THE NEW ARMENIAN
MEDICAL JOURNAL
Vol. 3 (2009), N 1, 44 - 58
www.ysmu.am

PECULIARITIES OF CENTRAL AND PERIPHERAL CONTROL OF THE SPINAL CORD FLEXOR AND EXTENSOR MOTOR NEURONS ACTIVITY

A.L. Minasyan[1], A.V. Aznauryan[1], V.A. Chavushyan[2], J.S. Sarkissian[2]

[1] Department of Morphology, Yerevan State Medical University, Yerevan, Armenia
[2]L. Orbeli Institute of Physiology, National Academy of Sciences of Armenia, Yerevan, Armenia

Abstract

Mechanisms of development of the hind limb nerve crush are intensively studied. However, the peculiarity of their restoraton has not been revealed *en masse* yet. As the appropriate experimental data are lacking, the comparative analysis of degree and velocity of flexor and extensor nerves regeneration and their selective central and peripheral control is of interest. For this purpose criteria of differentiation of spinal cord (SC) extensor and flexor motor neurons (MN) were studied by means of stimulation of corresponding nerves and brain special centers of their regulation. For differentiation of the latter, joint stimulation of central and peripheral structures, which control the flexor and extensor muscles activity (pyramidal tract, nucleus ruber-RMC – suprasegmental flexor center, nucleus Deiters' – supraspinal extensor center, flexor *n. gastrocnemius* and extensor *n. peroneus communis*), in different correlations were tested. The high frequency stimulation was used to cause tetanic (TP, TD) and posttetanic (PTP, PTD) potentiation and depression manifestations of different intensity and duration. In ideal cases the adequate activation of structures took place providing the excitation of some MN with reciprocal inhibition of antagonists. More frequently the clear-cut differentiation succeeded owing to reciprocal involvement of central and peripheral structures separately. The cases of uni- and differently directed effects of central and peripheral structures were often revealed. However, cases of unidirectional action of both central and peripheral structures, providing the synergism instead the antagonism remain to be "casual". It is proposed to use for MNs differentiation only cases of reciprocal correlation of antagonists and synergists, engaged in realization of unidirectional motor act (flexor or extensor), with corresponding inhibition of the antagonistic one. It appears optimal for MNs differentiation to use stimulation of structures mainly of central origin, in particular of the RMC and nucleus Deiters' with their reciprocal activation.

Keywords: single neuronal activity; spinal cord; tetanic stimulation; pyramidal tract, nucleus ruber; lateral vestibular nucleus; hind limb flexor and extensor nerves.

Introduction

The attempt was made to establish the reliable discrimination of corresponding motor neurons (MNs) of lumbar division of spinal cord (SC) for subsequent comparative study on degree and velocity of hind limb flexor and extensor nerves recovery after their compression (crush). Recording their activity to stimulation of pyramidal tract (Py), magnocellular part of ruber nucleus (RMC) and lateral vestibular nucleus (LVN) as substrates of super-segmented control on reciprocal activity of MNs flexor (*n. gastrocnemius*) and extensor (*n. peroneus communis*) collateral branches of hind limb sciatic nerve was realized.

Corticospinal (CST) or pyramidal (Py) tract present the most direct pathways of movements

*Address for Correspondence:
L. Orbeli Institute of Physiology, NAS (Armenia)
22 Orbeli Brothers Street , Yerevan 0028, Republic of Armenia.
E-mail: jsarkissyan@neuroscience.am

control, which in rodents and marsupials terminate predominantly on interneurons (INs) in dorsal horn of SC. In carnivorous and primates the number of CS axons grows and their endings shift progressively toward the INs of the intermediate zone and ventral horn ultimately forming great number of synaptic terminations directly on the MNs. Hence, the deficits resulting from CS lesions caused by insults, tumor, multiple sclerosis, trauma or amyotrophic lateral sclerosis are more expressed in humans than in animals, moreover that animals make greater use of additional descending pathways to control movement [*Schieber M., 2007]*. The examined pattern of termination of efferents from the primary motor cortex (M1) to cervical segments of the SC in monkeys (*Cebus apella* and *Saimiri sciureus*) revealed that CS terminations in cervical segments of cebus monkeys are located in a dorsolateral and dorsomedial regions of the intermediate zone and in ventral horn of SC. In turn, the CS terminations in the squirrel monkeys are located mainly within two first regions. These observations provide further support for the concept that the monosynaptic projections from the M1 to MNs in the ventral horn provide part of the neural substrate for dexterous movements of the fingers [*Bortoff G., Strick P., 1993*]. Cortico–MN fibers produce monosynaptic excitation of spinal MNs, which is more powerful for those acting distally, innervating extensor muscles of fingers and intrinsic hand muscles. Disynaptic inhibitory actions are produced by CS volleys via the common Ia inhibitory IN–possibly reciprocal actions produced over collaterals of cortico-MN fibers [*Porter R., 1987*]. The CS synaptic contacts were morphologically found mainly on small, medium and large proximal dendrites, as well as on cell bodies of MNs in dorsal and ventral horns of SC [*Ralston D., Ralston H., 1985*]. Moreover, the important evidence of direct cortico-MN connections for voluntary control of the hand (from CS neurons in M1 hand area) is presented below. Intracellular investigations show that 75% of upper limbs MNs in macaque monkey receive a monosynaptic projection from cortico–MN cells; each contributes a particular pattern of discharge during a skilled task. In addition to direct effects on targets muscles there might be potentially important effects derived from the synchronous binding of assemblies of output neurons. Therewith during grasp between these neurons the synchronous oscillations prevail, but disappear during finger movement [*Lemon R. et al., 1998*]. Finally, cortico-rubro-MN projections are principally involved in control of hand and foot movements with insignificant effect on more proximal musculature. Moreover, the mentioned massive projection is the part of a large cerebro-cerebellar communication system with motor and/or movement programming functions [*Humphrey D. et al., 1984*]. Of interest is data obtained in mammals that are at lower phyletic stage. Rats are lacking ultrastructural features of direct cortico–MN synaptic connections (within lamina IX by Rexed) between CS axon boutons and the proximal dendrites of forelimb MNs [*Yang H., Lemon R., 2003*]. The modulatory role of ventral uncrossed component of rats CST projection down to low spinal levels was found with large extension of the terminal arborizations in intermediate laminae of the SC [*Brösamle C., Schwab M., 1997*]. Finally, along with monosynaptic rubro-MN connections in a substantial portion of forelimb MNs (C8-T1 segments) in cats, there was no evidence suggesting immediate connections between cerebral cortex and forelimb MNs [*Fujito Y. et al., 1991*].

