—Report on Experiments and Clinical Cases—

A New Mathematical Approach for Approximating the Baseline of F-waves Using Spreadsheet Software

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Abstract

Objective: The aim of this study was to see if curved baselines of F-waves could be mathematically approximated with universal spreadsheet software.

Methods: The subjects were 3 healthy persons and 3 patients with cervical myelopathy. Supramaximal electrical stimuli were applied 200 times to the median nerve at the wrist. Compound muscle action potentials (CMAPs) of the abductor pollicis brevis were recorded. To make polynomial approximation equations that represent latter part of the M-waves, records without F-waves were analyzed.

Results: There were 193 CMAPs without F-waves out of all 1,200 records. Polynomial equations were made for each record. Determinant coefficients for all the approximation equations were greater than 0.998, and the overall standard deviation of the difference between original data and approximated value was 3.05 μV.

Conclusions: Curved baselines of F-waves were represented by approximation curves. Baselines of the F-waves could be approximated as flat lines by subtracting calculated values from the original data.

Significance: This method was useful for analyzing waveforms of F-waves.

(J Nippon Med Sch 2008; 75: 274–279)

Key words: evoked potentials, regression analysis, mathematical computing

Introduction

While we estimate the motor unit number of peripheral muscle by means of F-wave analysis, it is necessary to compare the waveforms and latencies of F-waves to find so-called repeater F-waves. Because the amplitudes of F-waves are extremely small, they cannot be easily distinguished by shape when they appear on the latter curved part of M-waves. Komori et al[1] have performed subtraction among the compound muscle action potentials (CMAPs) with and without F-waves to make the baselines of the F-waves flat for comparison of the shape of the waveforms. However, such comparison is not accurate when the slopes of the M-waves differ even if supramaximal stimulation is applied to a peripheral nerve. If the baselines of F-waves could be approximated individually with a mathematical method, comparison of the waveforms of F-waves could be more accurate. Stashuk et al[2] have described a method to make the baselines of F-

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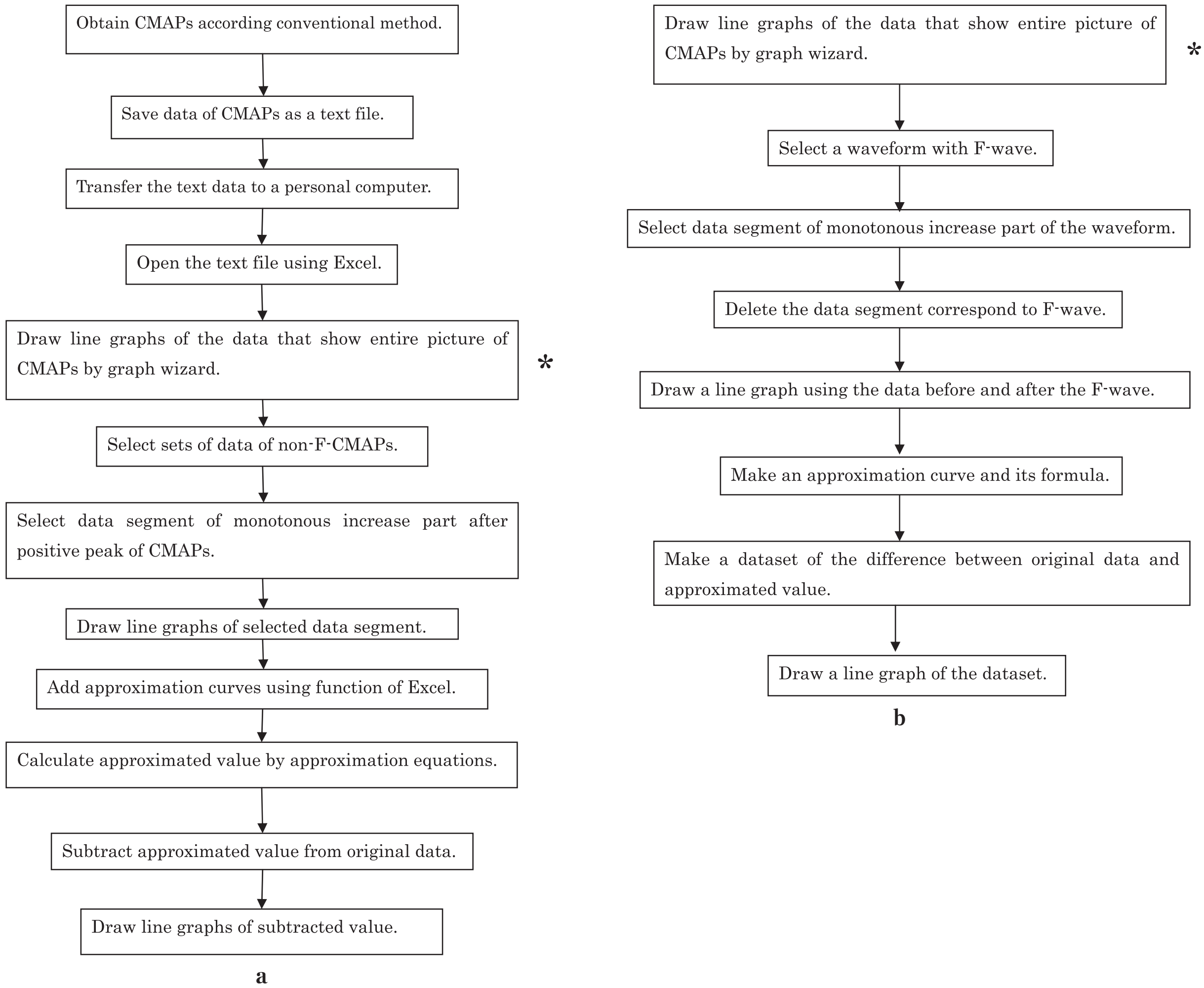


