

FULL-LENGTH ORIGINAL RESEARCH

Patterns of muscle activation during generalized tonic and tonic–clonic epileptic seizures

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SUMMARY

Purpose: Tonic seizures and the tonic phase of tonic–clonic epileptic seizures are defined as “sustained tonic” muscle contraction lasting a few seconds to minutes. Visual inspection of the surface electromyogram (EMG) during seizures contributed considerably to a better understanding and accurate diagnosis of several seizure types. However, quantitative analysis of the surface EMG during the epileptic seizures has received surprisingly little attention until now. The aim of our study was to elucidate the pathomechanism of the tonic muscle activation during epileptic seizures.

Methods: Surface EMG was recorded from the deltoid muscles, on both sides, during 63 seizures from 20 patients with epilepsy (10 with generalized tonic and 10 with tonic–clonic seizures). Twenty age- and gender-matched normal controls simulated 100 generalized tonic seizures. To characterize the signal properties we calculated the root mean square (RMS) of the amplitudes, the median frequency (MF), and the coherence. Based on the spectrograms of both epileptic and simulated seizures, we chose to determine the relative

spectral power (RP) in the higher (100–500 Hz) frequency domain.

Key Findings: During the tonic seizures there was a significant shift toward higher frequencies, expressed by an increase in the MF and the RP (100–500 Hz). The amplitude characteristic of the signal (RMS) was significantly higher during the tonic phase of the tonic–clonic seizures as compared to the simulated ones, whereas the RMS of the tonic seizures was significantly lower than the simulated ones. The EMG–EMG coherence was significantly higher during the epileptic seizures (both types) as compared to the simulated ones.

Significance: Our results indicate that the mechanism of muscle activation during epileptic seizures is different from the physiologic one. Furthermore the sustained muscle activation during the tonic phase of tonic–clonic seizures is different from that during tonic seizures: The tonic phase of tonic–clonic seizures is characterized by increased amplitude of the signal, whereas tonic seizures are produced by a significant increase in the frequency of the signal.

KEY WORDS: EMG, Epilepsy, Signal analysis, Tonic–clonic seizures, Tonic seizures.

Tonic muscle contraction constitutes the characteristic semiologic feature of several epileptic seizures. Tonic seizures are defined as sustained increase in muscle contraction lasting from seconds to minutes (Gastaut et al., 1963), whereas tonic–clonic seizures are defined as a sequence consisting of a tonic followed by a clonic phase (Commission on Classification and terminology of the ILAE, 1981). Clinically, it is not always easy to distinguish between pure tonic and tonic–clonic seizures. Is a tonic seizure a fragment of a tonic–clonic seizure or fundamentally different? It is still unclear whether these seizure types share a final com-

mon pathway of motor unit (MU) activation, leading to the characteristic, sustained tonic muscle activation, and it has not been elucidated whether the tonic muscle activation during the seizures is different from the physiologic one. The electroencephalography (EEG) during these seizure types is usually obscured by artifacts.

Visual inspection of surface electromyography (EMG) signals from polygraphic recordings contributed to identifying the pathomechanisms of several seizure-types: myoclonic (including negative myoclonus), atonic, myoclonic–atonic, epileptic spasms, and startle-induced reflex seizures (Mothersill et al., 2000). Recording surface EMG signals during seizures proved to provide valuable diagnostic information in the clinical practice: Tassinari et al., (2010) encouraged the use of off-line analysis of digital polygraphic recordings of epileptic seizures. Digital recording systems allow measuring precisely the time between the

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EEG and EMG signals, as well as the precise duration of the muscle activity (Rubboli & Tassinari, 2006; Tassinari & Rubboli, 2008).

Although quantitative analysis of EMG signals was investigated extensively in several types of movement disorders (Grosse & Brown, 2005), to the best of our knowledge myoclonus is the only seizure type in which this feature was addressed (Grosse et al., 2003; Panzica et al., 2003; Shibasaki et al., 1978).

