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Extraction and Analysis of the Single Motor Unit F-Wave of the Median Nerve

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1. Introduction

The matrix type multielectrodes have been proved to be useful for getting the information of motor unit (MU) properties (Monster et al., 1980; Reucher et al., 1987; Yamada et al., 1987; Masuda and Sadoyama, 1988; Kleine et al., 2000; Gazzoni et al., 2004). By this electromyography (EMG) technique, we can obtain many essential properties of MU that could not be obtained by conventional surface EMG and/or needle EMG. One of them is the waveform property of motor unit action potential (MUAP) which is enabled by extracting the single propagating MUAP. Another is the two-dimensional location of motor end-plates. There have been many applications of multichannel surface EMG for measuring voluntary muscle activities, but few for evoked EMG responses. However, recent studies have demonstrated the applications of the multichannel surface EMG for the measurement of muscle fiber conduction velocities (MFCVs) (Metani et al., 2005) , for the estimation of firing thresholds (Yamada, 2004), and for the motor unit number estimate (MUNE) (Blok et al., 2005; van Dijk et al., 2008).

The F-wave represents a long latency response detected from a muscle following stimulation of a peripheral nerve at supramaximal intensity. The F-waves are produced by antidromic activation of motor neurons. The latency and the waveform of the F-wave change with each stimulus. The F-wave studies are widely used in clinical neurophysiology as a quantitative estimation method of the objective pathological changes. The F-waves that consist of a single MUAP occur also with submaximal stimulation. Low intensity stimulation could increase the probability of the single MU F-wave (Komori et al., 1991; Doherty et al., 1994; Stashuk et al., 1994; Yamada, 2004), and reduce the discomfort of the subjects. Therefore, different MUAPs can be readily analyzed by classifying F-waves. Many studies concerned with the single MU F-wave were performed for the estimation of the conduction velocity of nerve fibers (Doherty et al., 1994; Felice, 1998; Wang et al., 1999) and the MUNE (Stashuk et al., 1994; Hara et al., 2000). The conventional surface EMG technique was used in these studies, and there were few applications of multichannel surface EMG for F-wave studies.

In a previous study, we investigated the classification and analysis of multichannel bipolar F-waves (Yamada et al., 2007). It is difficult to detect deep MUs from the bipolar EMG. So, in the present study, the thenar MUs F-waves were investigated by extracting single MU F-waves from monopolar multichannel surface EMG signals. By increasing the number of

processing data measured under different stimulus conditions, many single MU F-waves could be extracted, and the properties of F-waves and MUs could be analyzed successfully. Then we could find the single MU F-waves with the same waveform but different latencies.

2. Methods

2.1 Subjects and measurements

The subjects were 6 men, aged 22－60 years (mean±S.D., 30.2±14.9 years). None of them had a history of neurological disorders. All subjects gave informed consent prior to participation in the study. The subject sat comfortably on a chair with his right hand supinated. The right median nerve was stimulated at the wrist and the evoked responses were recorded from the thenar muscles with a matrix-type multielectrode. The multielectrode was composed of 32 silver electrodes (8x4 array), 1 mm in diameter, which were arranged on a silicone rubber board (thickness 2 mm) at 4 mm distance in both directions (Fig. 1). This electrode was fixed by bandages with the eight electrode arrays in parallel with the muscle fibers. A small diameter of electrode and a short distance of electrodes enabled the extraction of single MUAP from surface EMG signals. The use of a semi-solid type electrode paste enabled to measure EMG signals for a long period. A reference electrode and a ground electrode, both conventional Ag/AgCl electrodes, were attached to the bone of the dorsal hand. The block diagram of the multichannel surface EMG system is shown in Fig. 2.

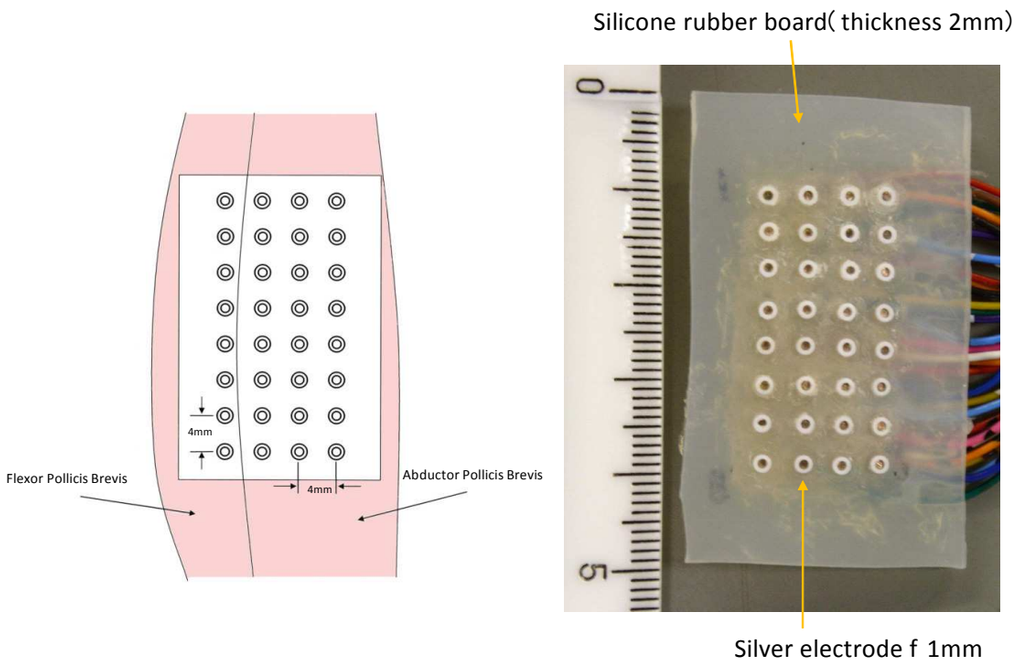

Fig. 1. Thirty-two channel matrix-type multielectrode. Each electrode (1mm in diameter) is arranged on a silicone rubber board at 4 mm distance in both directions.