As known, the RMC stimulation evokes the limbs flexure [*Eccles J. et al., 1975a; b; Ghez C., 1975*], mediated mainly by spinal INs [*Jankowska E., 1988*]. RMC exerts the most expressed action to INs exciting the flexor and inhibiting extensors [*Burke R. et al., 1970; Hongo T. et al., 1972*] by means of different systems of fibers, including the peripheral afferents [*Lundberg A., 1979*]. Finally, RMC participates in formation of central organization of movement by selective action on different components of executed movement circuit [*Fanardjian V., Sarkissian J., 1992*]. It is of interest that fields of SM cortex, acting as a source of CS system also originate the cortico-

rubro-spinal projection [*Rinvik E., Walberg E., 1963; Kuypers H., Lawrence D., 1967; Martin G., 1968*]. Along with the different role in movement initiation [*Martin J., Ghez C., 1988*], the interaction of indicated systems in rats is hindered by their divergence [*Brown L., 1974*].

In its turn, vestibule-spinal projection mainly originating from ipsilateral LVN of Deiters' [*Brodal A. et al., 1966; Mugnaini E. et al., 1967*] also essentially participates in polysynaptic activation of hind limb MNs, realizing the vestibular control of muscle tonus and posture by excitation of ipsilateral extensor MNs of limbs and body and inhibition of reciprocal flexor MNs [*Markham C., 1987*].

Materials and Method

In acute electrophysiological experiment in male albino rats (n=12, 250±30 *g*) after fixation of the skull in stereotaxic apparatus under Nembutal anesthesia (40 *mg/kg* i/p) the craniotomy, dorsal laminectomy of lumbo-sacral part of SM and separation of *dura mater* were carried out. Further, the animals were immobilized by 1% Dithylinum (25 *mg/kg* i/p) and transferred to artificial breathing. Glass microelectrodes (tip Ø=1-2 *μM*) filled with 2 M saline solution were inserted in anterior horn of gray matter of lumbar segments (L4-L5) of SC in region of MNs (VIII-IX laminae by Rexed) for extracellular recording of spike activity. High frequency stimulation (HFS) (50 *Hz* during 1 *s*) of extensor (*n. Peroneus communis* – P) and flexor (*n. Gastrocnemius* – G) nerves of hind limb was performed by bipolar silver electrodes (by rectangle pulses 0.05 *ms*, 0.10-0.16 *mA,* corresponding to 2 thresholds). By stereotaxically oriented cylindric bipolar electrodes, in coordinates of atlas [*Paxinos G., Watson C., 2005*] the stimulation (current parameters: 0.05 *ms*, 0.08 *mA,* frequency 50 *Hz* for 1 *s*) of Py (AP-10, L±0.7, DV+11 *mm*), LVN (AP-11, L±2.2, DV+7.0 *mm*) and RMC (AP-6, L±0.8, DV+7.7 *mm*). Poststimulus activity was revealed expressed as tetanic potentiation (TP) and depression (TD) with subsequent posttetanic manifestations in the form of posttetanic potentiation (PTP) and depression (PTD) of different expression, duration and latency. Owing to programmed analysis the possibility was created to extract artifacts during HFS thus allowing to mainly consider tetanic effects as strongly constant activation parameters in contrast to less stable PTP and PTD effects (even in norm). The recording was carried out with special software (developer: V.S. Kamenetski) supporting the "on-line" selection of spikes by means of amplitude discrimination. The impulse flow after selection was processed using programmed mathematical analysis with the subsequent obtaining for single neurons rasters of pre- and poststimule spikes flow distributed in real time, diagrams of summarized averaged frequency of spikes, presented in raster and constructed on their bases detailed analysis of selected trials with recording in separate neuron of spike timing, construction of summarized PETH (peri-event time histogram), cumulative histogram and histogram of frequency. For experimenter-selected compared groups of spikings neuronal activity averaged PETH (PETH Average), cumulative (Cumulative Average) histograms and histogram of frequency (Frequency Average) were constructed. The statistical analysis of obtained data was performed according to the specially developed algorithm.

Results

By technique of extracellular recording of background and evoked spike activity of single MNs to HFS of Py, LVN, RMC and nerves (G, P) jointly or in pairs and due to programmed analysis of separate units pulse flow, as well as all data massif of studied MNs (n = 148) we revealed that formation of responses and stationarization of pulse flow in single neurons were manifested as TP and TD, PTP and PTD of different expression, duration and time of origin.

Figure 1 illustrates the peristimulus histograms of sum spikes (above) of unidirectional excitatory effects in single SC MNs (A-C) constructed on the bases of their spike activity raster, pre- and poststimule manifestations at HFS of nerves G (A), P (B) and Py (C) in real time (10 *s* before and after HFS). From below – the diagrams of summarized average frequency of spikes, represented in raster with indication of

middle numerical meaning in real time (10 *s* before and after stimulation and during 1 *s* of tetanic stimulation). Here and in the following Figures: on the left side n – number of tests; BE (before event) – the time interval prior to stimulation, PE (post event) – after stimulation, TT –tetanization time, ordinate – sum spike in temporal succession, mentioned on abscissa. D – here and in subsequent Figures: average complex PETH (Average PETH), cumulative histogram (Cumulative Average) and histogram of frequency (Frequency Average) of MNs acitivity spiking at HFS of G (Group A), P (Group B) and Py (Group C) for TP. Near each group the number of tests is indicated; in the first two histograms bin=400 *ms*. E–G – the detailed analysis of selected examples of tests (marked by asterisks on raster) in MNs, responded at HFS of G (E), P (F) and Py (G). Here and in remaining Figures: Spike timing is activity in real time, Cumulative histogram – with differential curve (Df), Frequency histogram.

Figure 2 demonstrates the unidirectional inhibitory effects in single SC MNs under HFS of the same structures by examples of analogous rasters of their spike activity flow and diagrams of summarized average frequency of spikes (A-C), average complex histograms (D) and detailed analysis at one neuron with stimulation of all the mentioned structures (E-G).

In Figure 3 by examples of tests with construction of analogous histograms in the same MNs the inhibitory effects to HFS of both nerves (extensor and flexor) (A, B) were shown, in reciprocal correlation of the excitatory one in Py (C). This is obvious both in rasters and histograms of summarized frequency (A-C, respectively) and in average complex histograms (D) and detailed analysis in MNs (marked by asterisk in raster) at HFS of studied structures (E-G), testifying to absence of selective relation of Py to effects of tested nerves.

In other words, activating control of Py does not provide for different relation to this or that modality of innervations of the corresponding muscles for ensuring antagonistic effect, which is essential for isolated extensor and flexor manifestations.