The properties of the surface EMG signals can be described by characteristics in the time domain (variation in time of the amplitude) and in the frequency domain. The amplitude characteristics of the signal are reflected by the root mean square (RMS). The frequency domain characteristics can be visualized using spectrograms and they can be expressed by the median frequency (MF) and the relative power of the signal in the different frequency bands. The correlation between the muscle activation on the two sides can be reflected by the EMG–EMG coherence.

These quantitative parameters reflect different features of the MU activation and recruitment. To elucidate the pathomechanism of tonic muscle activation during seizures, we recorded surface EMG during tonic and tonic–clonic epileptic seizures, as well as seizures simulated by healthy volunteers. We calculated the RMS, MF, and coherence between the muscles on the left and right sides. Based on the changes observed in the spectrogram, we calculated the relative power of the signal in the frequency domain 100–500 Hz.

Epileptic seizures occur due to abnormal excessive or synchronous neuronal activity in the brain. We hypothesized that this will be reflected in the pathomechanism of the epileptic tonic muscle activation by a shift toward higher frequency domains, increase in coherence, and/or increase in the amplitude feature.

METHODS

Subjects

Fifty-seven consecutive patients admitted to our Epilepsy Monitoring Unit for diagnostic reasons and who had a history of tonic or tonic–clonic seizures in the referral were included. Twenty-three patients did not have seizures during the monitoring, 20 patients had seizures with tonic muscle activation (10 patients had tonic, and 10 patients had tonic–clonic seizures), and 14 patients had epileptic seizures other than tonic and tonic–clonic. In addition, 20 healthy controls who simulated epileptic seizures had been recruited. The project had been approved by the local ethics committee and all subjects received information on the project and gave their written consent.

In the group of the patients with epilepsy (7 female, 13 male) the mean age was 24.8 years (range 6–58). The group of healthy controls was age and gender matched: mean age 25.4 years (range 6–54), eight were female and

12 male (for the age: $p = 0.64$; for the gender: $p = 1$). The subgroup of patients with tonic seizures (four female, six male) had a mean age of 20.4 years (range 6–58), whereas in the subgroup with tonic–clonic seizures (three female, seven male) the mean age was 29.2 years (range 11–55). There was no significant difference among the two patient subgroups and the group of healthy controls concerning the age ($p > 0.1$) or concerning the gender ($p > 0.7$).

One patient with tonic–clonic seizures had idiopathic generalized epilepsy (juvenile myoclonic epilepsy); the other nine patients in this group had symptomatic focal epilepsy, with secondarily generalized seizures. In the group with generalized tonic seizures, one patient had cryptogenic epilepsy; all others had symptomatic focal or multifocal epilepsy. Seven patients in this group had symptomatic Lennox-Gastaut syndrome (Data S1).

Recordings

In addition to the standard EEG electrodes, surface EMG electrodes (silver/silver chloride 9-mm surface electrodes) were placed on the deltoid muscles on both sides in a monopolar setting (the active electrode was placed on the midpoint of the muscle belly, whereas the reference electrode was placed on the acromioclavicular joint, just proximal to the insertion of the muscle). We opted for this setting to circumvent the effects of phase-cancellation that occur in the bipolar setting, when both electrodes are placed on the muscle (Bischoff et al., 1999; McAuley et al., 2000; Staudenmann et al., 2010).

The surface EMG signals were sampled with a frequency of 1,024 Hz, and an anti-aliasing filter of 512 Hz. All EMG signals were notch (49–51 Hz) filtered with an infinite impulse response filter to remove noise from the power line and furthermore high pass (10 Hz) filtered with a finite impulse response filter, as the signal beneath 10 Hz is obscured because of the movements of the electrodes against the skin (Merletti & Parker, 2004). For both filters, the group delay was assessed and found not to interfere with the investigated frequencies.

Seizures

The long-term video–electroencephalography (EEG) recordings were reviewed by a clinical neurophysiologist and an epileptologist, who marked the time epochs containing a tonic seizure or the tonic component of a tonic–clonic seizure, based on visual analysis. These epochs were marked only if they unequivocally corresponded to a seizure–period. In case of the secondarily generalized seizures, the start of the bilateral symmetric phase was marked as the onset.