The 32 channel monopolar evoked potentials (8x4 array) were amplified through a bandwidth of 10-1000 Hz (gain 30dB). The amplified evoked signals were sampled at 10kHz with 16-bit resolution. The stimulation was squarewave pulse of 0.2 ms duration and frequency of 5 Hz or less. The high stimulus rate may cause muscle fatigue, and may change

the shape of MUAP. Therefore the low stimulus frequency was selected for recording consecutive evoked responses. The stimulation strength was set to submaximal, approximately 40-80 % of the supramaximal stimulation. Each of the record length was 50ms, and 300 consecutive evoked responses were recorded. Changing the stimulation intensity, several sessions of 300 evoked responses were recorded. The bipolar potentials were obtained by calculating the difference between the monopolar potentials of two adjacent electrodes placed along the muscle fibers.

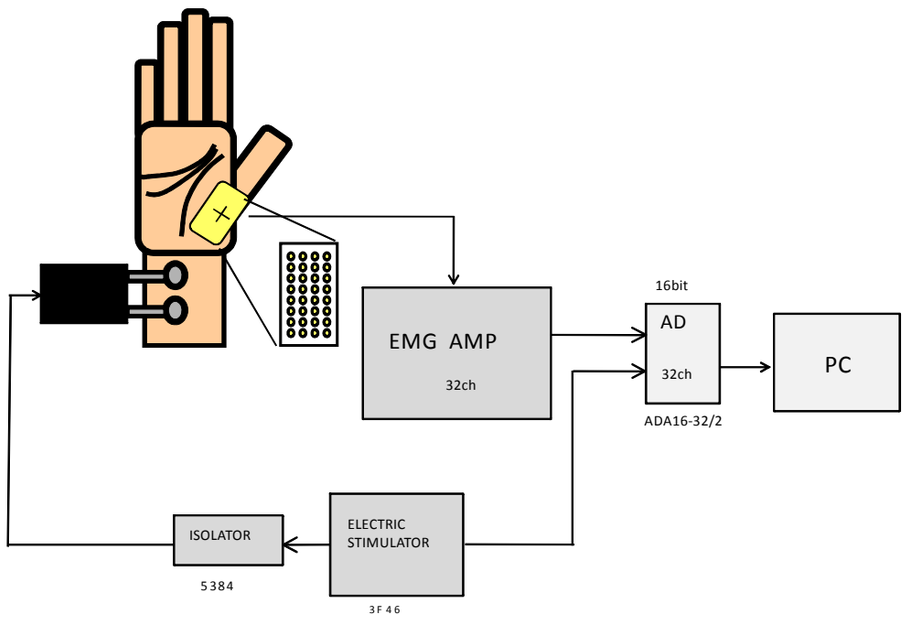

Fig. 2. Block diagram of the multichannel surface EMG system.

As in the case of bipolar signals (Yamada, 2004; Yamada et al., 2007), the origin of the F-wave could be also evaluated by the distribution pattern of monopolar MUAPs. It is presumed that the MUs whose center arrays estimated at array 1 and array 2 are originated from the abductor pollicis brevis (APB), and those estimated at array 3 and array 4 are originated from the flexor pollicis brevis (FPB). In Fig. 3(A), the distribution of 32 channel monopolar evoked potentials recorded in a thenar muscle is shown. This MU is originated from the APB muscle. Fig. 3(B) shows 8 channel records of the center array (array 1).

2.2 Classification of F-waves

The outline of the classification of F-waves is shown in Fig. 4. All channels evoked responses are digitally high-pass filtered in order to remove the late components of the M-waves with a drift filter which barely affects the waveform parameters of the F-waves. The superimposed traces in Fig. 5 show 10 sequentially evoked responses of one electrode array. Although the M-waves are almost uniformed, the F-waves show various patterns. When the evoked response contains the F-wave, the center of the MU in transverse section (center array) is evaluated by the sum of the peak-to-peak amplitude of F-waves in each electrode array. Then we select the records (latency 20-45 ms) in the array for the classification process.