Figure 4 presents the excitatory and inhibitory effects of given MNs in reciprocal correlation by combination of HFS of flexor and extensor nerves in raster of sum spikes and histograms of summarized frequency (A, C and B, D, respectively), as well as in averaged complex histograms (F) with corresponding designations. Finally, in some MNs we revealed the ideal reciprocal correlation conditioned by the excitatory and inhibitory effects of G and P nerves correspondingly or inversel correlation, but under invariable excitatory effect of Py as shown in raster and histograms of summarized frequency (G, H), as well as in summarized complex histograms conjoined with corresponding poststimule manifestations of mentioned nerves G and P (G, H). To this signify corresponding examples of detailed analysis at the level of the individual neuron in the following Figures 5a and 5b.

However, more reliable and frequently revealed phenomena are effects presented in Figure 6a: those of clear reciprocal relationship of the studied nerves and nuclei RMC and LVN shown by the example of two flexor (A-G) and two extensor (H-N) MNs. The given Figure illustrates the complex average PETHs (A, H), cumulative histograms (B, I) and histograms of frequency (C, J) of corresponding single MN activity to HFS of RMC, G, LVN and P (A-D, respectively), with distinctive reciprocal manifestations of excitatory and inhibitory effects. The same was shown in rasters and histograms of sum spikes, as well as in diagrams of summarized average frequency by the example of flexor and extensor MNs (D-G and K-N, respectively). Figure 6b illustrates the detailed analysis of effects of the separate neurons (marked with asterisk in previous Figure). The clear excitatory (O, P, S, T) and inhibitory (Q, R, U, V) activation of flexor (O-R) and extensor (S-V) MNs was observed from structures selectively controlling the involvement of corresponding muscles accordingly along with inhibition of antagonists, for execution of the given motor act.

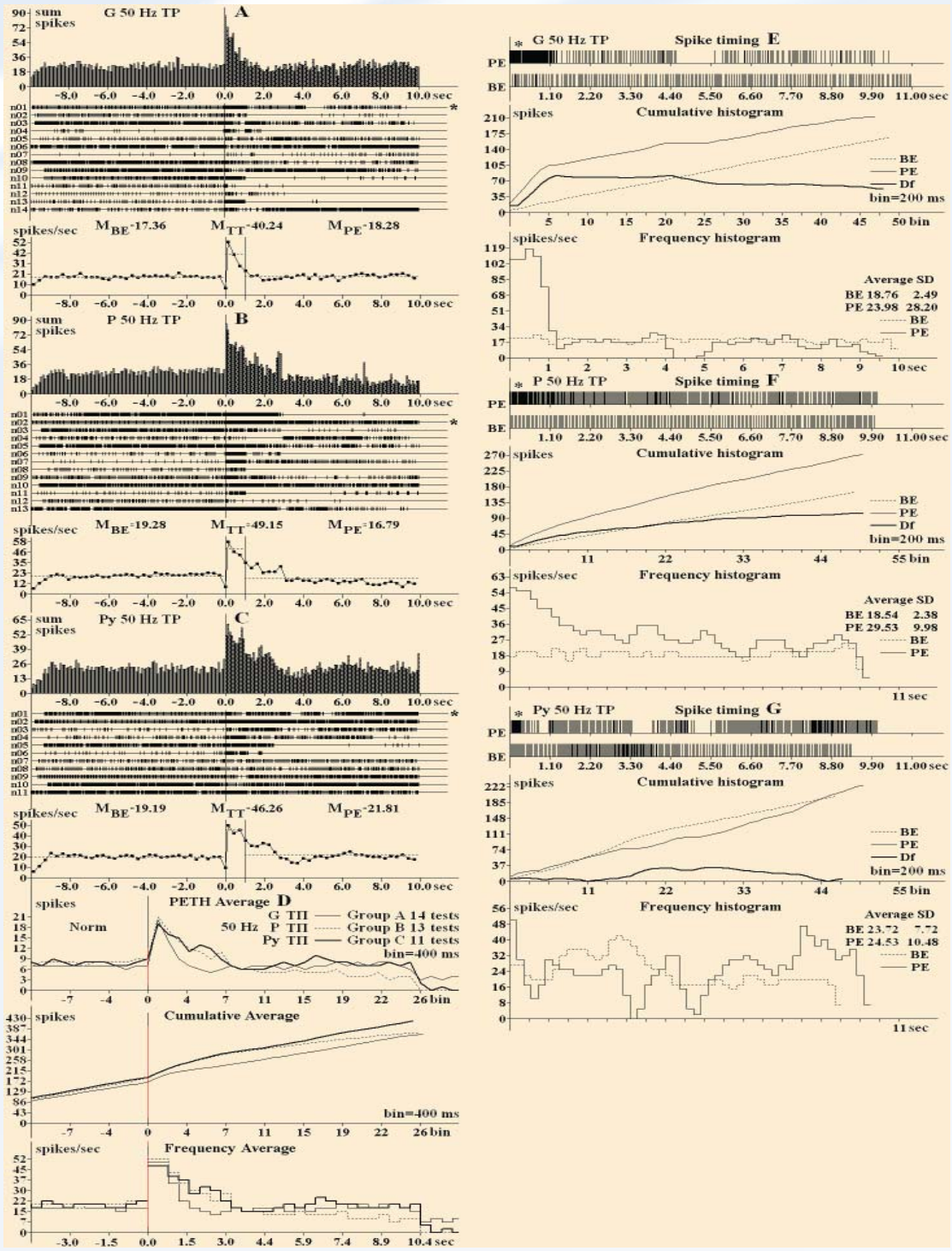

Figure 1. *A-C – the sum spikes peristimulus histogram (from above) constructed on the basis of raster of pre- and post-stimulus excitatory – TP (A-C) manifestations of spike activity of single MNs under HFS (50 Hz) of the flexor G (A), extensor P(B) nerves and pyramidal tract – Py (C) in real time; from below – diagrams of summarized frequency of spikes, represented in raster with indication of numerical meaning in real time. D – complex PETH Average, Cumulative Average and Frequency Average histograms of MNs acitivity spiking at HFS of G (Group A), P (Group B) and Py (Group C) for TP. E-G – detailed analysis of intentionally selected single neurons (marked with asterisks in rasters reacting at HFS G (E), P(F) and Py (G).*

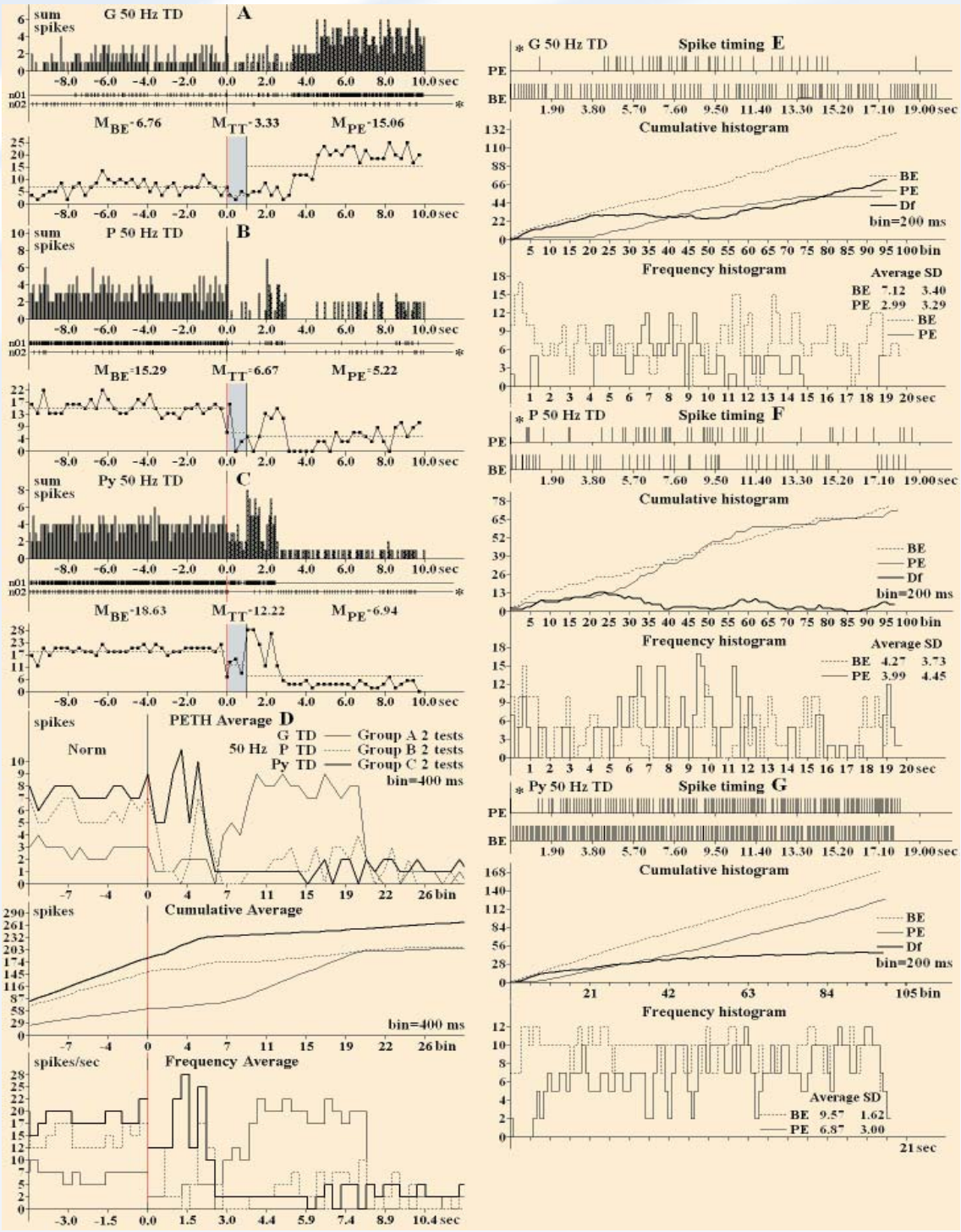

Figure 2. A-C – *peristimulus histograms of sum spikes (from above) constructed on the basis of raster of pre- and post-stimulus depressor – TP (A-C) manifestations of the single MNs spike activity at HFS (50 Hz) G (A), P (D) nerves and Py (B); from below – diagrams of spikes summarized frequency presented in raster of neurons, with indication of average numerical meaning. D – complex Average PETH, Average Cumulative and Frequency histograms of MNs spike activity at HFS G (Group A), P (Group B) and Py (Group C) for TD. E-G – detailed analysis of intentionally selected single neurons (marked with asterisk), reacting at HFS (50 Hz) G (E), P (F) and Py (G).*

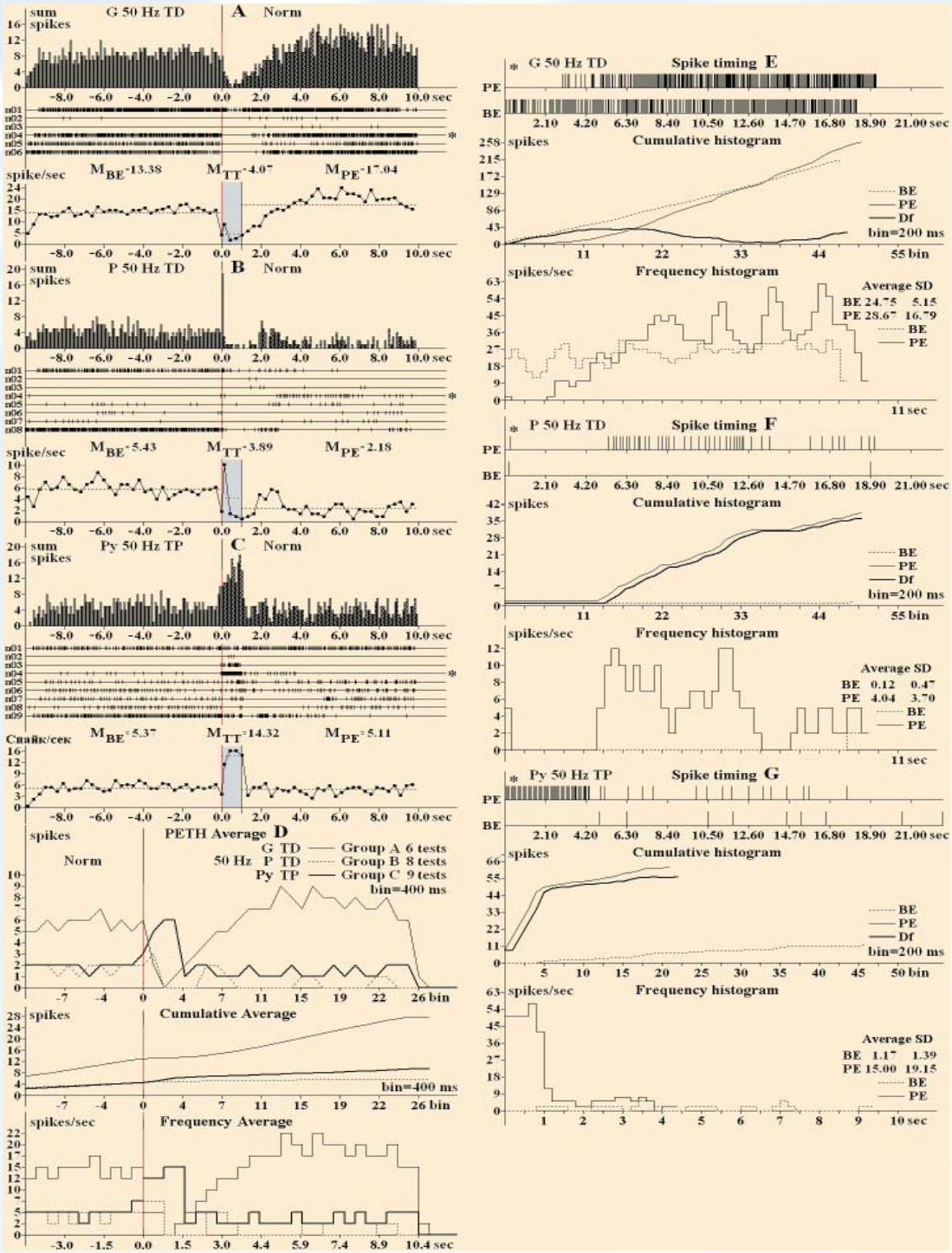

Figure 3. A-*C – peristimulus sum spikes histograms (from above) constructed on the basis of raster of pre- and poststimulus depressor – TD (A, B) and excitatory – TP (C) manifestations of single MNs spike activity under HFS (50 Hz) G (A), P (B) nerves and Py (C); from below – diagrams of spikes summarized frequency, presented in raster of neurons, with indication of average numerical meanings. D – complex PETH Average, Cumulative Average and Frequency Average histograms of İNs spike activity at HFS (50 Hz) G (Group A), P (Group B) for TD and Py (Group C) for TP. E-G – detailed analysis of intentionally selected single neurons (marked with asterisk), reacting at HFS (50 Hz) G (E), P (F) and Py (G).*

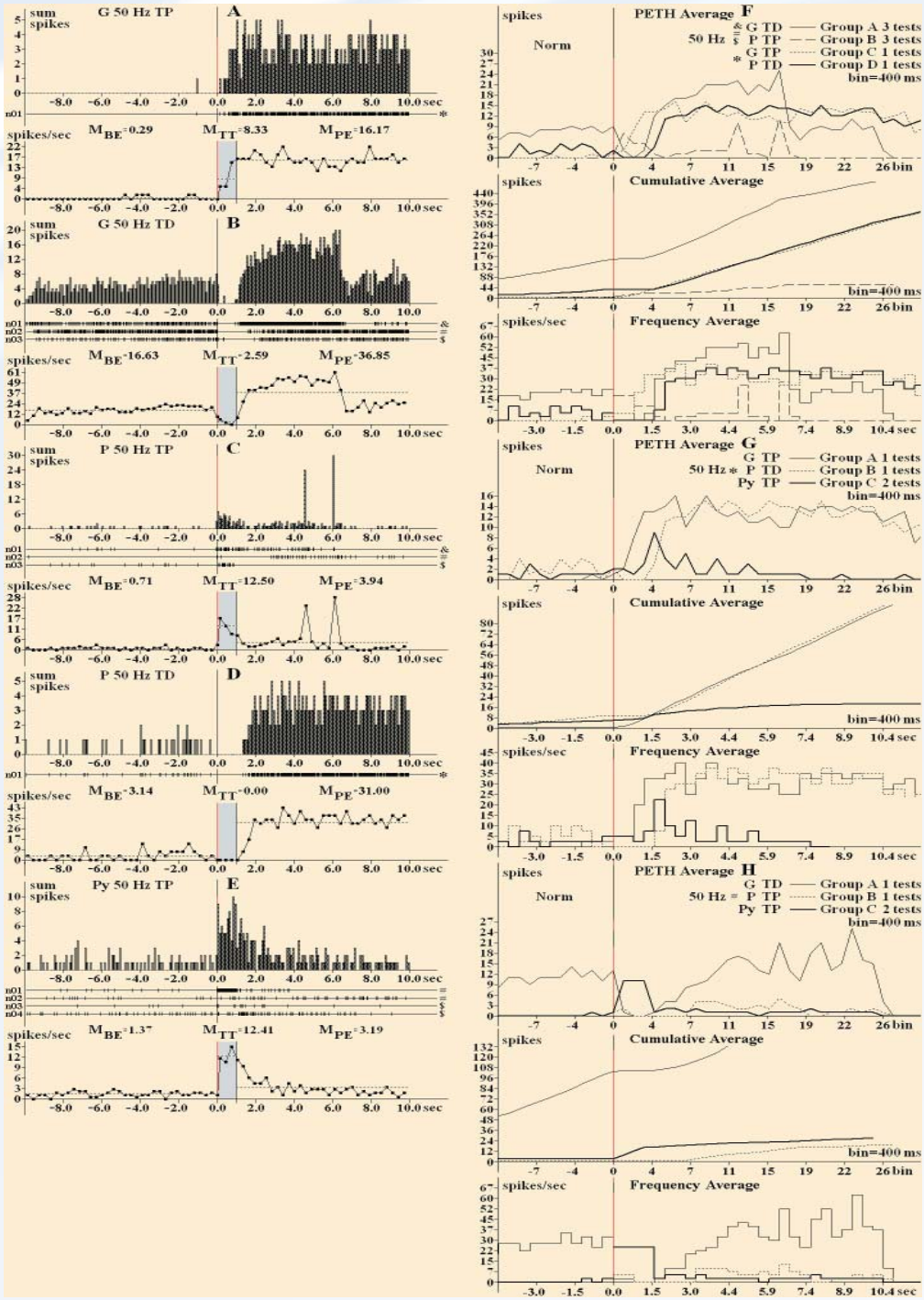

Figure 4. *A-C – peristimulus histograms of sum spikes (from above) constructed on the basis of raster of pre- and post-stimulus excitatory – TP (A, C, E) and depressor – TD (B, D) manifestations of single MNs spike activity under HFS (50 Hz) G (A, B), P (C, D) nerves and Py (E); from below – diagrams summarized spikes frequency presented in raster of neurons, with indication of average numerical meanings. F-H – complex PETH Average, Cumulative Average and Frequency Average histograms of MNs spike activity at HFS (50 Hz) G and P nerves (F) for TD (Group A and D) and TP (Group B and C), at HFS of G, P nerves and Py (G) for TP (Group A and C) and TD (Group B), at HFS of the same nerves in reverse correlation and Py (H) for TD (Group A) and TP (Group B and C).*

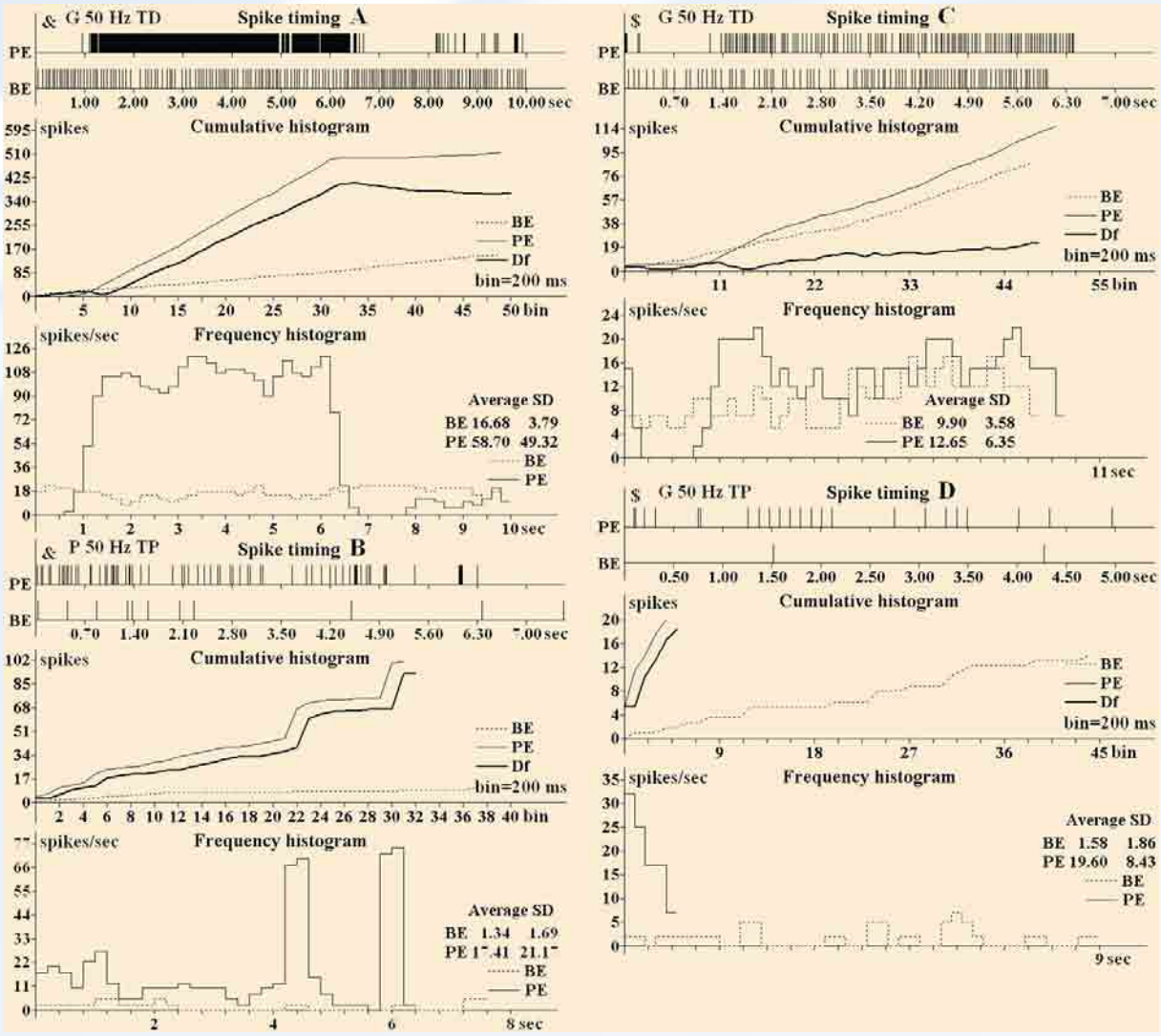

Figure 5a. *A-D – detailed analysis of intentionally selected single MNs (marked with asterisk in raster on preliminary Figure. 4), responsive at HFS (50 Hz) G (A, C), P (B, D) in reciprocal correlation for TP (B, D) and TD (A, C).*

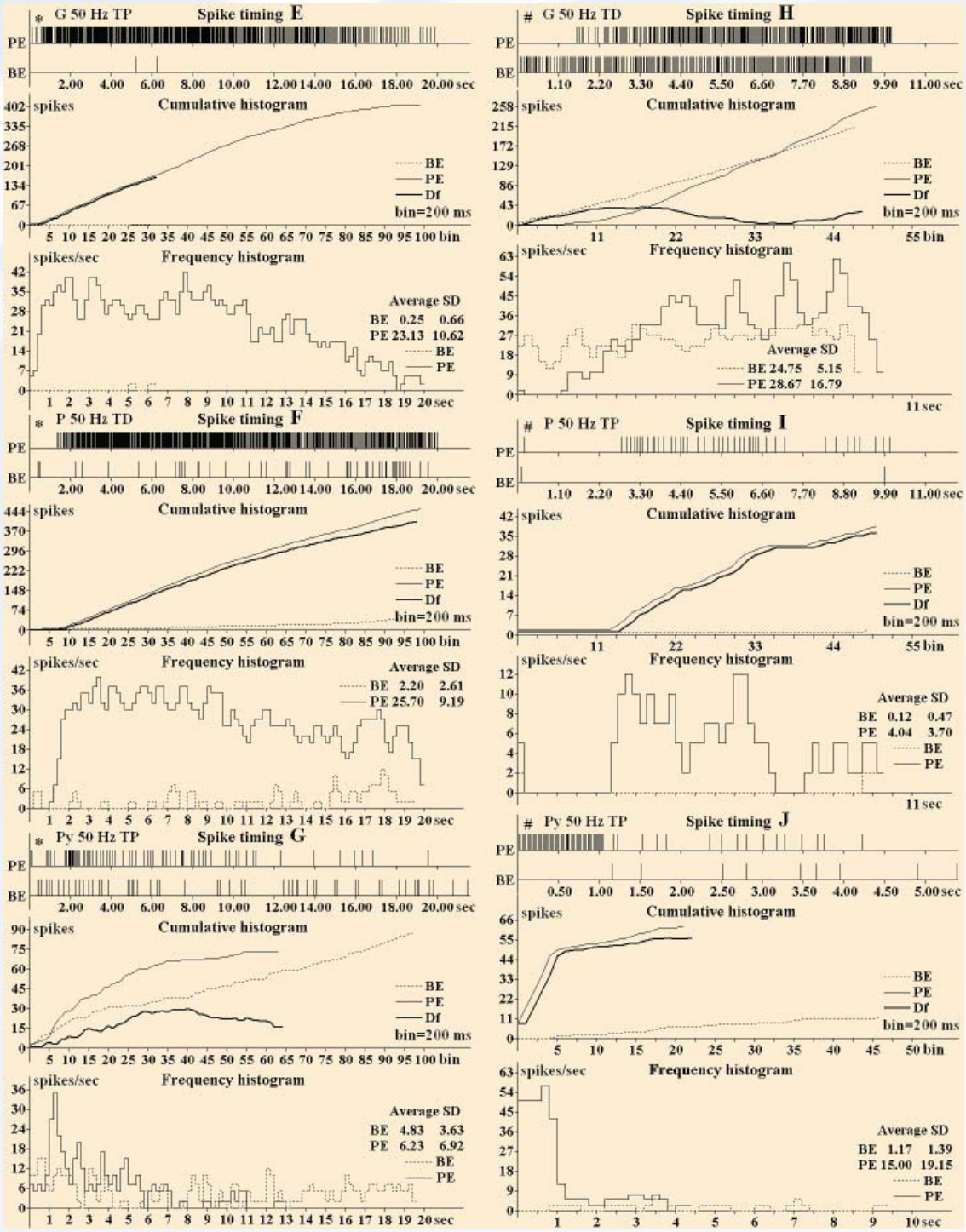

Figure 5b. *E-J – continuation of detailed analysis of intentionally selected single MNs (marked with asterisk in raster on preliminary Figure 4), reacting at HFS (50 Hz) G (E, H), P (F, I) nerves and Py (G, J) in reciprocal correlation for TP (E, G, I, J) and TD (F, H).*

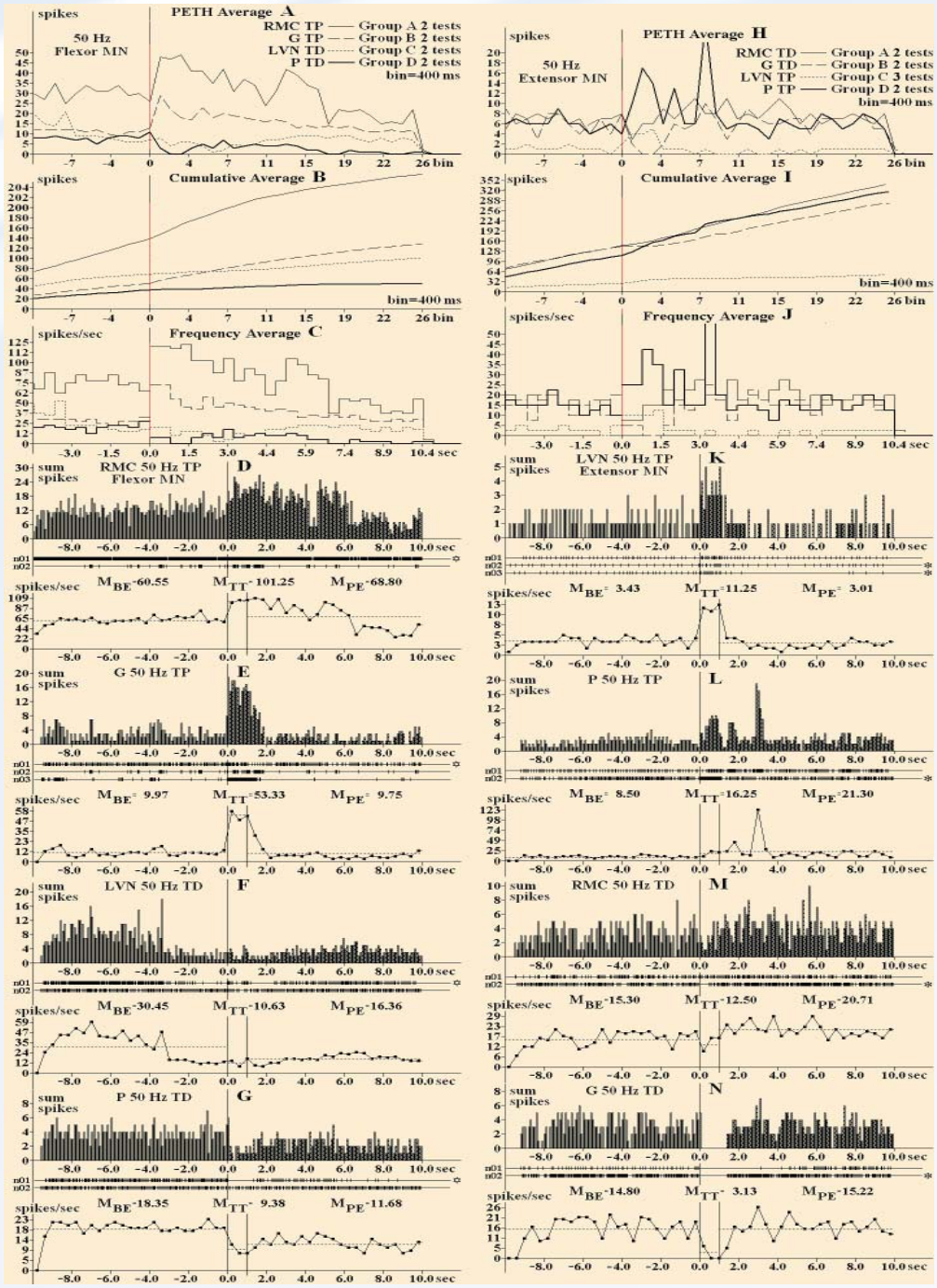

Figure 6a. *A-G and H-N for 2 flexor and 2 extensor MNs, correspondingly – complex PETH Average (A, H), Cumulative Average (B, I) Frequency Average (C, J) of MNs spiking activity at HFS of RMC (Group A), LVN (Group C) and G (Group B), P (Group D) nerves for TP (Group A, B and C, D) and TD (Group C, D and A, B) effects (on A-C and H-J, accordingly). On D-G and K-N – peristimulus histograms of sum spikes (from above) constructed on the bases of raster of the characteristic examples of tests of pre- and poststimulus excitatory (D, E and K, L) and inhibitory (F, G and M, N) manifestations of single MNs spike activity at HFS (50 Hz) RMC, G nerve and LVN, P nerve, accordingly; from below – diagrams of summarized spike frequency of neurons, represented in raster with indication of average numerical meaning.*

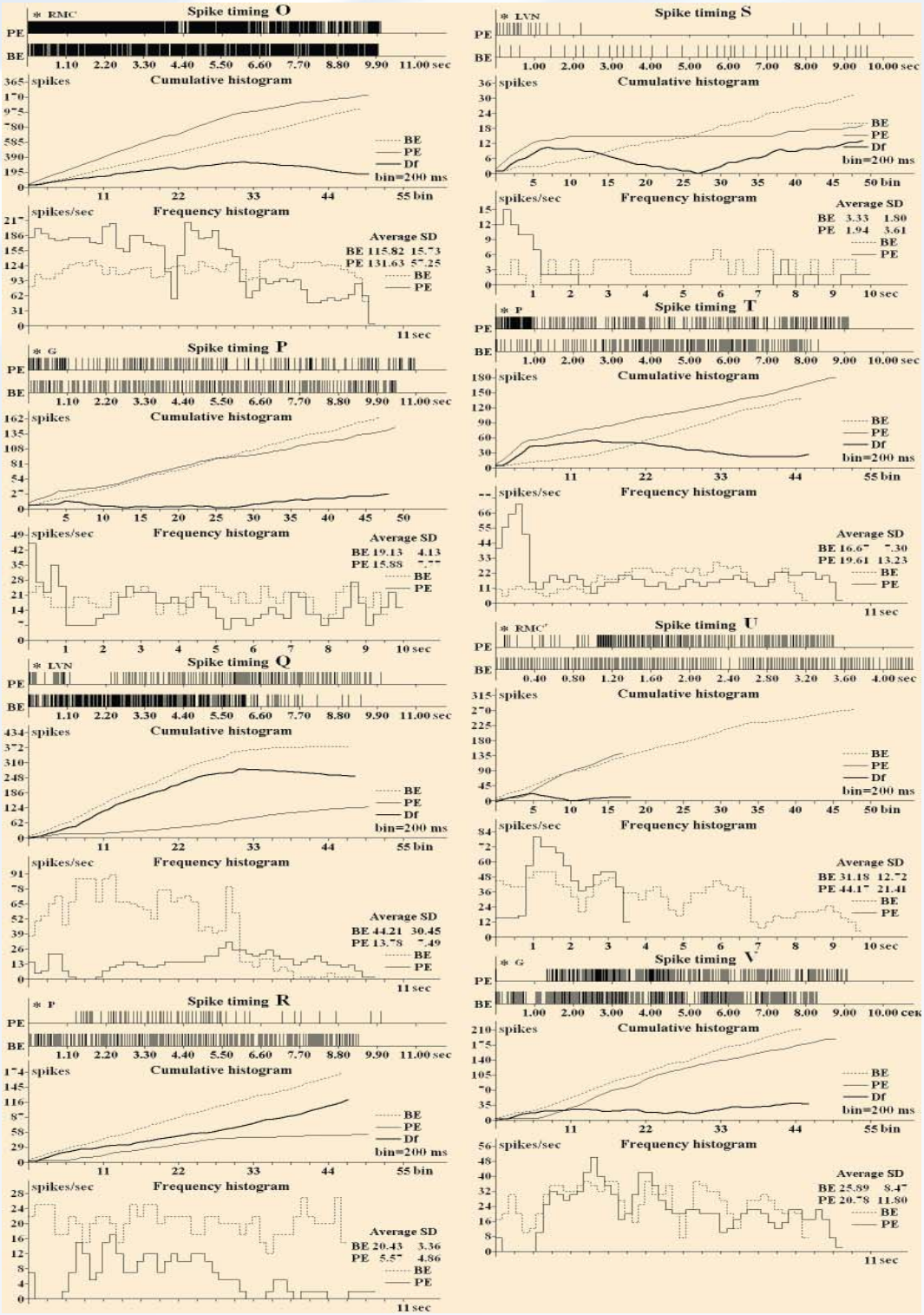

Figure 6b. *O-V – continuation of detailed analysis of intentionally selected single flexor (O-R) and extensor (S-V) MNs (marked with asterisk in raster on preliminary Figure 6a reacted at HFS of G (P, V), P (R, T) nerves, RMC (O, U) and LVN (Q, S) by TP (O, P, S, T) and TD (Q, R, U, V) in reciprocal correlation.*

Discussion

The technique of extracellular recording of background and evoked impulse activity flow of single MNs of SC at HFS in different correlations of Py, nuclei RMC, LVN, flexor (G) and extensor (P) nerves together with on-line programmed analysis of separate units and all the massif of MNs (n=148) allowed to reveal early and late excitatory and inhibitory poststimulus manifestations in type of TP, TD, PTP and PTD of different expression, duration and time of origin. The large variety of uni- and differently directed effects at HFS of mentioned structures in corresponding MNs of SC were registered. In case of HFS of suprasegmentar structures conjointly with peripheral nerves the reciprocal effects were more frequently revealed to be of the central (TP to RMC stimulation, TD to LVN stimulation and vice versa, - in flexor and extensor MNs, respectively) or peripheral (TP to G stimulation, TD to P stimulation and, inversely for flexor and extensor MNs, respectively) origin. In addition, the combination of reciprocal and unidirectional central and peripheral effects was also often recorded, in dependence on the type of MN. In other words, for identification of MNs there might be enough to achieve the pair reciprocity of both the central structures (managed by facilitation of flexion and inhibition of extension) and inversely, or peripheral structures of certain known orientation as well as their pair combination with those central uni- and differently directed. However, as an ideal was accepted the variant of conjoint reciprocal central suprasegmentar and corresponding peripheral neural activation and depression of flexor and extensor MNs. Notably, when flexor MNs responded by excitatory effects to HFS of RMC and nerve G, alongside with reciprocal inhibitory manifestations to LVN and nerve P HFS, the extensor MNs responded inversely (see Figures 6a and 6b). Therewith there is created an impression on the most reliability and clearness of stimulation in corresponding central structures rather than peripheral. As to casual cases of differentiation, not managing in mentioned scheme hereto indicates recent literature data. The same commissural INs that projected to contralateral MNs may be used by reticulo- and vestibulospinal neurons to coordinate the activity of the contralateral hind limb muscles. At INs level that mediates disynaptic excitation of commissural neurons by reticulo- and vestibulospinal neurons there might occur a separate modulation of commands from these two descending neuronal systems, thereby increasing their flexibility [*Krutki P. et al., 2003*]. The crossed inhibition of hind limb lumbar alpha-MNs is evoked via Ia INs that mediate reciprocal inhibition between flexors and extensors. The coordination of left and right hind limb movements based on crossed inhibition from reticulo- and vestibulospinal neurones depends on the degree of activation of Ia inhibitory INs by muscle spindle afferents and on their inhibition by Renshaw cells. These results also indicate that Ia inhibitory INs do not operate as last-order inhibitory INs in crossed trisynaptic pathways from group II afferents, even though they mediate inhibition evoked by INs in shared polysynaptic pathways of crossed flexor and extensor reflexes co-activated by group II and other high-threshold muscle, skin and joint ones [*Jankowska E. et al., 2005*]. Moreover, certain modeling is predicted and directions for future studies on organization of spinal locomotor central pattern generators, as in the SC the coordinated activation of flexor and extensor MNs during locomotion was produced [*McCrea D., Rybak I., 2008*].

Nevertheless, obtainment of reliable results ensuring the clear classification of peripheral or better on the central level activation and/or depression is sufficient for corresponding MNs differentiation.

References

1. *Bortoff G. A., Strick P.L.* Corticospinal terminations in two new-world primates: further evidence that corticomotoneuronal connections provide part of the neural substrate for manual dexterity. J. Neurosci. 1993; 13: 5105-5118.
2. *Brodal A., Pompeiano O., Walberg A.* [The Vestibular Nuclei] [published in Russian] Nauka Publishers, Leningrad-Moscow 1966; 169p.
3. *Brösamle C., Schwab M.E.* