Mandibular movements at maximum mouth opening and EMG activity of masticatory and neck muscles in patients rehabilitated after a mandibular condyle fracture

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SUMMARY. Objective: To assess rotation and translation movements of the mandible at maximum mouth opening in a group of patients successfully rehabilitated after condylar fractures. Materials and methods: Using a three-dimensional motion analyser, free movements of mouth opening were recorded in nine patients, and divided into their rotation and gliding components. Surface electromyography (EMG) of the masticatory and sternocleidomastoid (SCM) muscles was performed during maximum voluntary teeth clenching (MVC). Data were compared with those collected in healthy adults. Results: At maximum mouth opening, the total displacement of the mandibular interincisor point was 86% of reference value (p > 0.05, Student’s t test), with a reduced vertical displacement (84% of reference value, p = 0.012). Percentage mandibular rotation was significantly larger in patients (82%) than in reference subjects (77%, p = 0.005). During MVC, patients had more asymmetric EMG potentials (p = 0.018), with greater mandibular torque (p < 0.001), and reduced co-contraction of SCM (p = 0.003). EMG indices were used to formulate an overall performance score that was related to the characteristics of mouth opening (r = 0.557). Conclusion: Notwithstanding a good recovery in the total mandibular movement, the rotation/translation components of mouth opening were modified. The overall EMG performance score could be used to predict the characteristics of mandibular motion. © 2009 European Association for Cranio-Maxillofacial Surgery

Keywords: 3D, mandible, motion analysis, EMG, maxillofacial surgery

INTRODUCTION

In facial traumatology, mandibular fractures are very frequent, and 25–40% of them fall within the condylar related field (Marker et al., 2000; De Riu et al., 2001; Ellis and Throckmorton, 2005). These are subdivided according to their anatomical localization (intra- or extra-capsular, high- or low-position), the degree of dislocation of the articular head relative to the glenoid cavity (with or without dislocation), the distance between the fractured stumps (more or less than 4 mm) and, finally, according to the mono- or bilateral fracture, and to the presence or absence of associated fractures of the facial bones.

Both surgical (open) and functional (non-surgical, closed) treatment options are available to clinicians, the choice of the best treatment for a particular patient requires a careful consideration of the kind of fracture and of the patient’s characteristics. Indeed, no single opportunity exists, and the argument (surgery vs. functional) is still debated in the literature, with several investigations pointing out the limits and benefits of each of the options (Ellis and Throckmorton, 2005). Notwithstanding the kind of therapy, treatment aims at pain reduction, functional restoration of the temporomandibular joints (TMJ) (mouth opening larger than 40 mm, minimal lateral deviation at maximum mouth opening, unaffected laterotrusive and protrusive movements), re-establishment of occlusal contacts and of posterior facial heights with symmetrical gonial angles.

Treatment goals are sometimes directly measured, and several studies have assessed post-treatment TMJ and masticatory muscle function in patients, even on a longitudinal base. Overall, while the global function may appear clinically normal (for instance, with a normal amount of mouth opening), when examined closely, the pattern of motion is altered (Throckmorton et al., 1999). For instance, previous studies found modifications in the anterior and lateral excursions during the chewing cycle (Throckmorton et al., 1999), as well as reduced mandibular protrusion associated with increased posterior excursion during mouth opening (Talwar et al., 1998).

In a previous study, a mathematical model for the deterioration of the mandibular movements during mouth opening into their rotation (lower TMJ compartment) and translation elements (upper TMJ compartment) was developed, and applied to the analysis of healthy young adults (Ferrario et al., 2005). The investigation required the non-invasive acquisition of mandibular movements using an optoelectronic motion analyser.
AIM

The aim of the current study was to quantitatively assess the percentage contribution of rotation and translation movements of the mandible at maximum mouth opening in a group of patients surgically and functionally treated after condylar fractures. This information may provide useful hints about TMJ malfunctioning, with a non-invasive estimation of the movements occurring in the lower (rotation) and upper (translation) TMJ compartments. Additionally, surface electromyographic (EMG) activity of the masticatory and neck muscles during maximum voluntary teeth clenching (MVC) was performed. EMG data were statistically related to descriptors of mandibular motion in order to develop some simpler estimations of TMJ functioning.