We recorded 63 epileptic seizures with tonic muscle activation from the 20 patients (mean 3.2 seizures/patient; range 1–10). The patients with tonic seizures had more seizures (mean 4.5 seizures/patient; range 1–10) than the patients

with tonic-clonic seizures (mean 1.8 seizures/patient; range 1–4) ($p = 0.027$). To avoid an excessive influence on the group-data from the patients with more seizures, the mean of the seizures was calculated for each patient.

The healthy controls were trained to perform the sustained, maximal muscle contraction in all upper limb muscles in a position imitating the one during the epileptic seizures, as instructed and as shown on the video. The recording was done in the presence of two of the authors (including a physician with experience in evaluating long-term video-EEG recordings), and the healthy controls were asked to correct the way they activated the muscles if that was necessary. Each healthy control subject simulated five seizures, which gives in total 100 simulated seizures.

Data analysis

To characterize the surface EMG signals during the epileptic and the simulated seizures, several quantitative parameters were calculated. All data analysis was done using MATLAB 7.6 software (Mathworks, Natick, MA, U.S.A.).

Time domain

The amplitude is fluctuating within broad ranges, and outliers have huge influence. To avoid this, instead of the raw amplitude, an expression of the mean value of a short time window is used to characterize the amplitude (Arabadzhiev et al., 2010). An arithmetic mean of the raw signal would provide a value close to zero; therefore, the signal is squared before calculation of the mean and then to even out the square effect, the root is applied. This is called the root mean square (RMS) and is characterized using the RMS value:

$$\text{RMS}(x) = \sqrt{\frac{1}{N} \sum_{n=0}^{N-1} x(n)^2},$$

where $x(n)$ is the EMG signal and N is the window length. The RMS value was calculated for a window of a length of 3 s and each window overlapped the previous and the next one with 2 s. As there seems to exist no established definition for the minimum duration of a tonic contraction to qualify as a tonic seizure, we used for the successive time windows a duration of 3 s as proposed by Lüders et al., (1998).

Frequency domain

The frequency features were visualized using plots of the magnitude of the fast Fourier transform (FFT) and spectrograms, and they were quantified by the MF and the relative power (100–500 Hz).

MF is defined as the frequency that divides the magnitude spectrum in two parts of equal sizes (the area under the curve for the frequencies lower than MF equals the area under the curve for the frequencies higher than MF) (Gelli

et al., 2007; Wakeling, 2009), and it is expressed according to the formula:

$$\sum_{f=0}^{f_{MF}} |\text{FFT}_m(f)| = 0.5 \sum_{f=0}^{f_s/2} |\text{FFT}_m(f)|, m = 1, 2, 3, \dots,$$

where m is the window number, f_s is the sampling frequency, f_{MF} is the MF, and the FFT_m is the discrete frequency spectrum of the window m . $| \cdot |$ computed the absolute values of the discrete frequency spectrum. The MF values were calculated from time windows of 3 s duration, overlapping by 2 s.

Spectrograms (diagrams visualizing the power of the signal in the different frequency components across the time) were calculated for each seizure. The power was calculated for a small window of 125 samples, and each window was overlapping the previous and the next by 50%. This offered a frequency and time resolution of 7.5 Hz and 0.125 s, respectively. The frequency was represented on the y-axis, and the successive time windows on the x-axis. For each time window the power was visualized for all frequencies in a color-code (the size of the logarithm of the relative power for the particular time window and frequency band).

In addition, we determined the relative power (RP) in the higher frequency domain. Based on the visual inspection of the spectrograms we chose the frequency range 100–500 Hz. The RP was calculated by dividing the power in the 100–500 Hz frequency range by the total power of the signal in the whole frequency domain, in each time-window, of 3 s overlapping as for the other features by 2 s:

$$\text{relP}(m) = \frac{\sum_{f=100}^{500} |X_m(f)|^2}{\sum_{f=0}^{f_s/2} |X_m(f)|^2}, m = 1, 2, 3, \dots,$$

where $X_m(f)$ is the N -point discrete frequency spectrum ($N = 4,096$) of the m 'th window.

Coherence

Coherence is the correlation in the frequency domain between two oscillatory activities in spatially distinct systems (Mima & Hallett, 1999). This normalized measure of correlation has values between 0 and 1. A coherence value of 1 indicates a perfectly linear relationship, whereas 0 is when the two signals are completely independent.