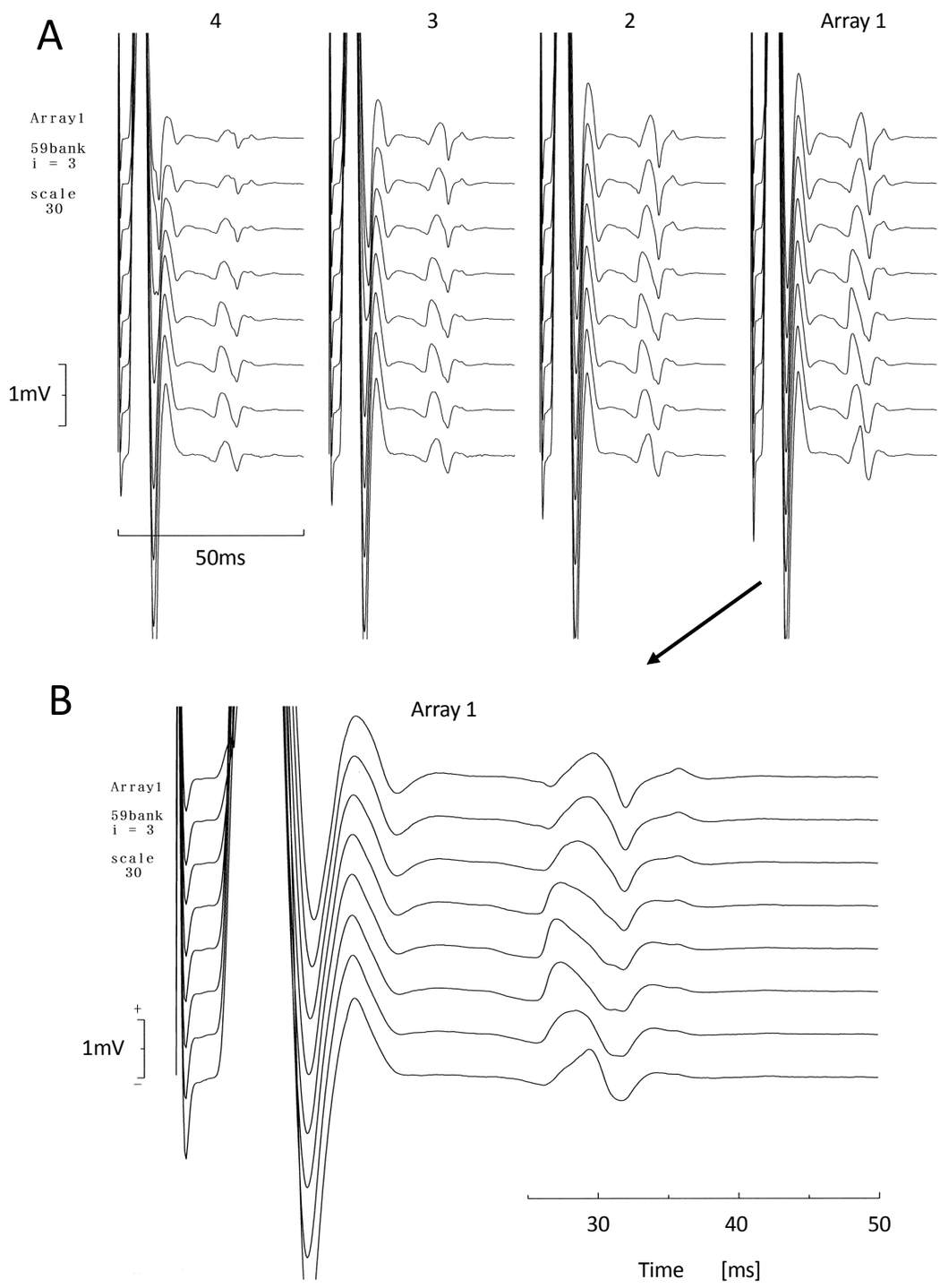

Fig. 3. Distribution of 32 channel monopolar evoked potentials in the thenar muscles at submaximal stimulation (A). Expanded 8 channel monopolar potentials of the center array (B). The signals were digitally high-pass filtered with a drift filter.

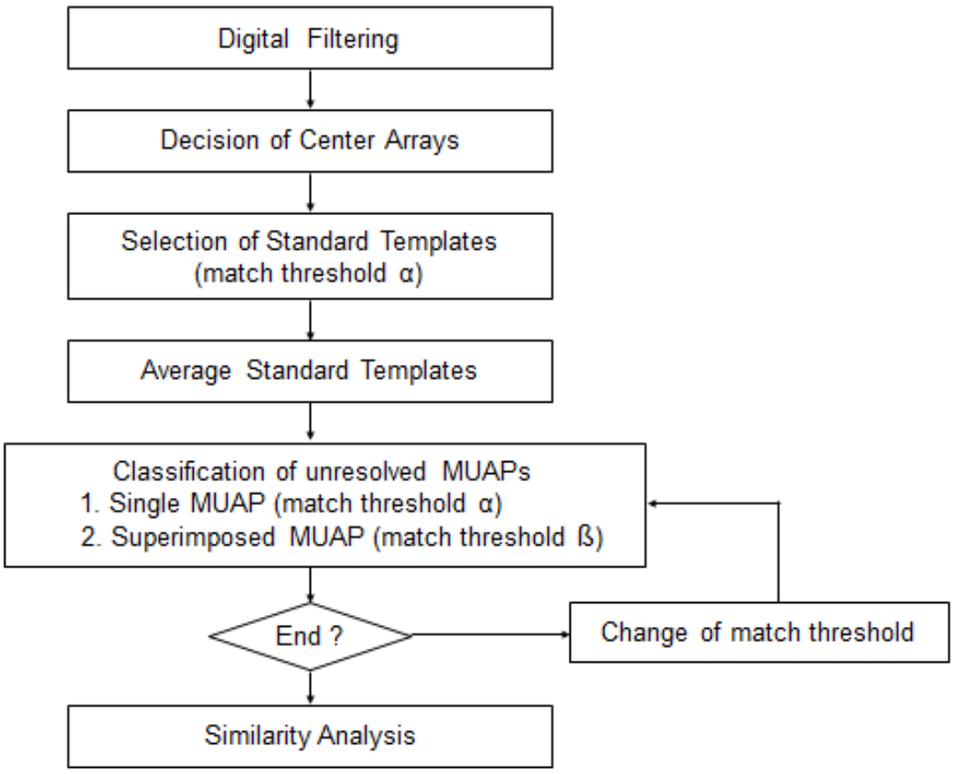

Fig. 4. Flow chart of the classification of F-waves.