MATERIALS AND METHODS

Patients

Nine patients (eight men, one woman; age range 18–58 years, mean 34 years, standard deviation [SD] 13) treated for fractures of the mandibular condylar process in the Unit of Maxillo-Facial Surgery of the IRCCS Galeazzi Hospital (University of Milan) were analysed. None of the patients had other medical problems.

Three patients had a unilateral fracture, while six had bilateral fractures; overall, nine fractures were intracapsular, four involved the condylar neck and two were subcondylar. The condylar fractures were treated by open reduction and rigid internal fixation (three patients), closed reduction and functional treatment (four patients), or a combined technique (two patients who received a surgical, open treatment on one side, and a closed treatment on the other side). The criteria for treatment selection were based on clinical considerations (amount of displacement [in all surgically treated patients it was larger than 4 mm or it deviated by more than 37°], anticipated practicability of surgical or functional treatment; dental formula [two patients were partially edentulous posteriorly, one patient was edentulous in the maxilla]; the patient’s preference was also taken into consideration), and no kind of random allocation was made. All surgically treated patients also underwent post-surgical functional therapy for approximately 40 days.

The patients were assessed 6–36 months (on average, 18 months, SD 11) after the fracture, at the end of their treatment, when a clinically satisfactory healing and restoration of function had been obtained (pain free, free mandibular opening larger than 40 mm with negligible lateral deviation, lateral excursions with canine disclusion, good protrusion index, symmetrical position of gonial angles).

In all patients, free, habitual movements of mouth opening were recorded; additionally surface EMG of the masseter, anterior temporalis and sternocleidomastoid (SCM) muscles of both sides was also performed, and standardized indices of muscular activity were obtained during maximum voluntary teeth clenching.

Data were compared with those collected from two groups of healthy subjects: mandibular motion with data recorded in 27 young adults (12 men and 15 women), EMG values of data recorded in 62 young adults (27 males, 35 females). The reference subjects had complete, permanent dentitions; no TMJ or cranio-cervical disorders, no anterior or lateral crossbite occlusion, no previous history of craniofacial trauma or congenital anomalies. Their data have been previously published (Ferrario et al., 2005, 2006).

Mandibular movements — data collection

Free, habitual movements of mouth opening were recorded using an optoelectronic three-dimensional motion analyser operating at 60 Hz (SMART System, E-motion, Padova, Italy). The method has been described in detail elsewhere (Ferrario et al., 2005). In brief, six high-resolution infrared sensitive charge-coupled device video cameras coupled with a video processor defined a working volume of 77 (width) cm × 66 (height) cm × 77 (depth) cm; metric calibration and correction of optical and electronic distortions were performed before each acquisition session. The patient was positioned inside the working volume sitting on a stool without a backrest, and was asked to perform free, habitual movements of maximal mouth opening and closing (Fig. 1). During the movement, for any TV camera, special software recognized the coordinates of the geometric centre of six passive markers. Subsequently, all the coordinates were converted to real metric data, and a set of x-, y-, z-coordinates for each landmark in each frame that constituted the movement was obtained.

For each patient, 6-mm hemispheric reflective markers were located on the cranium (three cranial landmarks, one on the glabella, and one on each cutaneous projection of the lateral pole of the left and right mandibular condyles), and on an extraoral equilateral triangular antenna fixed on the mandible at the centre line (three landmarks). The antenna was fixed buccally on the mandibular anterior gingival line just out of dental contact using surgical adhesive (Stomahesive; Convetec Inc., Deeside, United Kingdom). The three head markers defined a cranial plane of reference, and the location of the hinge (intercondylar) axis. The three extraoral markers defined a mandibular plane and described its movements relative to the cranial plane of reference. An additional mandibular dental landmark, adhered to the incisal edge of the midline, was used as a static reference to identify a dental (occlusal) landmark relative to the cranial plane of reference and the extraoral antenna. The position of this marker, together with the extraoral antenna and cranial landmarks was recorded in an additional acquisition while the patient kept the mouth open (Fig. 2).

Three records were taken for each patient, and mean values computed.