We calculated EMG–EMG coherence between the right and left sides, using the standard methods in this field (Brown et al., 1999; Farmer et al., 1993b; Halliday et al., 1995; Kilner et al., 1999). We opted for including in this article results from the analysis of the unrectified EMG signals because previous studies have suggested that rectification might impair the oscillatory input between two EMG signals (Neto & Christou, 2010). Furthermore, one of the previous studies showed that this analysis method is reliable

also for unrectified data (Brown et al., 1999). However, we also analyzed the rectified data, and the results were similar (Data S2). We plotted the coherence spectra for each subject and furthermore calculated the coherence in the whole frequency band (10–512 Hz) as the mean of the coherence values in this domain.

For each subject we calculated the mean of the RMS, MF, RP, and coherence values of all time windows, during all seizures, and the mean of the values from the left and right deltoid muscles were entered into the statistical analysis. Therefore, for each patient only one (mean) value was entered into the statistical analysis, regardless of the number of seizures the patient had. We did this to avoid the bias toward the data from patients with more seizures.

Because the surface EMG parameters (calculated from the time windows of 3 s) were not constant within the seizures, besides determining the mean value of the different parameters for the whole seizure period (as described above), we also calculated the 95th percentile (peak) values, for each patient and for each quantitative EMG parameter. This way we can express the highest level of activation for a certain parameter, for each patient, without being biased by the outlier values (upper 5th percentile).

Statistics

The normality of the data distribution was assessed using Kolmogorov-Smirnoff test. Because the data were not normally distributed we compared the quantitative EMG parameters among the subject groups using Wilcoxon test. To assess the matching of the gender between the two groups and further between the subgroups, Fisher's exact test was used.

RESULTS

Examples of the EMG signals from the different groups are shown in Fig. 1. The quantitative EMG parameters are presented in Table 1.

Median frequency

The magnitude spectrum visualizes the distribution of the signal at the different frequency components (Fig. 2). During the epileptic seizures (especially the tonic ones) we observed a shift to the right (toward the higher frequencies). The FFT of the simulated seizures (Fig. 2C) are mostly below 100 Hz.

The MF (Table 1) was significantly higher during the epileptic seizures as compared with the simulated ones ($p = 0.005$).

The subgroup analysis showed that MF was significantly higher during the tonic seizures than during the simulated seizures ($p = 0.001$), and furthermore significantly higher than during the tonic phase of the tonic-clonic seizures ($p = 0.03$). There was no significant difference between the

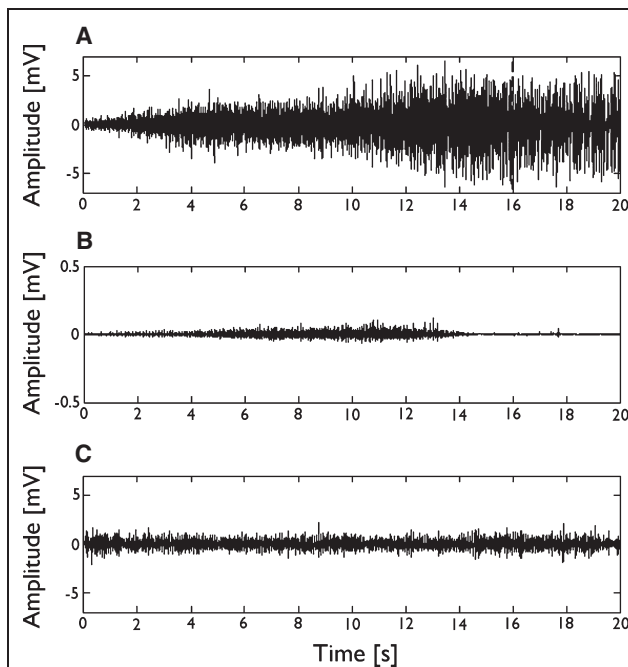


Figure 1. EMG signals of representative seizures: (A) the tonic phase of a tonic-clonic seizure; (B) tonic seizure; (C) simulated seizure. The vertical, dotted line in figure A marks the end of the tonic phase/beginning of the clonic phase, as seen on the video-EEG recordings. The scale of the y-axis is different for the three seizures.