Eight channel MUAP waveforms in its center array are classified using a template-matching method based on the least-square error criterion where an initial match threshold α is set to 5% of the objective area value typically. If the F-wave and templates do not match, the waveforms on both sides of the center array are also estimated, because the decision of center arrays is critical and not always proper. After this procedure, the standard templates are selected by the decision rule dependent on the identified number of the corresponding template, and the average waveforms are computed for the next procedure. The group of F-waves, which is not identified as one of the standard templates, is repeatedly classified into an averaged standard template or 2-3 combinations of them by the same method in the selection of standard templates. The match threshold β in case of superposition is initially set to lower than α (typically 4.5% of the objective area value), because high thresholds tend to lead to incorrect combinations of standard templates. After having thresholds α and β gradually increased, the unresolved F-waves are repeatedly processed. By these procedures, the single MU F-waves are classified. Five sessions of recordings measured at different stimulus intensities were processed to extract many single MUs. Fig. 6 shows 38 single MU F-waves extracted and classified from the thenar muscles of a subject.

2.3 Estimation of F-wave parameters

The amplitude of a single MUAP was evaluated from measuring the largest peak-to-peak amplitude in 8 channel MUAP waveforms in its center array, and the latency was obtained

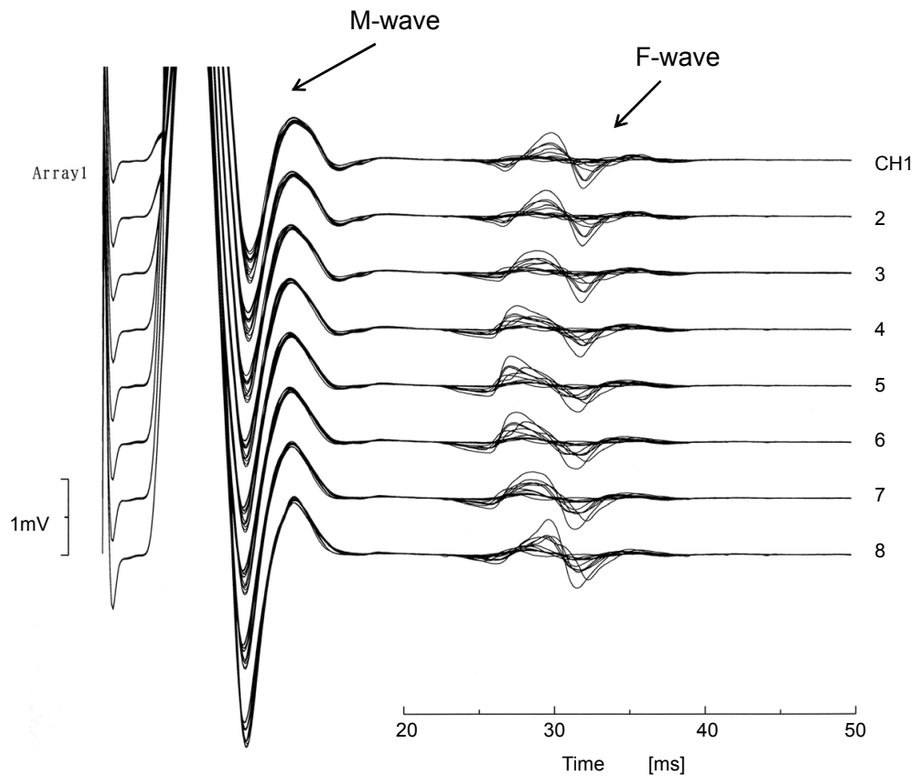

Fig. 5. Superimposed 10 evoked responses of one electrode array.

from measuring the fastest onset of MUAP in the array. In the case of MUAPs showing propagating time delays, the MFCV was calculated from the time delay of a single pair of MUAPs in the array. The MUAPs in the region of the motor end-plates band indicated non-linear propagating time delays, and we estimated the conduction velocity in the area a small distance on either side of the band, where the conduction velocity was uniform along the length of the muscle. The muscle fiber conduction velocities of all classified MUAPs, excepting superimposed ones, were computed according to the above considerations, and other parameters were estimated automatically as well.

Statistical analysis was carried out for F-wave parameters. The correlation coefficients among amplitudes, latencies and MFCVs were calculated in each subject. The level of statistical significance was set at $p<0.05$.

2.4 Detection of single MU F-waves with the same waveform but different latencies

From these classified F-waves, the F-waves with the same waveform but different latencies (latency differences above 0.5 ms) were searched using 8 channel and 32 channel similarity values between the two averaged F-waves.

In the case of similarity values higher than 0.8, the comparison of two F-waves was performed by examining 8 channel propagation patterns of MUAPs in its center array and 32 channel distribution patterns of MUAPs in a superimposed form and in an averaged form. In addition, bipolar waveforms were also compared for reference. The F-wave analysis is planned to execute interactively, or automatically. At present, the operator is required in some processes to obtain reliable and accurate results.

