtained from the patient after a thorough description of all modalities used: MEPs and SSEPs to assess both motor and sensory pathways, and CN EMG for the assessment of condylar screw placement. Risks of IONM needle placement, such as tongue hematomas, were explained to the patient. In this study, two patients experienced small (approximately 1 cm) tongue hematomas, which resolved after a few days.

For cases without MEPs, a 0.5-MAC (minimum alveoli concentration) inhalation agent with propofol and remifentanil anesthesia regimen was used. In procedures in which the surgeon requested MEPs, total intravenous anesthesia was used. For MEPs, scalp stimulating arrays were placed at C3, C1, C2, and C4, with interhemispheric montages C1–C2 or C3–C4 and recording from the same sternomastoid, trapezius, and tongue, as well as distal upper and lower extremities, according to the American Society of Neurophysiological Monitoring position statement on MEPs.[19]

Neuromuscular blocking agents were used for induction only. Subdermal needle electrodes were placed at the following 10–20 positions for recording SSEPs following

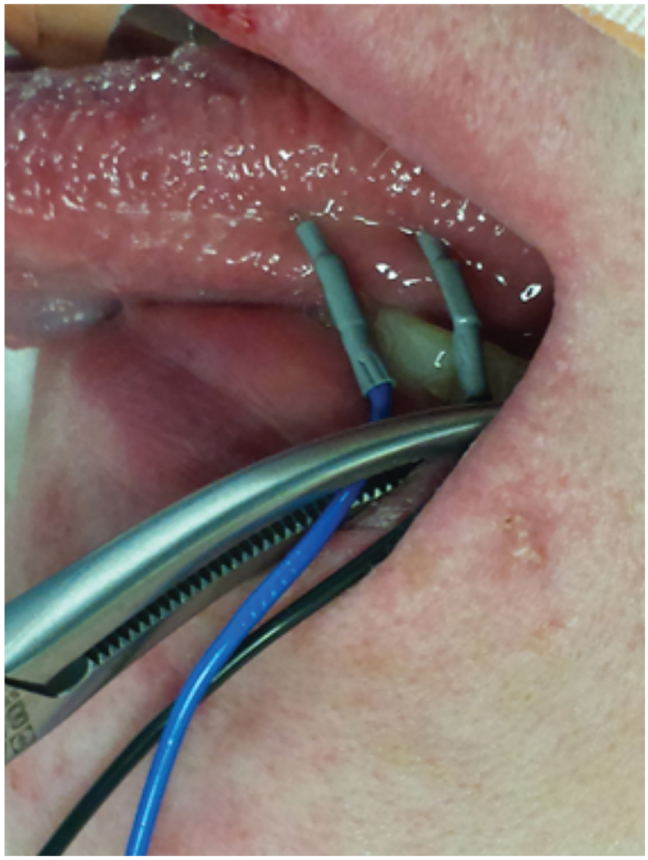

FIG. 1. Placement of subdermal needles into the tongue. Needles are placed in the posterolateral part of the tongue. Please note that the tongue is pulled slightly forward so the posterolateral aspect of the tongue is exposed and available for needle placement.

stimulation of the median nerves (for upper extremities) and posterior tibial nerves (for lower extremities): Cz′; Fpz; C1′; C2′; C3′; C4′; and Cv. To record peripheral responses for upper SSEPs and lower SSEPs, subdermal needle electrodes were placed at the left and right Erb's points and the bilateral popliteal fossa, respectively.

Two pairs of subdermal needle electrodes were placed in the following muscles bilaterally for recording CN EMG: sternocleidomastoid (CN XI), trapezius (CN XI), and tongue (CN XII). Special attention was paid to needle placement in the tongue to ensure that the needles were in its posterolateral aspect (Fig. 1). Neuromuscular junction functionality was assessed by a train-of-four technique from posterior tibial nerve stimulation and recording from the abductor hallucis and was maintained at 4/4 throughout the procedure. Adequate electrical grounding was applied for both upper and lower extremities. All electrodes were connected to a neurophysiological monitoring system (NIM Eclipse; Medtronic).

Baseline EMG and EP data were obtained before positioning the patient prone in a Mayfield frame. Postpositioning data were obtained and compared to prepositioning data. The surgeon adjusted the patient's head positioning and alignment in the event of any changes in postpositioning data in conjunction with radiographic im-

TABLE 1. Summary of screw placement thresholds and incidents

Group	Subgroup	Threshold (mA)	Free-Running EMG Alert
I, n = 21	Ia, n = 14	<2.7	Yes, at placement; breach confirmed by palpation & fluoroscopy
	Ib, n = 7	<2.7	No EMG alert at placement, but breach confirmed by palpation & fluoroscopy
II, n = 90*	IIa, n = 29	2.7–9.0	Yes, on alignment
	IIb, n = 61	2.7–9.0	No
III, n = 283†‡		>9.0	No

* $p < 0.001$, group II vs group I.
† $p < 0.001$, group III vs group II.
‡ $p < 0.001$, group III vs group I.

ages. Two methods of intraoperative imaging were used in our study: 1) intraoperative digital fluoroscopy during the steps of drilling, tapping, and screw placement; and 2) intraoperative CT after repositioning the craniocervical junction in extraction and mild extension.