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MF during the tonic phase of the tonic-clonic seizures and the simulated ones ($p = 0.18$).

Relative power

Figure 3 shows spectrograms of the RP for the different frequencies. Inspection of the spectrograms suggested higher power for the frequency domains above 100 Hz during the epileptic seizures as compared with the simulated ones. To express this quantitatively we calculated the RP for the frequency range of 100–500 Hz.

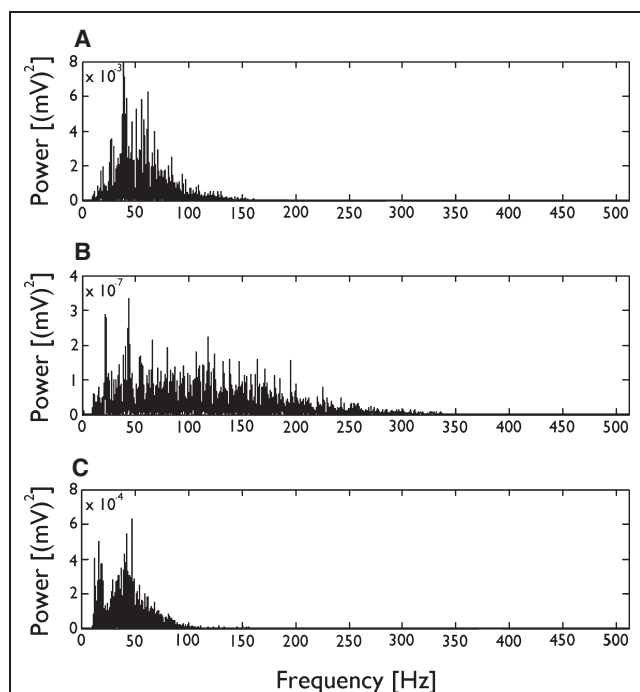
The RP (100–500 Hz) was significantly larger during the epileptic seizures as compared with the simulated ones ($p = 0.006$). RP (100–500 Hz) was higher during the tonic seizures than during the tonic phase of the tonic-clonic seizures ($p = 0.009$) and higher than during the simulated seizures ($p = 0.0004$). There was no significant difference between the RP (100–500 Hz) during the tonic phase of the tonic-clonic seizures and the simulated ones ($p = 0.37$).

Amplitude characteristics

The visual inspection of the EMG signals suggested that amplitudes were higher during the tonic phase of the tonic-clonic seizures as compared to the seizures from the other subjects (Fig. 1).

Table 1. Median values of the whole seizure period for all patients (and in parentheses 95% confidence intervals) for the different surface EMG parameters

	Epileptic	Tonic	Tonic-clonic	Simulated
MF (Hz)	76.8 (59.0–112)	86.2 (63.3–113)	73.6 (59.0–80.8)	63.9 (56.9–83.9)
RP (100–500 Hz)	0.151 (0.047–0.395)	0.217 (0.114–0.401)	0.110 (0.041–0.176)	0.079 (0.039–0.207)
RMS (mV)	0.636 (0.055–2.20)	0.251 (0.053–0.784)	1.16 (0.356–2.46)	0.440 (0.170–1.10)
Coherence	0.120 (0.050–0.255)	0.117 (0.048–0.178)	0.120 (0.063–0.289)	0.071 (0.046–0.109)