Fig. 1 (a) The method used in this study to normalize the baseline of F-waves. When this method is applied to waveforms with F-waves, the steps should be modified after the step marked by an asterisk. The latter part of the method is shown in Figure 1 (b).

waves flat by using mathematical approximation, but their method requires special software for computer analysis. The objective of this study was to examine whether a polynomial equation can accurately approximate the latter part of M-waves by means of spreadsheet software.

Materials and Methods

The subjects of this study were 3 healthy persons and 3 patients with cervical myelopathy. The subjects were given explanations before the test, and all subjects gave consent for the examination. Supramaximal electrical stimuli were applied 200 times to the median nerve at the wrist. The frequency of stimulation was set to 1 Hz. The CMAPs of the abductor pollicis brevis were recorded with surface electrodes (NE-132B, Nihon-Kohden, Tokyo) according to the Berry tendon method. Examinations were performed with an evoked potential / electromyography measuring system (MEB-2200, Nihon-Kohden). A high-cut filter was set at 2 kHz, and low-cut filter was set at 20 Hz. The analysis time for each record was set at 200 milliseconds. After 200 consecutive waveforms were collected, the data of the records were saved as a text file in the electromyogram. When the data of a waveform is saved as a text file, the record of 1 CMAP consists of 2,048 numerical values. Sets of numerical values that represent CMAPs were transferred to a personal computer. The text files were opened with spreadsheet software (Excel, Microsoft Corp., Redmond, WA), and further analysis was performed. To make an approximation curve that represented the latter part of the M-waves, the CMAPs in which F-waves were not evoked were

Table 1 Overall results of the approximation

	No. of non-F CMAPs	Determinant coefficient	Average of difference (μV)	SD of difference (μV)
Subject 1 (HV)	71	0.999<	0.45	2.67
Subject 2 (HV)	27	0.998<	0.14	3.15
Subject 3 (HV)	48	0.998<	0.10	3.17
Subject 4 (CM)	31	0.998<	0.03	3.08
Subject 5 (CM)	13	0.998<	0.56	4.21
Subject 6 (CM)	3	0.998<	0.27	2.84
Overall	193	0.998<	0.27	3.05