Monitoring Procedure

EMG settings were as recommended by the American Society of Neurophysiological Monitoring's position statement, with display settings maintained at a 500-msec sweep length and a 20-µV display sensitivity.[33]

EMG monitoring from both CN XII and CN XI is crucial during condyle dissection. However, during hole preparation and condyle screw insertion, the primary focus was on CN XII—tongue EMG due to the risk of perforation or pressure-related breach of the wall of the hypoglossal canal. The surgeon was immediately informed of EMG activity (single spike, burst, or sustained train) observed during insertion and any subsequent activity. In the event of any EMG activity during drilling or screw placement, the surgeon reassessed and modified the trajectory of the screw. The absence of surgically induced EMG activity in the tongue muscle was considered an initial indicator of a safely placed screw, ready for stimulation.

Electrical stimulation of condylar screws was used to assess screw placement safety and integrity of the hypoglossal canal and nerve. Before stimulation, blood, irrigation, and other fluids were suctioned out to reduce possible current shunting. To test the completion of electrical circuitry, the surgeon first stimulated exposed musculature. A subdermal needle electrode, the anode, was inserted into the exposed musculature. A second subdermal needle electrode, the cathode, was also placed in the same musculature. Both electrodes were connected to the stimulator port of the NIM Eclipse. An electrical current stimulus at a rate of 5.1 Hz and 100-µsec duration was applied at an intensity of 10 mA until the surgeon observed muscle fasciculations from the exposed musculature. After confirming the electrical current flow, the surgeon then placed the same cathode directly over the condylar screw. An electrical stimulus at a rate of 5.1 Hz and 100-µsec duration was applied in 0.1-mA increments until a compound muscle action potential (CMAP) was observed from the triggered EMG tongue channel. In this study, a positive or acceptable outcome for a safely placed condylar screw was indicated by the absence of CMAPs below 2.7 mA—which was considered the minimum acceptable threshold (MAT) (see *Results* for details). The surgeon repositioned any condylar screw with lower thresholds, and the triggered EMG test was repeated. Fluoroscopy images were obtained to confirm screw positioning.

Following acceptable triggered EMG outcomes and fluoroscopy, the surgeon closed the surgical wound temporarily and then realigned the patient's cervical spine to be in the desired anatomical position. Any EMG activity observed during these final steps was immediately reported to the surgeon. CT images were then obtained and read by the surgeon, and decisions about screw adjustment were made. Once the surgeon was satisfied with the imaging studies and EMG results, rods were placed and locked down on each side. Any EMG activity observed was reported to the surgeon in real time.

Statistical Analysis

Data were assessed with Simplot 14.0 statistics software. The threshold of significance was taken as $p < 0.05$. The data presented failed the normality Shapiro-Wilk test, and therefore Mann-Whitney rank-sum test nonparametric analysis was used to assess the data. For correlation assessment, the Spearman rank-order correlation test was used.

Results

Several critical maneuvers place CN XI and CN XII at risk during OC fusion procedures. This requires use of both free-running and triggered EMG during condyle dissection, drilling holes, screw insertion, and spine realignment in preparation for rod placement. Therefore, a combined set of alert criteria was used in this study. These criteria constitute the definition of events that include the following: 1) free-running EMG—alert on screw placement and/or final alignment; 2) triggered EMG—alert on low threshold (below 2.7 mA); or 3) combined criterion—alerts on 1 and 2 together.

A total of 394 condylar titanium screws (Medtronic) were implanted in 197 patients in this report. The total number of trajectories tested was 444, with 225 on the right and 219 on the left. The total number of screws modified was 50 (Table 1)—21 screws were modified based on anterior or superior breaches, palpable with a feeler and visible on fluoroscopy; 29 screws were modified based on EMG firing during realignment.

Typical Responses

Figure 2A shows a typical sustained train of EMG activity from the tongue. Such EMG activity constituted an incident and therefore was reported to the surgeon in real time. In other cases, bursts of activity were noted, reported, and documented in like manner.

Typical triggered EMG responses from tongue to stimulation through condylar screws are shown in Fig. 2B and C. Figure 2B shows a typical CMAP response. The mor-

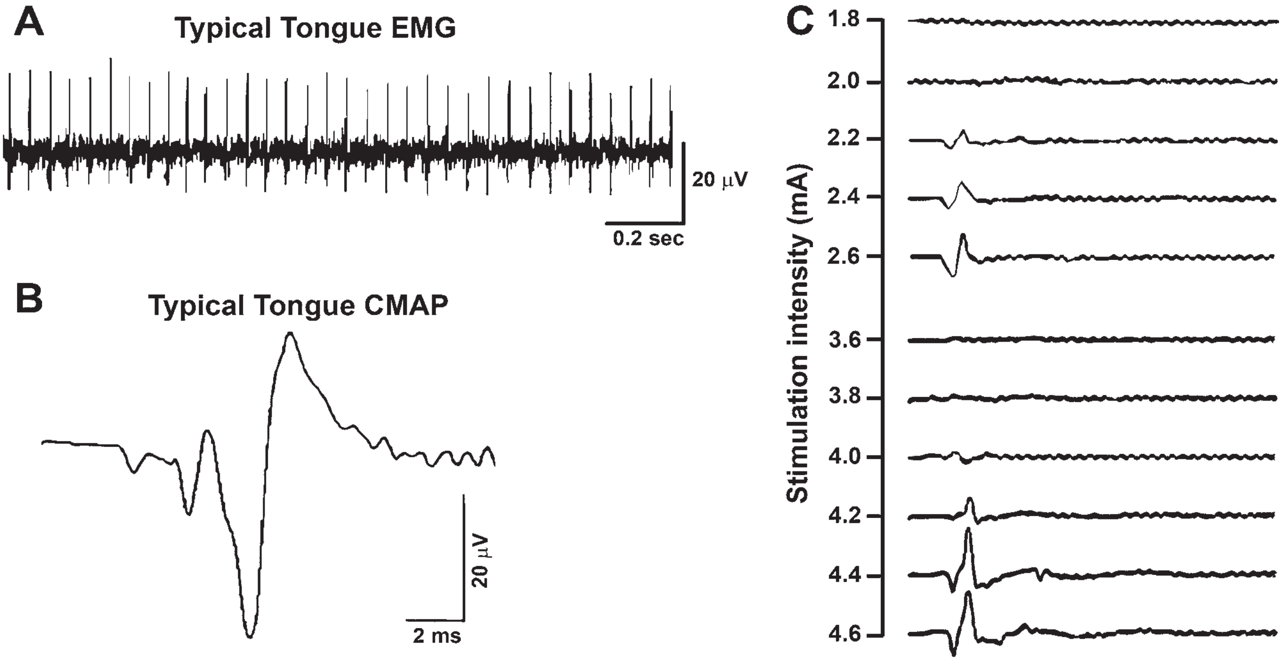

FIG. 2. Representative traces of EMG recorded from the tongue with posterior-lateral needle placement. **A:** A typical train EMG activity from the tongue elicited during condyle decompression or screw placement. **B:** A typical CMAP response from the tongue evoked by condylar screw stimulation. Note an initial prominent negative downward component followed by a sharp positive peak. **C:** Representative CMAPs obtained at different stimulation thresholds during the condylar screw stimulation. Upper portion of panel: subthreshold (2.7 mA) response (i.e., 2.2 mA) requiring the modification of the screw; lower portion of panel: above-threshold (2.7 mA) response (i.e., 4.2 mA) after modification of the screw.

phology is an initial prominent negative downward component followed by a sharp positive peak.

Figure 2C shows a representative CMAP obtained at different stimulation thresholds during the stimulation of the OC screw. The upper panel shows a subthreshold response (2.2 mA) requiring modification of the screw; the lower panel demonstrates the above-threshold response (4.2 mA) after modification.

Representative Cases

The first case (Fig. 3) shows tongue EMG activity observed during drilling and cessation of activity as the drill was slightly backed up (Fig. 3A–C). The screw was then placed under EMG monitoring and caused no EMG activation. No new neurological deficits were observed postoperatively. The CT scan, sagittal view, shows the final position of the screw (Fig. 3D).

In the second case (Fig. 4), no EMG activity was detected during drilling, yet the screw stimulation revealed a low threshold of 2.1 mA, below the MAT (Fig. 4A and B). The screw probably caused an expansion of the condylar bone toward the canal, which was detected by screw stimulation. After the screw was repositioned, the threshold increased to 7.7 mA, which is above the MAT (Fig. 4C and D). No new neurological deficits were observed postoperatively.

Threshold Findings and Criteria Evaluation

In this study, a positive/acceptable outcome of a safely placed condylar screw was indicated by the absence of a CMAP below 2.7 mA and/or the absence of free-running EMG during screw placement, neck realignment, rod placement and locking.

We chose 2.7 mA as an MAT because each time (21 screws; Table 1) a screw had a threshold lower than 2.7 mA, a condylar wall breach was confirmed. We grouped our results based on the presence or absence of incidents as defined above (Table 1 and Fig. 5).

Group I had 21 screws (5%) with condylar wall breach. In group Ia, 14 (approximately 4%) provoked tongue EMG activity on placement and showed thresholds below 2.7 mA (mean 2.0 mA, median 2.2 mA, maximum 2.6 mA, minimum 1.1 mA) on triggered EMG. In group Ib, 7 did not show EMG activity on placement, yet their thresholds were below 2.7 mA (mean 1.8 mA, median 1.7 mA, maximum 2.4 mA, minimum 1.4 mA) on stimulation.

Group II had 90 screws (23% of the screws placed) contained in two subgroups. In subgroup IIa there were 29 screws (7.3%) with thresholds ranging from 2.7 mA to 9.0 mA (mean 5.7 mA, median 5.8 mA, maximum 8.6 mA, minimum 2.9 mA). These screws exhibited EMG activity on the realignment of the cervical spine, albeit their stimulating thresholds were above 2.7 mA. In subgroup IIb there were 61 screws (15%) with thresholds ranging from 2.7 mA to 9.0 mA (mean 5.7 mA, median 5.7 mA, maximum 8.8 mA, minimum 2.9 mA), with no EMG incidents noted at any stage of the procedure.

Group III had 283 screws (72%) with thresholds above 9.0 mA (mean 13.1 mA, median 12.3 mA, maximum 26.0 mA, minimum 9.0 mA), with no EMG incidents noted at any stage of the procedure.