**Figure 2.**

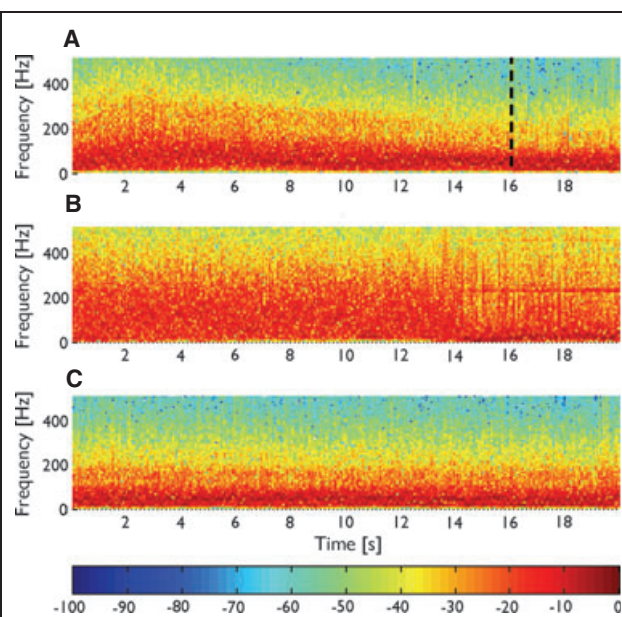
Power spectra of representative seizures: (A) the tonic phase of a tonic-clonic seizure; (B) tonic seizure; (C) simulated seizure. The scale of the y-axis is different for the three seizures. For the simulated seizures most of the power is in the frequency band <100 Hz. During the epileptic seizures (especially the tonic seizure) one can observe a shift toward the higher frequencies.

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The RMS (Table 1) for the group of epileptic seizures was not significantly different from that for the simulated seizures ($p = 0.47$). However the subgroup analysis showed that the RMS during the tonic phase of the tonic-clonic seizures was significantly higher than during the simulated seizures ($p = 0.001$), and furthermore significantly higher than during the tonic seizures ($p = 0.0008$). The RMS during the tonic seizures were significantly smaller than during the simulated seizures ($p = 0.045$).

Coherence

The visual inspection of the EMG signals showed bilateral-synchronous, sustained muscle activation during the analyzed seizure periods in all groups. The coherence

**Figure 3.**

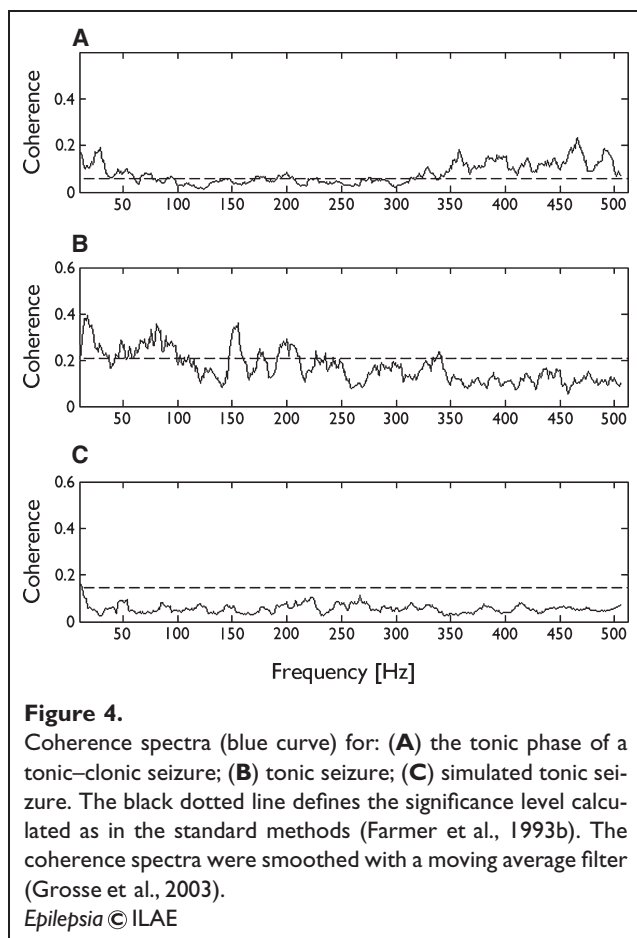
Spectrograms (time-frequency plots) of representative seizures: (A) the tonic phase of a tonic-clonic seizure; (B) tonic seizure; (C) simulated seizure. The vertical, dotted line in figure A marks the end of the tonic phase/beginning of the clonic phase, as seen on the video-EEG recordings. The color code represents the size of the logarithm of the relative power.