Mandibular movements — data analysis

As detailed by Ferrario et al. (2005), the patient’s head and neck movements were subtracted from the raw mandibular movement using the three cranial markers, and only movements at the TMJ were further considered. Subsequently, the relative distances of the dental
(interincisal point) marker from the markers on the extraoral antenna (mandibular mobile plane), and from the intercondylar axis (head reference axis) were calculated. The distance between the dental marker and the midpoint of the intercondylar axis was used as an estimate of mandibular size. Finally, the mandibular movements at the interincisor point were reconstructed through the use of the intraoral marker and its movement relative to the cranial plane of reference (Ferrario et al., 2001). The origin of axes was set in the midpoint of the hinge axis ($x$-axis); the vertical component (sagittal plane projection) of the total movement was also computed.

Using a mathematical model of mandibular motion (Ferrario et al., 2005), the mandibular movement at the interincisal point was divided into its rotation and translation components, and the relative, percentage contribution of the two components to the total movement was calculated for each frame of motion. In particular, the situation at maximum opening was assessed. The rotation (in degrees) of the mandibular plane relative to the start position (anatomical plane of reference) around the intercondylar axis was also computed.

**Surface EMG recordings**

Surface EMG of the masseter, temporalis anterior and SCM muscles of both sides was performed using pregelled disposable silver/silver chloride bipolar surface with a diameter of 10 mm and an interelectrode distance of $21 \pm 1$ mm (Duo-Trode; Myo-Tronics Inc., Seattle, WA, USA). After careful skin cleaning, the electrodes were positioned on the muscular bellies parallel to muscular fibres, with a disposable reference electrode applied to the forehead. For all tests, the patients sat with their head unsupported and were asked to maintain a natural erect position (Ferrario et al., 2006, 2007).

EMG activity was recorded using a computerized instrument (Freely, De Götzén srl; Legnano, Milano, Italy). The analogue EMG signal was amplified (gain 150, bandwidth 0–10 kHz, peak-to-peak input range from 0 to 2000 $\mu$V) using a differential amplifier with a high common mode rejection ratio (CMRR = 105 dB in the range 0–60 Hz, input impedance 10 G$\Omega$), digitized (12 b resolution, 2230 Hz A/D sampling frequency), and digitally filtered (high-pass filter set at 30 Hz, low-pass filter set at 400 Hz, band-stop for common 50–60 Hz noise). The signals were averaged over 25 ms, with muscle activity assessed as the root mean square (r.m.s.) of the amplitude (unit: $\mu$V). EMG signals were recorded for further analysis.

Two standardization recordings were performed: to standardize the EMG potentials of the six analysed muscles with tooth contact, two 10-mm thick cotton rolls were positioned on the mandibular first and second molars of each subject, and a 5-s MVC was recorded. Additionally, to standardize the SCM potentials, a maximal rotation of head and neck without moving shoulders was performed. The head was moved slowly on each side, and the subject remained in the extreme right and left positions for approximately 5 s. During head–neck rotation, the contralateral SCM muscle is maximally activated (Ferrario et al., 2006).

Surface EMG activity was then recorded during an MVC in intercuspal position; the patient was invited to clench as hard as possible, and to maintain the same level of contraction for 5 s. The test was repeated three times. During these test performances, the patients were verbally encouraged to perform at their best.

**Surface EMG data analysis**

For all tests, the 3-s period with the most stable signal was automatically selected by the software and used for all subsequent analyses. For each subject, the EMG potentials of the six analysed muscles recorded during the MVC tests were expressed as a percent of the mean potential recorded during the standardization test (MVC on the cotton rolls), unit: $\mu$V/$\mu$V $\times$ 100. All subsequent calculations were made with the standardized potentials. In addition, a second standardization was made for SCM muscle with the potentials obtained during head–neck rotation, unit: $\mu$V/$\mu$V $\times$ 100. Standardized potentials...
were used for the calculation of cervical load (see below). The values obtained in the three MVC tests performed by each subject were averaged.

Several EMG indices were computed (Ferrario et al., 2006): symmetry, torque, masticatory muscle activity, co-contraction of SCM muscle.

To assess muscle symmetry, the EMG waves of paired masseter and temporalis muscles of each patient were compared by computing a percentage overlapping coefficient (POC, unit: %). POC is an index of the symmetric distribution of muscular activity as determined by occlusion. The index ranges between 0% and 100%: when two paired muscles contract with perfect symmetry, a POC of 100% is obtained.