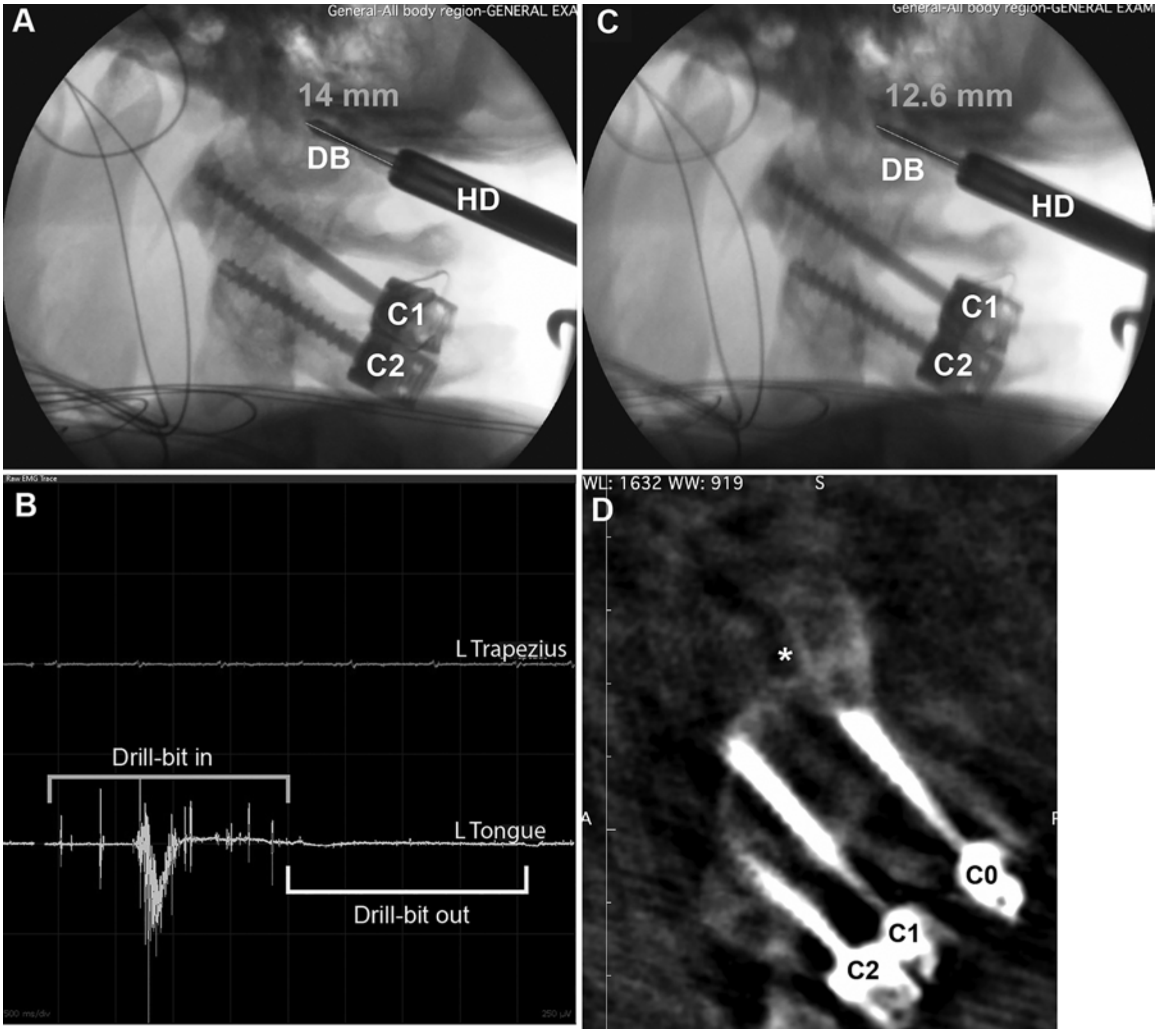

FIG. 3. Intraoperative fluoroscopy and CT images of the instrumentation during craniocervical fusion supplemented by tongue EMG. **A:** Fluoroscopy showing the position of a drill bit when a burst of tongue EMG occurred (**B**; *gray bracket*). **C:** Fluoroscopy showing the position of a drill bit after a 1.4-mm backing out, resulting in cessation of EMG activity (**B**; *white bracket*). The screw was carefully inserted under EMG monitoring, bearing in mind the above information. **D:** Intraoperative CT, sagittal view, showing the final position of the screw after repositioning the craniocervical junction in extraction and mild extension. *Asterisk* designates hypoglossal canal. C0 = condylar screw; C1 = lateral mass C1 screw; C2 = pedicle C2 screw; DB = drill bit; HD = hand drill.

Special Considerations

Screw thresholds that fell into the range of 2.7–9.0 mA (Table 1 and Fig. 5) raised interesting observations. There was no statistically significant difference in the threshold values between subgroups IIa and IIb ($p = 0.924$). However, an additional factor contributed to the evaluation of this group: the presence or absence of alerts. As shown in Table 1, 29 screws (group IIa or 32%) of a total of 90 screws in the threshold range of 2.7–9.0 mA provoked alerts on alignment. These are shown in yellow in the scatterplot (Fig. 5). These data indicate that screws falling into the range between 2.7 and 9.0 mA have a probability of 0.32 of incidents (EMG firing) occurring during realignment. Moreover, further statistical correlation analyses (Spearman rank-order correlation, Sigma plot 14) demonstrated no correlation between the threshold and presence or absence of an incident within the threshold range of 2.7–9.0 mA.