HV: healthy volunteer, CM: cervical myelopathy

included in the study. Generally, a waveform of a CMAP can be considered to be composed of negative and positive peaks and a slope that represent a monotonous increase curve after a positive peak. As the F-waves are recorded on the slope of the monotonously increasing part of the M-waves in the upper extremities, the values corresponding to such parts were selected and line graphs were drawn with the graphing wizard of Excel. Cubic approximation curves were made for each set of data, and polynomial equations of the curves and determinant coefficients for approximation were calculated with Excel. After the approximation equations were obtained, differences between original data and approximated values were calculated for all plotted data. The steps of analysis are summarized in **Figure 1 (a)**.

Results

Of the 1,200 CMAPs recorded in the 6 subjects, F-waves were not evoked in 193. Polynomial equations were made individually for these 193 records. Determinant coefficients of all the equations were greater than 0.998. Averages of the difference between original data and approximated values were less than 0.56 μV, and the standard deviations of calculated differences were distributed between 2.67 and 4.21 μV (**Table 1**).

An example of approximation: Subject 1 was a 27-year-old healthy female volunteer. There were 71 records of nonevoked F-waves among 200 consecutive records of the CMAPs. A waveform of a CMAP in which no F-wave was evoked is shown in **Figure 2**. This is the first record of a CMAP out of

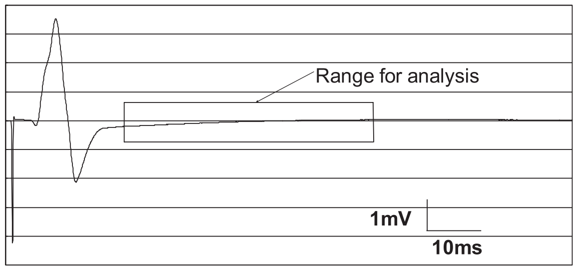
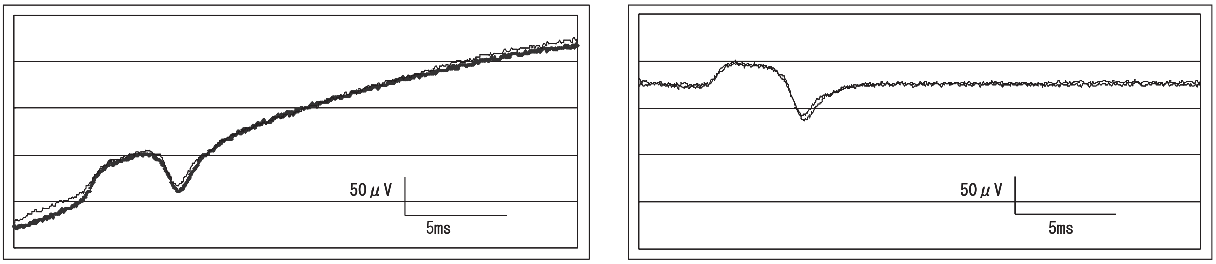


Fig. 2 An entire picture of a CMAP recorded from the abductor pollicis brevis. The F-wave is not evoked in this waveform. The range surrounded by a rectangle was analyzed in this study.

the 200 consecutive records. When an F-wave was evoked, it was recorded on the monotonously increasing part of the curve after the positive peak because the latencies of F-waves are approximately 25 milliseconds in the abductor pollicis brevis muscle. Then, F-waves usually appeared in a range surrounded by a rectangle in the figure. An approximation was performed for the range. Coefficients of approximation equations, determinant coefficients, the average difference between the original data and the approximated value for each waveform, and the standard deviations of such differences of all non-F-CMAPs are shown in **Table 2**. Each equation has slightly different coefficients. The overall standard deviation of the differences was 2.67 μV. The approximation equation agrees well with the original data, as shown by high determinant coefficients and the small difference between the original data and approximated values. When this method is applied to the CMAPs with F-waves, approximation curves could be made according the method described by Stashuk et al[2]. **Figure 1 (b)** shows the method for normalizing the