Because an unbalanced contractile activity of contralateral masseter and temporalis muscles, for instance left temporalis and right masseter, might give rise to a potential lateral displacing component, the torque coefficient (TC, unit: %) was assessed. TC ranges between 0% (complete presence of lateral displacing force) and 100% (complete absence of lateral displacing force).

The mean (masseter and temporalis) total standardized muscle activities (unit: μV/μV s %) were computed as the integrated areas of the EMG potentials over time.

The percentage ratio between the SCM muscle potentials recorded during MVC (this should be a submaximal contraction for SCM muscle) and the muscle potentials obtained during the maximum contraction standardization task (eg, contralateral neck rotation against resistance) was calculated as SCM “cervical load” (unit: %). This value indicates if (and how much) the SCM muscles co- contract with the jaw elevator muscles during clenching: a cervical load of 0% denotes no concomitant activity, while a cervical load of 100% implies a maximal contraction of SCM muscles during MVC.

**Statistical analysis**

Descriptive statistics (mean and SD) were computed for all variables (mandibular motion and EMG). Patient data were compared with data collected in healthy subjects using unpaired Student’s t tests.

Additionally, EMG indices were used to formulate an overall performance score that could predict some characteristics of mandibular motion. An indexed statistical pointer, with a weigh structure to sum 100, was created using the EMG variables (Landoni, 1994). Each EMG variable was first standardized against the values collected in the healthy subjects by calculating absolute (sign less) z scores (patient value – mean reference value/SD of the reference group).

Standardized weights were then assigned to the variables according to their biological importance and clinical influence in the function of the stomatognathic apparatus: 70% of the weights were given to the stabilization of occlusion, while 30% interested the stabilization of the head on the neck. Temporalis and masseter POC were given a 15% weight each; both muscles are active during MVC, the temporalis muscle with a stabilization action, the masseter muscle performing the main clench activity. An imbalance of their left–right standardized activity may result in abnormal loads over the TMJs (Ferrario and Sforza, 1994). The torque index was given a 25% weight: the potential lateral displacing component produced by unbalanced contractile activities of contralateral masseter and temporalis muscles might produce an unstable position of the mandibular condyles in the articular fossa (Ferrario and Sforza, 1994). The SCM “cervical load” received a 30% weight: this index measures the percentage of SCM co-contraction necessary for head stabilization during MVC (and therefore also during swallowing) (Ferrario et al., 2006). Lastly, the mean total standardized muscle activities of the masticatory muscles (which indicate the overall contraction of masseter and temporalis muscles during MVC) were given a 15% weight. This index has recently been found to be altered in patients with temporomandibular disorders (Ferrario et al., 2007).

The total index (overall performance score) was therefore a global z score: the larger the value deviated from the expected value of 0 (for definition, in a population the z score has mean = 0 and SD = 1), the more the patient weighted EMG data globally differed from those of the reference group. Values larger than 2 differ more than 2 SD from the reference. The significance of the overall performance score was assessed by paired Student’s t test (null hypothesis: expected value of 0; alternative hypothesis: mean value different from zero).

The overall performance EMG score was related to the variables predicting mandibular motion by correlation analysis.

The level of significance was set at 5%.

**Method error**

The method error of mandibular movements was assessed in the reference subjects, and has been previously reported (Ferrario et al., 2005): the intraclass correlation coefficients (five subjects, three independent sessions) ranged between 0.571 and 0.760, without significant differences among sessions.

Measurement variability in EMG measurements was tested by repeated analyses of seven subjects chosen at random; the intraclass correlation coefficient ranged between 0.629 and 0.977, without significant differences among the two measurement sessions (Ferrario et al., 2006).

**RESULTS**

The patients were significantly older than both the healthy subjects used as references for mandibular motion (Table 1, p < 0.001, Student’s t test for independent samples), and the healthy subjects used as references for surface EMG (Table 2, p < 0.001).