Discussion

This report analyzed and established clinically significant EMG events and MAT for condylar screw placement by condylar screw stimulation. Reports describing the OC fusion with condylar screw placements are more focused on the surgical approach than on monitoring the condylar screws and, therefore, lack EMG assessment.[17] Our study is the first to 1) establish an MAT and 2) suggest criteria to evaluate the safety of condylar screw placement, and thus to contribute to the decision-making process for the surgeon.

This study used the basic principle of pedicle screw stimulation described by Calancie and colleagues[21] and applied this to condylar screws. Electrical current is passed through a probe to the screw, which transmits current to the bone. Then, the same current is transmitted to the spinal nerve in proximity, eliciting a CMAP in the in-

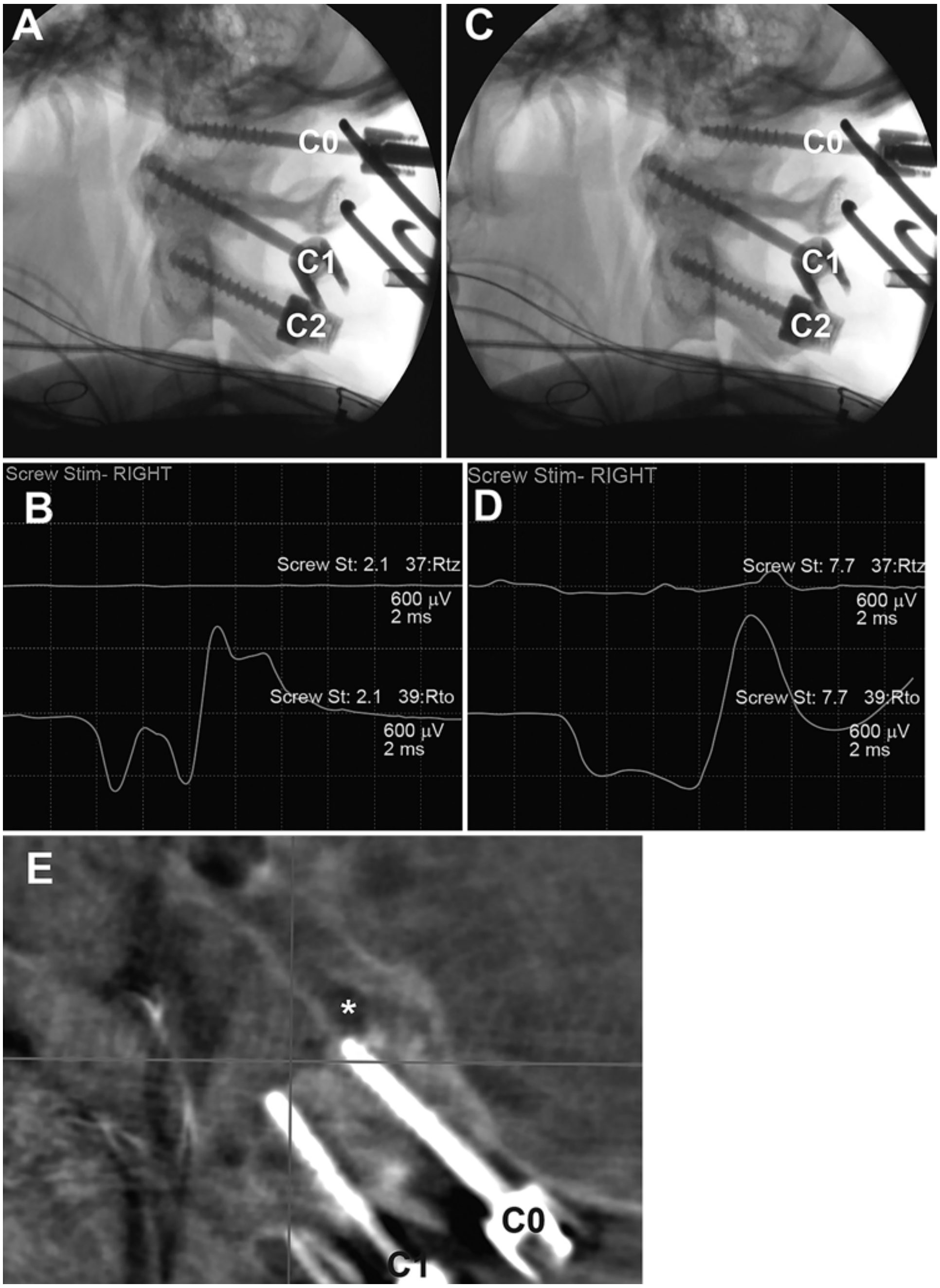

FIG. 4. Intraoperative fluoroscopy of condylar screws during the placement. **A:** Fluoroscopy demonstrating the initial position of a condylar screw corresponding with a low-threshold stimulation (2.1 mA; **B**). **C:** Fluoroscopy showing modified screw placement, resulting in a stimulation threshold higher than the MAT of 7.7 mA of EMG activity (**D**). **E:** The curved parasagittal intraoperative CT scan showing that the former screw trajectory was tangential to the inferior wall of the hypoglossal canal. In this case the monitoring was uneventful during the hand drilling, but the screw probably caused an expansion of the condylar bone toward the canal, which was detected by the screw stimulation. Rto = right tongue; Rtz = right trapezius; Screw St = condylar screw stimulation value in mA. *Asterisk* designates hypoglossal canal. C0 = condylar screw; C1 = lateral mass C1 screw.