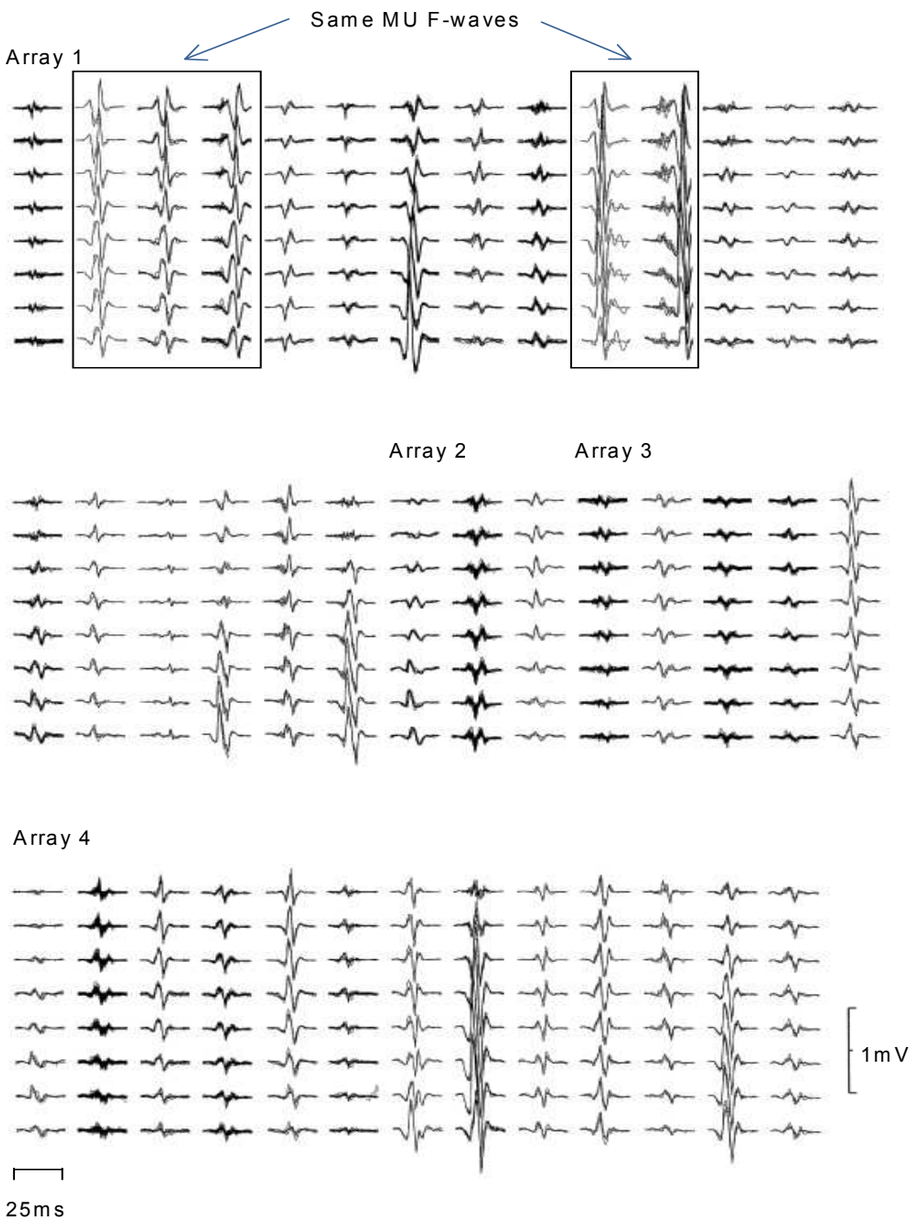

Fig. 6. Thirty-eight single MU F-waves extracted and classified in the thenar muscles of one subject. Two APB MUs with the same waveform but different latencies are shown in the top traces.

3. Results

Single MU F-waves were classified by using the template-matching method. The classification results and estimated F-wave parameters of thenar MUs in 6 normal subjects are shown in Table 1 and Fig. 7. The mean F-wave persistence (occurrence rate) was high (88.8%), and a total of 7724 F-waves were detected in the evoked responses. The numbers of MUs extracted from 5 sessions of data (1500 responses) were increased by 75-116%

Subjects	F-wave (n=1500)	MU			
		n(APB+FPB) (FPB)	Amplitude Mean ± SD. (mV)	Latency Mean ± SD. (ms)	MFCV Mean ± SD. (m/s)
1	1376(91.7%)	38(18)	0.367±0.304	28.07±2.08	5.369±1.065(11)
2	1279(85.3%)	41(22)	0.179±0.130	27.20±1.63	5.425±1.096(2)
3	1413(94.2%)	35(10)	0.317±0.222	25.99±2.95	6.200±0.000(3)
4	1080(90.0%)*	30(6)	0.142±0.107	25.30±0.97	3.832±1.331(5)
5	1236(82.4%)	31(15)	0.250±0.188	26.20±2.25	4.112±1.020(10)
6	1340(89.3%)	26(3)	0.183±0.186	27.90±1.23	4.753±1.56(3)
Total	7724(88.8%)	201(74)	0.251±0.222	26.74±2.25	4.800±1.237(35)

*n=1200

Table 1. Classification results for the F-waves in 6 normal subjects: the numbers of F-waves, the numbers of MUs and the estimated MU parameters.

(mean±S.D., 92±15%) compared with those from the maximum sessions (300 responses). The numbers of MU in 6 subjects were 38, 41, 35, 30, 31 and 26, respectively. The total of 201 thenar MUs were extracted from the F-wave data.