Table 2 Results of approximation of subject 1

Wave No.	Constant term	Primary coefficient	Secondary coefficient	Third coefficient	Coefficient of determination	Average of difference (μV)	SD of difference (μV)
1	−1,276.8	3.4546	−0.0023	0.00000033	0.999	1.14	2.08
14	−1,323.7	3.0443	−0.0009	−0.0000005	0.999	1.44	2.63
18	−1,305.4	2.696	−0.0001	−0.0000009	0.999	−1.43	2.58
30	−1,257.9	3.2691	−0.0014	−0.0000003	0.999	−0.90	2.56
35	−1,263	2.9477	−0.0004	−0.0000008	1	−2.54	3.01
36	−1,314.3	3.172	−0.0009	−0.0000006	0.999	3.06	3.59
43	−1,350.4	2.8009	−0.0002	−0.0000008	0.999	−1.69	2.42
44	−1,336.5	2.6618	−0.0001	−0.0000008	0.999	−0.85	2.04
46	−1,292.3	2.9018	−0.0006	−0.0000006	0.999	0.31	2.50
50	−1,346.7	2.7929	−0.0003	−0.0000007	0.999	−1.60	2.68
52	−1,311.6	2.5933	0.0003	−0.000001	0.999	−5.01	6.03
58	−1,299.1	2.4283	0.0004	−0.000001	1	−2.74	4.07
59	−1,342.1	2.6012	0.0002	−0.000001	0.999	−2.96	3.43
64	−1,321.6	2.7201	−0.0004	−0.0000006	1	1.03	1.77
69	−1,298.9	2.6172	−0.0001	−0.0000008	1	−0.34	1.72
70	−1,286.6	2.5979	−0.0001	−0.0000008	1	0.27	1.65
74	−1,325.6	2.6213	−0.00007	−0.0000008	1	−0.69	1.79
80	−1,251.5	2.4662	−0.00002	−0.0000008	0.999	−0.04	1.75
81	−1,240.5	2.4421	0.0002	−0.000001	1	−0.04	1.59
82	−1,290.9	2.5148	−0.000007	−0.0000008	1	−0.38	1.65
83	−1,247.2	2.562	−0.0001	−0.0000008	1	1.73	2.47
85	−1,261.5	2.3997	0.0003	−0.000001	1	−1.29	1.87
87	−1,242.5	2.3999	0.0002	−0.0000009	1	−0.84	1.62
88	−1,256	2.4113	0.0003	−0.000001	1	−1.15	2.16
89	−1,250.8	2.53	−0.0001	−0.0000008		1.20	2.19
94	−1,261.9	2.4436	0.00003	−0.0000008	1	−0.47	1.53
106	−1,235.2	2.4303	0.0001	−0.0000008	1	−0.62	1.58
109	−1,229.7	2.4985	0.0000074	−0.0000008	1	0.47	1.55
113	−1,228.5	2.4721	0.0002	−0.0000009	1	−1.86	2.40
115	−1,202.9	2.3416	0.0004	−0.000001	1	−1.81	2.23
116	−1,214.3	2.3114	0.0004	−0.000001	1	−0.94	1.99
117	−1,211.6	2.3612	0.0002	−0.0000009	1	2.38	2.50
118	−1,214.4	2.3835	0.0003	−0.0000009	1	−2.64	3.03