nervated muscle. The minimum current at which a CMAP is evoked is the threshold current. We analyzed a total of 394 condylar screws, which were implanted in 197 patients during OC fusion procedures. To obtain reliable results, we ensured the correct placement of subdermal needles in the tongue, specifically targeting the genioglossus muscle, which forms the largest portion of the tongue body (Fig. 1). Incorrect needle placement in the tongue musculature (in anterior parts of the tongue) may result in false-negative results. The neurophysiological responses from the tongue we describe here are typical for triggered EMG from hypoglossal nerve stimulation described by Redmond and Di Benedetto[34] and Skinner[35] (Fig. 2B). EMG activity (bursts and trains) was observed at several stages of the proce-

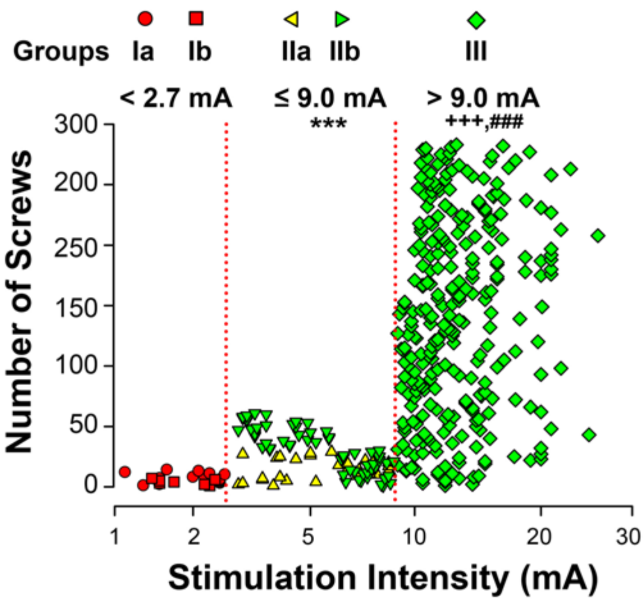

FIG. 5. Scatterplot of data showing triggered EMG thresholds and the number of screws. Three major groups are established based on the threshold range: Group I, < 2.7 mA (n = 21), screws that either demonstrated a threshold below 2.7 mA (*red squares*, n = 7; group Ib) or EMG activity during placement and threshold below 2.7 mA (*red circles*, n = 14; group Ia). Threshold values were not significantly different for these subgroups (p > 0.005). Group II, 2.7–9.0 mA (n = 90); screws that exhibited thresholds in a range between 2.7 and 9.0 mA. Note that the *yellow triangle* subgroup consisted of screws that exhibited EMG activity on realignment (n = 29; group IIa) and the *green triangle* subgroup included screws that did not exhibit any incidents (n = 61; group IIb). Threshold values were not significantly different for these subgroups (p > 0.005). Group III, > 9.0 mA (n = 283), demonstrated no incidents at any stage of the procedure (*green squares*). Note that the threshold values are significantly different ($^{***}p < 0.001$ for group II vs group I; $^{+++}p < 0.001$ for group III vs group II; $^{\#\#\#}p < 0.001$ for group III vs group I) between all three groups.

dures: condylar dissection, screw placement, and realignment of the spine. Such activity falls into the classification described by Romstöck and colleagues[36] and presents a significant risk of hypoglossal nerve injury.

Confounding Factors

Technical Factors

Pedicle screw stimulation is performed by placing a 3-mm-diameter ball tip stimulating probe on the head of the screw. A 0.4-mm-diameter subdermal needle return electrode is placed in the exposed musculature. In this study, for stimulating condylar screws, however, we used a 0.4-mm-diameter, 13-mm-long, subdermal needle electrode. A similar return needle electrode was placed in the musculature as used in pedicle screw stimulation. Because of differences in charge density between a sharp point (0.4 mm) and a wider ball tip (3 mm), further studies need to be done to compare results. There are several other compounding factors whose influence on the data is difficult to quantify. First, even though efforts were made in each case to make the surgical wound as dry as possible to reduce current shunting, there was always some fluid that could cause current shunting and skew triggered EMG thresholds. Second, we used constant-voltage stimulation settings in all procedures. Relevant literature has reports of variability in the actual current delivered at the screw head.[37] According to the manufacturer of the equipment used, the NIM Eclipse machine displays the actual current delivered. However, the variability in screw resistance remains a confounding factor that was not addressed in this report. Third, occipital condyles manifest significant anatomical and morphometric variability, including the thickness of the condyle.[14,38,39] This may significantly contribute to the results. It is known that pedicle screw stimulation results depend on pedicle bone quality.[21] Condylar bone quality also differs from patient to patient.[40] If the quality of the condylar bone is low, triggered EMG thresholds may be low regardless of the surgeon's best efforts in carefully placing screws. Besides, the consistency of the condylar bone, in both its subcortical and cortical components, is somewhat softer compared with what is usually encountered during drilling, tapping, and screw insertion at C1 and C2 (personal communication with the surgeon, Paolo Bolognese, July 2019). This factor is comparable to the pedicular bone in bone quality–compromising conditions such as osteoporosis. Fourth, variations in condylar wall thickness in different races were not considered in this report. Fifth, there have been concerns regarding the electrical conductance of pedicle screws.[37] The same could be expressed for condylar screws. More research is needed on this factor and how it affects the accuracy of results.