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spectra demonstrated that there were several frequencies with significant coherence for each patient (Fig. 4), and that these frequencies varied from subject to subject. In the absence of certain, dominating frequencies for the significant level of coherence, we opted to calculate the coherence for the whole frequency band and to compare this among the groups. The coherence was significantly higher during the epileptic seizures than during the simulated ones ($p = 0.0005$). There was not any significant difference in coherence between the two subgroups of epileptic seizures ($p > 0.3$), but in both epilepsy subgroups the coherence was higher than in the group with simulated seizures ($p \leq 0.007$).

Peak values

To reflect the highest level of activation achieved by each patient/subject, in addition to mean values for the whole-seizure period (detailed above), we also calculated the 95th



percentile of the parameters (peak values). The shift toward the higher frequencies during the tonic seizures, the increase in the amplitude characteristic (RMS) during the tonic phase of the tonic-clonic seizures, and the increase in the coherence in the epileptic seizures (both types) were even more pronounced when analyzing the peak values (Data S3).

The effect of duration

There was no statistically significant difference between the duration of the tonic seizures and the duration of the tonic phase of the tonic-clonic seizures in our patients (median: 14.66 and 15.95 s, respectively; $p = 0.6$). There was no significant correlation between the duration and the quantitative EMG parameters that distinguished between the two seizure-types: RP 100–500 Hz, MF, RMS ($p > 0.12$). A multiple regression analysis for categorical (seizure-type: tonic vs. tonic-clonic) and continuous (duration) predictors showed that it was only the seizure type that predicted these quantitative EMG parameters.

DISCUSSION

We found a significant shift toward higher frequencies during tonic seizures. Patients with tonic-clonic seizures

had significantly increased amplitude characteristic (RMS), whereas patients with tonic seizures had significantly lower RMS than the simulated seizures. The EMG–EMG coherence was significantly higher during the epileptic seizures (in both subgroups).

The mechanism of muscle activation in the healthy volunteers simulating the seizures is obviously a physiologic one. Although, based on visual assessment, the posturing and muscle contractions appeared similar during the simulated and the epileptic seizures, the mechanisms of muscle activation were different.

As the surface, EMG parameters were not constant within the seizures; in addition to determining the mean value of the different parameters for the whole seizure period, we also calculated the 95th percentile (peak) values. Our results were even more pronounced when analyzing the peak values than when analyzing the mean values of the whole seizure periods.

Quantitative analysis of the surface EMG demonstrated significant differences between the two subgroups of epileptic seizures in which the qualitative (visual) assessment showed “sustained muscle activation”: tonic seizures are produced by a significant shift toward the higher frequency bands, whereas the tonic phase of the tonic-clonic seizures is produced by an increase in the amplitude characteristic. These differences between the tonic seizures and tonic phase of the tonic-clonic seizures are not merely a function of time, as there was no significant difference in duration between the two seizure types, and the quantitative EMG parameters that differentiated between them did not show a correlation with the duration of the tonic muscle activation.

Except for one patient with idiopathic generalized epilepsy (JME) all patients (in both epileptic subgroups) had symptomatic or unknown etiology. When excluding the JME patient from the tonic-clonic group we obtained similar results for all analyses. However, it is interesting to point out that the patient with JME was an outlier: The increase in the RMS and coherence was even more pronounced than in the other patients.

Although various quantitative surface EMG parameters have been used to infer details about the central nervous system (CNS) control mechanism of muscle activity, the technical limitations of the method should be emphasized, as the surface EMG reflects both peripheral and central properties of the neuromuscular system (Farina et al., 2004). However, the shift toward higher frequency domains during the muscle activation has been attributed to the recruitment of more motor neurons, including the ones with higher threshold (Wakeling, 2009; Riley et al., 2008). The increase in the amplitude characteristic (RMS) of the surface EMG signal can be caused by synchronization of the MU activity or by lengthening of the muscular action potential (Arabadzhiy et al., 2010).