Patients and healthy subjects had similar estimated mandibular dimensions (distance between the incisal marker and the midpoint of the intercondylar axis) (p > 0.05). At maximum mouth opening, on average, the patients had a somewhat smaller total displacement of the mandibular interincisor point, but the difference was not statistically significant (p > 0.05). In contrast, the vertical displacement was significantly reduced: on average the patients reached only 84% of the reference
value \((p = 0.012)\). The inter-individual ratio between the vertical and the total displacement was not significantly different between patients and healthy subjects. At maximum mouth opening, the percentage of mandibular movement explained by pure condylar rotation was significantly larger in patients than in reference subjects \((p = 0.005)\), with corresponding angles of 26° (patients) and 33° (reference subjects) \((p < 0.001)\).

During MVC, tooth contact produced more asymmetric EMG potentials in both the temporalis anterior \((p = 0.016)\) and the masseter muscle of the patients when compared with the healthy subjects (Table 2). For masseter, the difference did not reach statistical significance. The torque index was significantly larger in patients than in healthy subjects \((p < 0.001)\), while the co-contraction of SCM muscle was significantly reduced \((p = 0.003)\). No significant differences were found for the standardized masticatory muscle activity.

No constant relationship between the kind of condylar fracture (unilateral, bilateral; position), or the kind of treatment (surgical, functional), and the kinematic variables describing mandibular motion or the EMG indices was found.

EMG indices were used to formulate an overall performance score that was significantly different from the expected value of 0 (paired Student’s \(t\) test, \(p = 0.016)\). Patients M02, M07 and F01 differed more than 2 SD

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<th>Table 2 – Standardized EMG variables during maximum voluntary tooth clenching, and overall performance score with relevant weights</th>
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POC: percentage overlapping coefficient (index of left–right muscular symmetry); TC: torque coefficient (potential lateral displacing component); cervical load: contraction of SCM muscle during MVC as % of standardization potentials; activity standardized: integrated areas of the EMG potentials over time during tooth clenching in intercuspal position as % of integrated areas of the EMG potentials over time during clenching on cotton rolls; weight: standardized weights used in the indexed statistical pointer.

\(p\): Probability value of an unpaired Student’s \(t\) test, 34 degrees of freedom; NS: not significant, \(p > 0.05\).

\(x\): Probability value of a paired Student’s \(t\) test, 8 degrees of freedom.

\(p\): Probability value of an unpaired Student’s \(t\) test, 62 degrees of freedom; NS: not significant, \(p > 0.05\).

\(x\): Probability value of a paired Student’s \(t\) test, 8 degrees of freedom.
from the reference. In all three patients, all characteristics of mandibular motion deviated from the values of the reference group. The overall performance score was related to the ratio between the vertical component (sagittal plane projection) of the displacement of the mandibular interincisor point at maximum mouth opening and its total displacement, with \( r = 0.557 \). In the normal subjects, this ratio, which described one of the three-dimensional characteristics of mouth opening, was significantly related to the estimated degrees of rotation of the mandibular plane around the intercondylar axis (\( r = -0.500, p < 0.01 \)) (Ferrario et al., 2005).

**DISCUSSION**

On average, the displacement of mandibular interincisor point at maximum mouth opening in patients was comparable to previous results obtained with similar follow-ups (Talwar et al., 1998; Throckmorton and Ellis, 2000; De Riu et al., 2001; Haug and Assael, 2001; Yang et al., 2002). In normal subjects, the values recorded for the three-dimensional movements of the interincisor point had already been reported to be similar to most of (as reviewed by Ferrario et al., 2005), but not all (Gallo et al., 1997; Talwar et al., 1998; Throckmorton and Ellis, 2000) literature reports. Different criteria of inclusion, as well as different motion analysers, may explain these differences that were found in both directions (larger and smaller mouth openings).

The principal finding of the current study is the mathematical demonstration that the percentage of mandibular movement explained by rotation at maximum mouth opening was significantly larger (\( p = 0.005 \)) in patients (82%) than in reference subjects (77%).

After a bilateral fracture of the mandibular condyle, Throckmorton et al. (1999) found an altered pattern of mandibular motion during chewing, with reduced lateral and anterior excursions. In particular, they reported a reduced vertical component of jaw movement at greatest mouth opening, a finding in good accord with the current reduction in the vertical component (sagittal plane projection) of the displacement of the mandibular interincisor point at maximum mouth opening. Unfortunately, their motion analyser (an electromagnetic device) assessed the movement of a single mandibular point, and they could not perform a reconstruction of the actual motion of the mandibular (occlusal) plane (Throckmorton et al., 1999). Nevertheless, they hypothesized a reduction in the condylar translation during mouth opening, and this hypothesis was mathematically demonstrated in the current study.