Surgical Factors

Surgical details of the procedure will be described in a subsequent study. However, there are a few interrelated issues that deserve discussion here. There are risks for two types of breaches during condylar screw placement: superior and anterior. The superior breach occurs when the path of the screw has a high pitch/aim and/or if the hypoglossal canal is bigger than usual. The hand drill, tapping device, and condylar screw can potentially impinge on the hypoglossal nerve, leading to a temporary or permanent partial or total deficit. In these cases, the violation of the hypoglossal canal is usually felt during the hand drilling as a sudden decrease in resistance, along with the appearance of a sudden burst of EMG activity of variable amplitude. The required correction mandates a complete redirection of the drilling, tapping, and screw insertion, with a lower path within the condyle, away from the hypoglossal canal. These superior breaches stopped being a problem, even in the face of hypoplastic condyles. Using IONM data as a guide, we adopted the following corrective strategies: 1) extending the dissection of the soft tissues to obtain a clear and complete view of the condyle; 2) lowering and medializing our entry point for condylar screw insertion; and 3) shaving the overlying supraocciput to allow a lower trajectory within the condyles, thus increasing the chances of remaining clear of the condylar canal.

An anterior breach occurs while trying to achieve the goal of bicortical purchase. It is quite frequent for the condylar screws to have a "proud" position through the anterior wall, an anatomical configuration easily identified on intraoperative CT imaging. When limited to a small

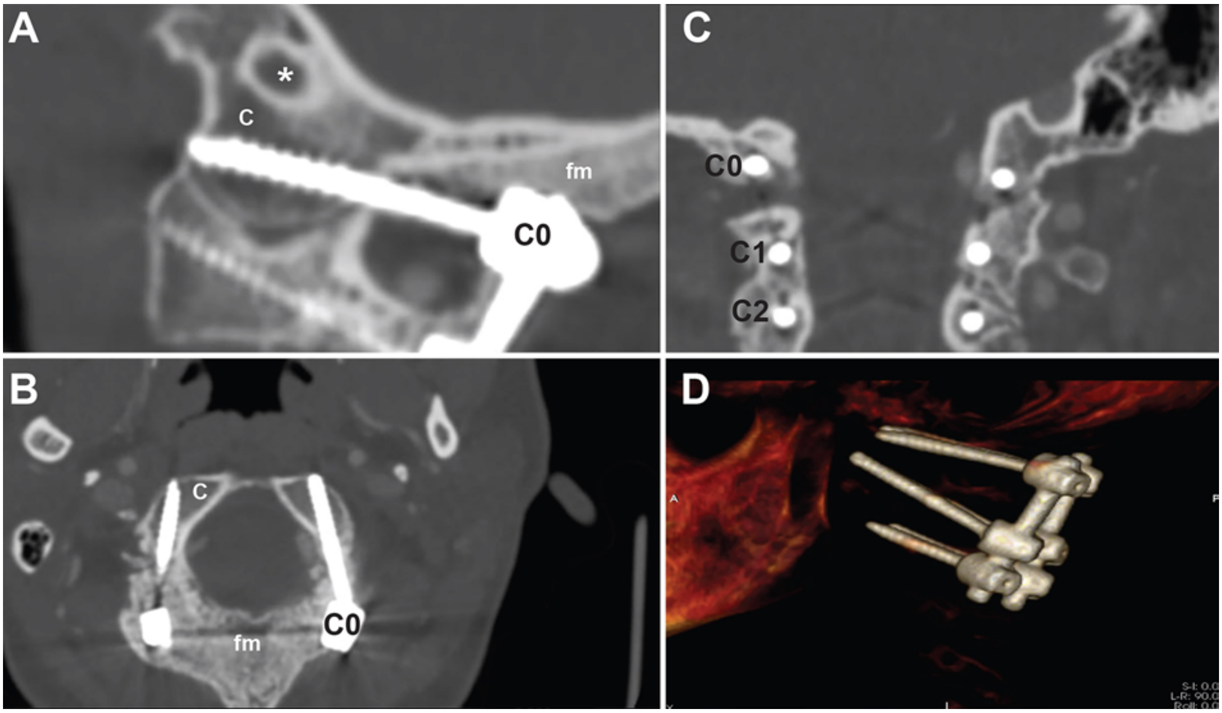

FIG. 6. A: Sagittal view. **B:** Axial view. **C:** Coronal view. **D:** 3D reconstruction. *Asterisk* designates hypoglossal canal. C = condyle; C0 = condylar screw; C1 = lateral mass C1 screw; C2 = pedicle C2 screw; fm = fusion mass.

protrusion (1–2 mm), this "proud" anatomical position is entirely innocuous because it does not affect any essential anatomical neighboring structures. For the anterior breach to be dangerous, it would have to protrude several millimeters through the anterior wall. This can be avoided under fluoroscopic guidance and corrected intraoperatively by simply backing up the screw.