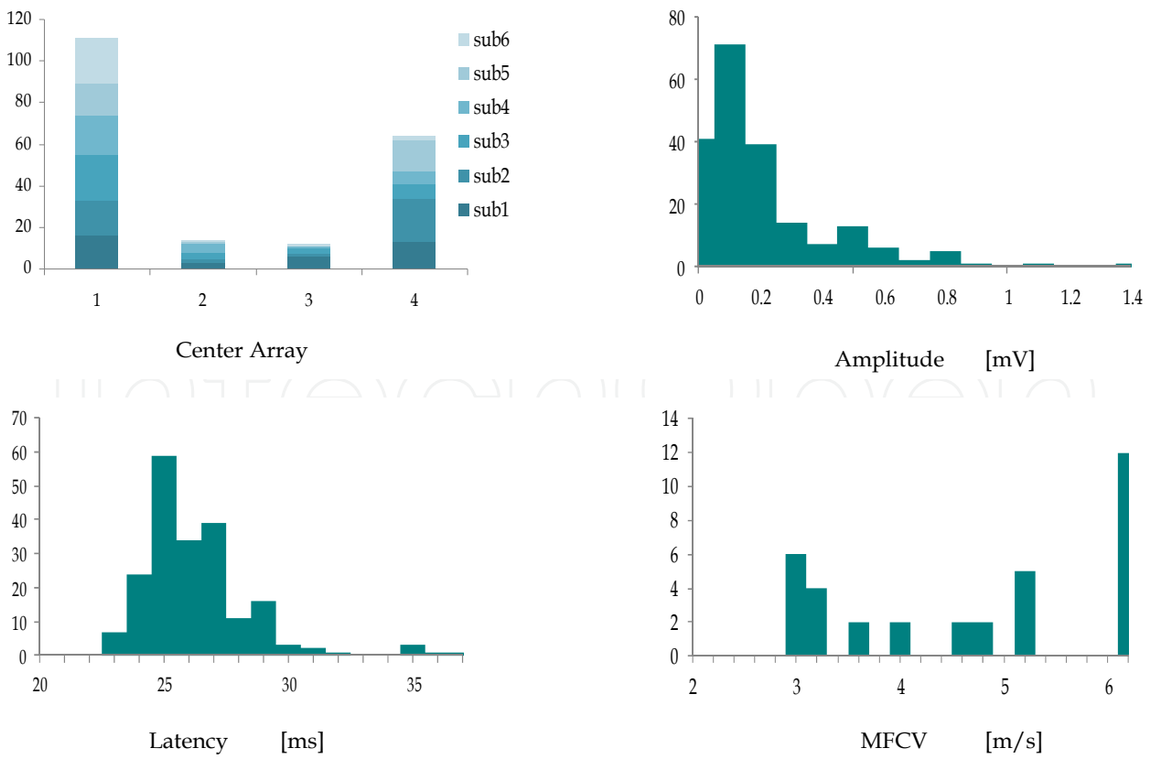

Fig. 7. Estimated parameters of single MU F-waves: Center array, Amplitude, Latency and MFCV.

The numbers of MUs originated from the APB and FPB were 127 (63.2%) and 74 (36.8%). In 5 out of 6 subjects, the numbers of APB MUs were larger than those of FPB MUs. Fig. 6(a) shows the histogram of the center arrays of 201 MUs. Thirty-eight single MU F-waves classified in a subject are shown in Fig. 7. This example shows 20 APB MUs and 18 FPB MUs. The mean peak-to-peak amplitudes, latencies, and MFCVs were 0.251±0.222 mV, 26.74±2.25 ms and 4.80±1.24 m/s. The long latencies greater than 30 ms were detected in 11 MUs (5 subjects). The numbers of MUs in which MFCVs could be evaluated in 6 subjects were 11, 2, 4, 5, 10 and 3, respectively. The total was 35 MUs (17.4%). The significant correlations were not found between amplitudes, latencies and MFCVs in all subjects.
An example of single MU responses (FPB MU) with the same waveform but different latencies is shown in Fig. 8. The latencies of the two responses were (a) 25.7 ms and (b) 36.1 ms, and the latency difference was 10.4 ms. The similarity values for 8 channel and 32 channel signals were high, namely 0.91 and 0.90 respectively.

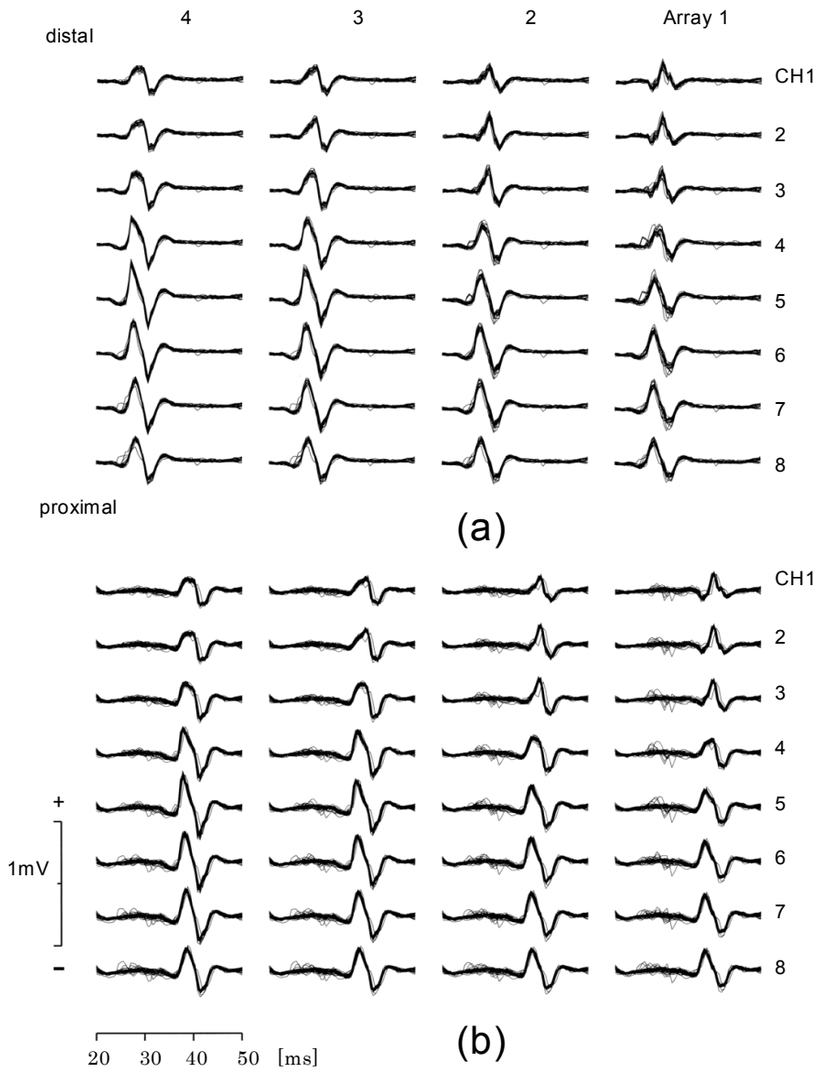

Fig. 8. Distributions of 32 channel MUAPs with the same waveform but different latencies. The latencies were (a) 25.7 ms and (b) 36.1 ms, and the latency difference was 10.4 ms.