119	−1,212.3	2.2782	0.0005	−0.000001	1	−3.12	3.84
121	−1,194.8	2.4127	0.0002	−0.0000009	1	0.17	1.52
125	−1,193.3	2.5209	−0.0001	−0.0000007	1	−1.25	1.93
128	−1,183.3	2.5331	−0.0001	−0.0000007	1	−1.47	2.00
129	−1,201.3	2.4944	−0.00002	−0.0000008	1	1.38	2.05
131	−1,199.1	2.4916	−0.0001	−0.0000007	1	−0.64	1.68
132	−1,208.8	2.5845	−0.0003	−0.0000006	1	−0.43	1.38
135	−1,183.5	2.4291	0.00003	−0.0000008	1	−0.34	1.68
137	−1,198.5	2.5101	−0.0001	−0.0000007	1	−1.67	2.02
138	−1,199.3	2.5663	−0.0003	−0.0000006	1	0.66	1.52
141	−1,218.4	2.4603	−0.000005	−0.0000008	1	−0.09	1.38
142	−1,190.1	2.4807	−0.0001	−0.0000007	1	−1.73	2.09
144	−1,249	2.6161	−0.0004	−0.0000005	1	−0.01	1.50
145	−1,196.8	2.468	−0.00008	−0.0000007	1	−1.35	2.14
147	−1,214.7	2.5626	−0.0004	−0.0000005	1	−0.28	1.44
148	−1,184.2	2.407	−0.0001	−0.0000007	1	0.33	1.44
149	−1,190.7	2.5056	−0.0003	−0.0000006	1	−0.08	1.40
150	−1,194.9	2.429	−0.0001	−0.0000007	1	−0.17	1.45
153	−1,209.4	2.4975	−0.0004	−0.0000005	1	1.24	1.73
155	−1,196.3	2.5378	−0.0004	−0.0000005	1	−0.52	1.54
157	−1,193.5	2.375	−0.00008	−0.0000007	1	0.36	1.31
160	−1,193.1	2.4249	−0.0003	−0.0000006	1	2.65	2.92
161	−1,191.1	2.4717	−0.0003	−0.0000006	1	1.52	2.22
166	−1,202.4	2.5021	−0.0004	−0.0000005	1	−0.24	1.36
168	−1,198	2.5771	−0.0004	−0.0000005	1	−2.06	2.35
171	−1,200.3	2.6184	−0.0004	−0.0000005	1	−2.30	2.84
172	−1,171.4	2.5664	−0.0003	−0.0000006	1	−1.91	2.26
174	−1,193.5	2.6224	−0.0006	−0.0000004	1	0.74	1.43
175	−1,158.7	2.4249	−0.0001	−0.0000007	1	−0.73	1.48
178	−1,202.1	2.5587	−0.0004	−0.0000005	1	−1.07	1.93
179	−1,178.8	2.5679	−0.0005	−0.0000005	1	1.35	1.85
182	−1,183	2.5861	−0.0006	−0.0000004	1	1.21	1.82
184	−1,199.2	2.6715	−0.0005	−0.0000005	1	−0.39	1.54
186	−1,185.7	2.8498	−0.0007	−0.0000004	1	−2.53	2.89
190	−1,197.7	2.6507	−0.0003	−0.0000007	1	0.34	1.69
195	−1,205.9	2.6054	−0.00009	−0.0000008	1	−0.58	1.67
197	−1,204.9	2.6508	−0.0003	−0.0000007	1	1.10	1.98