In this study we assessed data for both superior and anterior breaches. Preliminary data suggest a difference in latency of the evoked responses with superior versus anterior breach. However, the differences between anterior and superior breaches are the subject of another study.

Another factor that presents anatomical and surgical challenges to condylar screw placement is hypoplasia. Hypoplasia results in flattening of the condyles and elevation of the atlas and axis of the skull base.[40] In this series, one-third of the condyles were hypoplastic.

In this study the surgeon did not use intraoperative navigation. He relied on anatomical landmarks and IONM. However, navigation may be preferred by other surgeons. An example of a successfully placed condylar screw is shown in Fig. 6.

Condylar Screw Stimulation Threshold

The MAT was established based on the confirmation of the condylar breach on the screw's thresholds below 2.7 mA. The surgeon confirmed the breach by inspecting the condylar wall with a probe. Additionally, screw stimulation values were compared with intraoperative CT imaging, postoperative CT scans, and clinical observations.

Condylar screws are much smaller than regular pedicle screws. The lateral distance between the nerve root and the pedicle ranges from 2.4 to 9.6 mm in the lumbar spine.[41] It came as no surprise that condylar screw thresholds were generally much lower than those for pedicle screws. As a result, the MAT (2.7 mA) in this study is much lower than what was established for pedicle screws.[42] Based on the threshold and EMG events, we categorized all screws placed into three groups (Table 1). We had a total of 21 screws with thresholds below 2.7 mA. However, 14 of 21 screws also exhibited EMG activity during screw placement, providing us with an additional warning criterion for the surgeon. Although the results from groups I and III were expected and relatively straightforward for interpretation, group II required special attention from both the IONM team and the surgeon.

Even though screws with thresholds in the range of 2.7–9.0 mA would be considered safe by MAT criteria alone, we found that 29 screws (or 32%) in this range had shown EMG activity on realignment and were therefore modified (repositioned, replaced, backed up a few turns) by the surgeon. The absence of a significant direct relationship between the threshold and the presence/absence of incidents within the threshold range of 2.7–9.0 mA indicate that the incident is not a function of a threshold per se. One could attribute this observation to possible low condylar bone density (see above) or screw placement trajectory. We found that lower trajectories within the condyles required a lower entry point (and additional dissection), but allowed bicortical purchase with a lower risk of hypoglossal injury, as demonstrated by intraoperative CT and the values of screw stimulation. In preliminary studies, we also found that high trajectories within the condyle (closer to the hypoglossal canal) had a lower range of detected values when compared to the data coming from lower trajectories. However, this observation needs to be investigated further. Lower trajectories also yielded anatomical benefits[43] of clearing the hypoglossal canal superiorly, the vertebral artery inferiorly, and the spinal cord medially.

Limitations

As mentioned in the *Methods* section, SSEPs and MEPs were used to assess the integrity of the sensory and motor pathways during positioning and surgical manipulation. Applications of these modalities to spine surgery have been widely described.[19,20,28] However, to ensure the safety and integrity of the hypoglossal nerve and assess the degree of possible injury, corticobulbar MEPs (CoMEPs) are recommended.[44] Although we had a few cases in which CoMEPS produced results consistent with EMG findings, it was not enough to include these findings in this study. The value of CoMEPs for the condylar screw placement procedures remains to be investigated. This study was limited to evaluating only triggered and free-running EMG for condylar screw placement.

Conclusions

In this study we determined parameters and accepted thresholds for condylar screw placement as follows: threshold < 2.7 mA—high likelihood of an anterior or superior condylar breach; 2) threshold 2.7–9.0 mA—acceptable, but the surgeon is advised to modify the screw based on the EMG during realignment; and 3) threshold > 9.0 mA—solidly placed, acceptable screw.

The combination of free-running and triggered EMG is efficient and sufficient in detecting condylar screw misplacement that might endanger the integrity of the hypoglossal nerve. Together with palpatory and radiographic assessment, it will aid safe and secure condylar screw placement. Therefore, intraoperative monitoring of free-running and triggered EMG could be a critical tool for improving the results of condylar screw placement, thus improving surgical outcomes and reducing the incidence of surgical revision interventions.

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Disclosures

The authors report no conflict of interest concerning the materials or methods used in this study or the findings specified in this paper.

Author Contributions

Conception and design: all authors. Acquisition of data: all authors. Analysis and interpretation of data: Avshalumov, Mugutso, Warnecke. Drafting the article: Avshalumov, Mugutso, Bolognese. Critically revising the article: Avshalumov, Warnecke, Bolognese. Reviewed submitted version of manuscript: Avshalumov. Approved the final version of the manuscript on behalf of all authors: Avshalumov. Statistical analysis: Avshalumov. Administrative/technical/material support: Avshalumov. Study supervision: Avshalumov.

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