Similar conclusions (mandibular rotation without translation) were reached by Turp et al. (1996) and by Talwar et al. (1998). Turp et al. (1996) assessed three-dimensional condylar movements in patients who had had a fracture of the condylar process. They used an optoelectronic motion analyser, but they did not actually perform mathematical calculations with their measurements.

Overall, the modifications in TMJ movement pattern could be explained by a functional adaptation or remodeling of the mandibular condyle after the fracture, as well as by anatomical and functional alterations in the muscular control. In particular, alterations in the lateral pterygoid muscle and temporomandibular ligament had been hypothesized (Throckmorton et al., 2003). Central compensation mechanisms, acting within the neuromuscular TMJ feedback system, may also modify the global motion pattern to consent a basically good function (Turp et al., 1996), even if the translation component of condyle motion is inferior to that found in the normal population.

Indeed, the patients examined in the current study had a good recovery as far as the total mandibular movement was concerned, but they had a modification in the rotation and translation components of mouth opening. As already underlined (Travers et al., 2000), the amount of maximum mouth opening cannot be used to evaluate TMJ function, whereas the use of the reciprocal amount of translation and rotation could provide useful information.

The EMG indices measured in the patients differed from those recorded in normal subjects; unfortunately, no comparisons can be made with the EMG assessments reported by Hjorth et al. (1997) and Throckmorton et al. (1999), because they were performed mainly during chewing and did not report standardized (normalized) values.

The EMG indices were used to develop some estimate of TMJ function. Indeed, while the assessment of EMG activity of the masticatory and neck muscles is a relatively simple task that can be performed even outside specialized research laboratories (Ferrario et al., 2007), the measurement of three-dimensional mandibular motion must be made using dedicated instruments that cannot be moved to meet the patients. The overall EMG performance score could therefore be used to predict the characteristics of mandibular motion.

The group of patients analysed in the current study was limited, and heterogeneous, with different kinds of condylar fractures and subsequent treatments. They were enrolled in the study according to their clinical outcome: they all had a satisfactory restoration of TMJ function. Notwithstanding this variability, no relationships between the characteristics of their condylar fractures and the analysed variables were found. The reduced number of patients did not allow statistical comparisons to be made between the various clinical subgroups, and this aspect should be investigated in more detail with a larger number of patients.

A limitation of the current study is the limited follow-up period (up to 36 months). Previous investigations assessed patients after a much longer interval (up to 23 years, Turp et al., 1996), and some further modifications in the three-dimensional characteristics of mandibular movements could occur in the currently measured patients, as long as the neuromuscular adaptations of their stomatognathic apparatus progress (Talwar et al., 1998; Throckmorton and Ellis, 2000; Ellis and Throckmorton, 2005). Nevertheless, these present findings (increased rotation component and decreased translation component) are in good accord with those hypothesized by the investigations who made longer follow-ups (Turp et al., 1996; Talwar et al., 1998; Throckmorton et al., 1999), and Throckmorton and Ellis (2000) found that the improvement rate for mandibular movements was not linear, being faster in the months soon after the trauma.

A further limitation is that the current healthy, control subjects were not age-matched with the patients, who
were significantly older. A similar limitation was reported by Throckmorton et al. (1999), who analysed masticatory movements after condylar fractures. They assumed that age-related differences were limited, but no data about maximum mouth opening or about biomechanical models of TMJ functioning seem to exist.

CONCLUSION

In conclusion, in the current group of patients, notwithstanding a good recovery in total mandibular movement, a modification in the rotation/translation components of TMJ motion at maximum mouth opening was found.

Additionally, during MVC, the EMG indices measured in the patients differed from those recorded in normal subjects. These indices were used to develop an overall EMG performance score that could be used to predict the characteristics of mandibular motion.

The study should be repeated with a larger number of patients, and with longitudinal assessments during the subsequent phases of healing.

CONFLICT OF INTEREST STATEMENT

The authors declare that they have no conflicts of interest related to the current investigation. They received no sources of funding for the current investigation outside their annual grant from Milan University (to CS, ABG, and VFF).

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