a b

Fig. 3 Example of baseline normalization of F-waves.

a: An original plot of two F-waves with curved baselines derived from subject 1. The thick line is the plot of wave no. 20, and the thin line shows wave no. 189. Both waveforms have similar shapes, but the baselines of the waves are slightly different. There seems to be a small difference in the onset of the waveforms.

b: After the normalization of the baseline. Wave numbers are the same as above. Because the difference in the baselines have been decreased, the two waveforms fit each other. The approximation equations used in these waveforms are shown below.

Wave no. 20: $y=-3.3\times10^{-7}x^3-1.1\times10^{-3}x^2+3.1x-1267$ Wave no. 189: $y=-7.4\times10^{-7}x^3-1.1\times10^{-4}x^2+2.5x-1173$

baseline of the waveform in which F-wave is recorded. An example of the application of this method to waveforms with F-waves is shown in **Figure 3**.

Discussion

Motor unit number estimations are neurophysiological examinations that analyze the peripheral muscle action potentials evoked by electrical stimulation applied to a peripheral nerve. Several methods have been described, such as F-wave analysis[2], incremental stimulation method[3], statistical analysis[4], and the multiple point stimulation method[5]. The normal values of estimation are said[6] to be the same order of magnitude even if the methods of estimation are different, and such results are equal to anatomical examinations of motor units[7,8]. When we perform motor unit number estimation by means of F-wave analysis, it is necessary to compare the shape of F-waves exactly to find F-waves with the same waveforms and latencies. Hara et al[9] have tried to find the same F-waves by visually comparing the waveforms on screens and print-outs. However, it is difficult to compare the shape of the waves when the baselines of the waves differ among the waves. Komori et al[1] have tried to make the baselines of the F-waves flat by subtracting CMAPs without F-waves from CMAPs with F-waves. Because the excitability of anterior horn cells are altered in pathological conditions, Aoki et al[10] have examined patients with cervical myelopathy and have found that the persistence of F-waves is 100% in most cases. The method of subtraction described by Komori[1] is difficult to perform in such cases. On the other hand, we often find that the shapes of CMAPs are slightly different even if supramaximal stimulation is applied to a peripheral nerve. Comparison of the waveforms of the F-waves is difficult when the F-waves with a small amplitude appear on the curve after the positive peak. Stashuk et al[2] have described a mathematical method to approximate the baselines of F-waves to develop a method for automated analysis of F-waves. Because they did not describe details of the approximation, it is not known how accurately the mathematical approximation could represent the curved baselines of F-waves. Furthermore, their method requires special electromyographic equipment and software. Generally, baselines of F-waves are most severely curved when the amplitude of M-waves are maximal. Several investigators[1,11] of single motor unit F-waves have used stimulus intensities that evoke M-waves of maximum amplitude. Therefore, supramaximal stimulus intensity was chosen in the present study to examine the effects of approximation. In the present study, we noticed that the curve after the positive peak of CMAPs showed a relatively monotonous increase in almost all cases. We tried to create cubic polynomial equations to represent approximation curves for the latter part of

CMAPs using commercial spreadsheet software. A total of 193 polynomial equations were made for the monotonously increasing part of CMAPs, and the results of approximation expressed as determinant coefficients were all greater than 0.998. It is said that if the regression fits perfectly to the original data, the determinant coefficient would equal 1[12]. The approximation curves fit very well to the original curves when the curves were plotted. Therefore, it is thought these approximation curves reproduce original values well. The monotonously increasing part of the curve after the positive peak of a CMAP was found to be well expressed by polynomial equations.

When the noise of the F-waves is not small, it is not easy to analyze F-waves with small amplitudes. Several investigators[13,14] of F-waves have limited their studies to F-waves of more than 40 μV to avoid the effects of noise. In the present study, the overall standard deviation of the values determined by subtracting the original data from the approximated value was 3.05 μV. This result means that when the values obtained by subtraction were plotted, the standard deviation of the deflection of baselines was about 3 μV. When we plotted a set of values obtained by subtraction, it was nearly a flat line. Furthermore, when the baseline of the F-waves is changed to a flat line, the recognition of the waveforms of small-amplitude F-waves becomes more precise. An examiner will thus be able to better judge whether the waveforms are identical. When an investigator analyzes the waveforms by this method, it is not necessary to use any specific device or software except for commercially available spreadsheet software. This method is easy to perform for many investigators and is useful for comparing the waveforms of F-waves evoked in peripheral muscles of the upper extremities.

Conclusions

We examined a mathematical method to normalize the baselines of F-waves using spreadsheet software. Determinant coefficients for all approximation equation of the baselines of the F-waves were greater than 0.998, and the overall standard deviation of the difference between original data and approximated values was 3.05 μV. The baseline of an F-wave is normalized by a polynomial equation of 3 degrees. This method is useful for comparing the waveforms and latencies of F-waves.

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(Received, December 6, 2007)
(Accepted, July 23, 2008)