The single MU F-waves with the same waveform but different latencies were detected in 5 out of 6 subjects, the total number was 12 MUs (8 APB MUs and 4 FPB MUs, 6%). The estimated F-wave parameters of these MUs are summarized in Table 2.
The latency differences of the two responses ranged 0.9 to 10.4 ms (mean 2.82±3.22 ms), and half of them were around 1 ms. There was no significant relationship between the stimulus intensities and the latencies in these MUs. Figs. 9(a) and 9(b) show the examples of the single MU F-waves (a: FPB MU, b: APB MU) with 0.9 ms and 1.2 ms latency differences. One of the MUs with 3 different latencies (APB MU, 26.3, 29.4 and 32.2 ms) is shown in Fig. 10(a)-(c). The waveforms in Fig. 10(b) differ slightly from those in Figs. 10(a) and 10(c), because the F-waves in Fig. 10(b) are overlapped by the FPB MU with small amplitude MUAPs. These results were confirmed by the distribution and propagation patterns of the MUAPs.

Subject	Array	Amplitude (mV)	Latency 1 (ms)	Latency 2 (ms)	Latency 3 (ms)	Similarity (8CH)	Similarity (32CH)
1	1	1.08	24.0	33.5(9.5)		0.96	0.95
	1	0.57	26.3	29.4(3.1)	32.2(5.9)	0.94	0.91
2	4	0.18	23.9	26.0(2.1)		0.92	0.83
	1	0.68	24.4	25.3(0.9)		0.86	0.89
	4	0.53	24.8	26.0(1.2)		0.90	0.87
	4	0.56	25.7	36.1(10.4)		0.91	0.90
3	1	0.12	25.3	26.3(1.0)		0.87	0.89
	2	0.21	25.7	27.0(1.3)		0.81	0.79
	1	0.26	25.7	27.0(1.7)		0.82	0.72
4	4	0.41	24.8	26.0(1.2)		0.94	0.94
	1	0.19	24.8	26.6(1.8)		0.85	0.83
5	1	0.12	27.1	28.0(0.9)		0.88	0.93
Mean		0.41±0.29	25.2±0.95	28.0±3.23 (2.82±3.22)		0.89±0.05	0.87±0.07

Table 2. Estimated parameters of single MU F-waves with the same waveform but different latencies.

4. Discussion

The F-wave persistence in monopolar recordings was high compared with that in bipolar signals, because it is thought that the deep MUs, which could not be detected from bipolar waveforms, might be detectable from monopolar waveforms. Accordingly, the numbers of MUs that were extracted and classified from evoked responses were increased than those in the previous study (Yamada et al., 2007). In the case of bipolar signals, the noise and interference are lower than those in the monopolar signals. Then, the MUAPs can be classified precisely, and the superimposed MUAPs can be decomposed into its constituent MUAPs. On the other hand, in the case of monopolar signals, the decomposition processing of superimposed MUAPs had a little problem with the classification accuracy.
By using the distribution and propagation patterns of the MUAPs measured by the multichannel surface EMG technique, the single MU F-waves could be extracted and

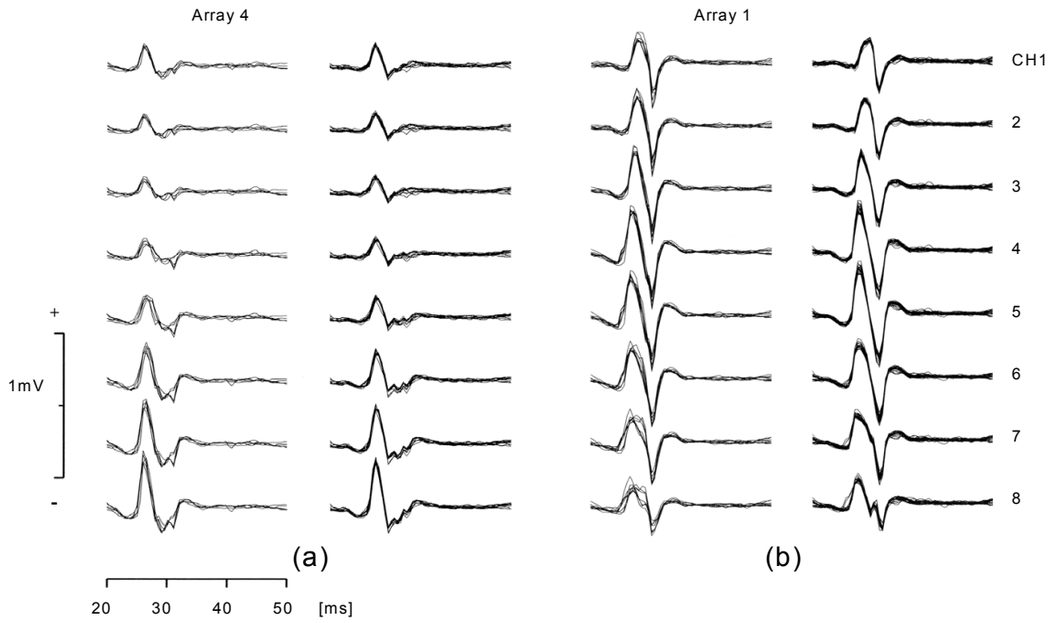

Fig. 9. Single MU F-waves (a: FPB MU, b: APB MU) with 0.9 ms and 1.2 ms latency differences.

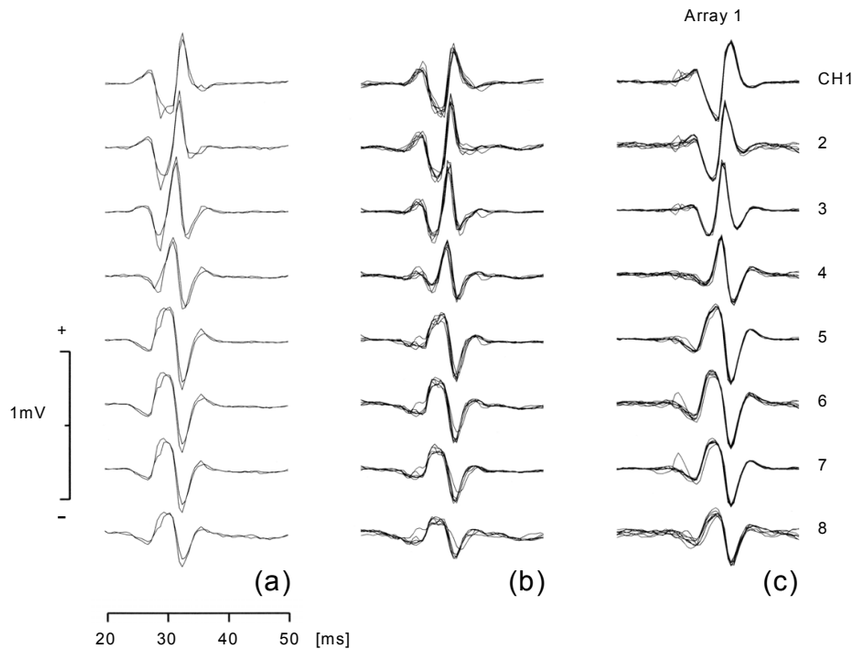

Fig. 10. Single MU F-waves with 3 different latencies ((a) 26.3 ms, (b) 29.4 ms and (c) 32.2 ms). The latency differences were (b)-(a) 3.1 ms and (c)-(a) 5.9 ms.

classified precisely, and the origin of the F-wave is evaluated easily. In the case of bipolar signals, the extracted numbers of APB MUs were larger than those of FPB for all the subjects, and most of the MUs (84.5%) were originated from the APB muscle (Yamada et al., 2007). In this study, 127 APB MUs (63.2%) were extracted from monopolar signals. These results suggest that the number of APB MU is greater than that of FPB MU.

The F-wave amplitude and persistence were increased with increasing the stimulus intensity (Yamada et al., 2007; Fisher et al., 2008). On the other hand, low intensity stimulation increased the probability of single MU F-wave (Komori et al., 1991; Doherty et al., 1994; Shefner, 2001; Yamada et al., 2007). By investigating in detail the relationship between stimulus intensity and the properties of the extracted MUs, it seems that the experimental conditions of stimulus intensity and the combination of intensities, from which more MUs can be extracted, may be determined.

The latency of F-wave is useful to detect alterations in peripheral nerves (Fisher, 1992; Panayiotopoulos and Chroni, 1996; Toyokura and Murakami, 1997; Nobrega et al., 2001). Moreover the latency varies in each MU, so this parameter is useful for classifying individual F-waves. By using the multichannel surface EMG technique, the latency may be measured precisely than other methods, because the locations of motor end-plates, where the MUAPs begin to propagate along muscle fibers in both directions, are readily identified in the two-dimensional plane (Yamada et al., 1991; Yamada, 2004).

The single MU responses with the same waveform but different latencies were detected in 12 MUs out of 201 extracted MUs (6%). Though the latency differences of the two single MUAPs ranged 0.9 to 10.4 ms (Table 2), many of the differences were around 1 ms (50%). In these examples, it suggests that the prolonged latencies occurred due to synaptic delays in the spinal interneuronal network. The synaptic delay is usually of about 0.5 ms (Guyton and Hall, 1996). Therefore, in the case of one interneuron in the pathway, the time delay will be about 1 ms. The long-latency reflexes (LLRs) can be elicited by electric stimulation of the median nerve at the wrist during voluntary contraction of the thenar muscles (Upton et al., 1971; Conrad et al., 1977; Deuschl et al., 1989; Burke et al., 1999). As shown in Figs. 8 and 10 (10.4 ms, 3.1, 5.9 ms), it was confirmed that single MUAP LLRs with prolonged latencies were included in F-wave data. In the present study, the record length was set to 50 ms. By using a longer record length, single MUAP LLRs with longer latencies may be detected further.

In the MUNE by the F-wave method, the same MUs with prolonged latencies should be excluded from the calculation of the mean MUAP. In particular, the MUs with long latencies, which were due to supraspinal or transcortical pathways, should not be included in the MUNE process, because they will affect the MUNE values more sensibly than in the case of small latency differences.

5. Conclusions

The extracted number of single MU F-waves could be increased by increasing the number of processing data measured under different stimulus conditions, then the properties of many MUs could be analyzed easily, and we could find the single MU responses with the same waveform but different latencies. The similarity analysis was useful to search the same waveform pair from many pairs of single MU responses. It is suggested that the prolonged latencies occurred due to spinal interneuronal pathways, in the case of large differences in latencies, supraspinal pathways, or transcortical pathways.

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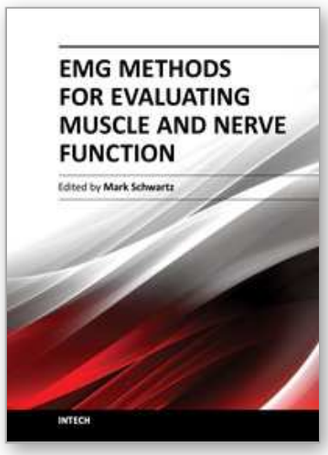

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