The shift toward higher frequencies during the tonic seizures can thus be explained by an increase in the

recruitment of more, high threshold motor neurons. Patients with Parkinson's disease have an altered pattern of MU recruitment: There is a preferential activation of the low-threshold MUs suggesting that the extrapyramidal system is involved in coordinating the recruitment of the high threshold MUs (Glendinning & Enoka, 1994). Based on this, we hypothesize that the observed shift toward the higher frequencies during tonic seizures is due to excessive activation of the extrapyramidal system. In the early electroclinical studies of the tonic seizures, Gastaut opined that these seizures result from an activation of the subcortical/extrapyramidal structures (Gastaut et al., 1963). This is consistent with our findings and the recently published ictal single photon emission computed tomography (SPECT) data showing hyperperfusion in the basal ganglia during focal tonic seizures (Wong et al., 2010).

The increase in the amplitude characteristics of the EMG signal during the tonic phase of the tonic-clonic seizures can be explained by an increased synchronization in the recruited motor neuron pool. Studies of patients with lesions of the corticospinal tract demonstrated the importance of these pathways in the presynaptic synchronization of the spinal motor neurons (Farmer et al., 1993a; Smith et al., 1999). This suggests that the increase in the amplitude during the tonic phase of the tonic-clonic seizure could be attributed to an excessive activation of the corticospinal pathways, as opposed to the possible extrapyramidal dominance during the tonic seizures.

As early as 1963, Gastaut, based on visual analysis of the surface EMG in polygraphic recordings described that the tonic phase of the tonic-clonic seizures was "more intense" than the contraction of tonic seizures (Gastaut et al., 1963). Our quantitative analysis demonstrating higher amplitude characteristic of the tonic phase of the tonic-clonic seizures are consistent with these early observations. Our findings further support that tonic seizures are not merely truncated manifestations or fragments of tonic-clonic seizures (i.e., minus the clonic phase), not even at the level of the final pathway (the MUs). We suggest that the "sustained tonic contraction" has to be defined differently for tonic and tonic-clonic seizures, emphasizing the increase in frequency in the case of the tonic seizures and the increase in amplitude for the tonic-clonic seizures. A different aspect that we did not include in our study is the transition in tonic-clonic seizures from the tonic to the clonic phase with its cycles of inhibition interrupted by reappearance of the tonic contraction, producing atonia alternating with violent flexor spasms (Zifkin & Dravet, 2008).

The healthy controls were trained to activate simultaneously and synchronously the muscles on the two sides. The visual analysis of the recordings showed that the "sustained" muscle activation during all analyzed seizures in all patients and subjects were bilateral, symmetrical, and synchronous. However, the coherence was significantly higher

during the epileptic seizures (in both subgroups for the whole seizure period) as compared with the simulated ones. This suggests that the neural networks on both sides are synchronously activated also in the efferent pathways. Grosse et al., (2003) found markedly increased EMG-EMG mean coherence between the muscle pairs on the two sides in nine patients with high frequency rhythmic myoclonus. Our findings in patients with generalized tonic and tonic-clonic seizures are consistent with this.

In conclusion we demonstrated distinct patterns of muscle activation during tonic seizures and the tonic phase of tonic-clonic seizures. Our results provide further insight into the pathomechanism of the muscle activation during epileptic seizures. In addition, our results have potential diagnostic significance. A combination of these parameters could provide supplementary information in selected, difficult cases where the differentiation between epileptic and nonepileptic seizures is difficult only based on video-EEG data. A combination of these distinct EMG features could also be used to design algorithms for automatic seizure detection based on surface EMG data.

To the best of our knowledge this is the first publication addressing the quantitative analysis of the surface EMG signals during tonic and tonic-clonic epileptic seizures.

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DISCLOSURE

None of the authors has any conflict of interest to disclose. We confirm that we have read the Journal's position on issues involved in ethical publication and affirm that this report is consistent with those guidelines.

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SUPPORTING INFORMATION

Additional Supporting Information may be found in the online version of this article:

Data S1. Clinical data of the 20 patients with epilepsy (T, tonic seizures; TC, tonic-clonic seizures).

Data S2. p-Values for the coherence of rectified and unrectified EMG data, respectively. Median values of the whole seizure period for all patients (and in parentheses 95% confidence intervals) for the coherence of the rectified and the unrectified surface EMG data.

Data S3. Median values of the peak values for all patients (and in parentheses 95% confidence intervals) for the different surface EMG parameters.

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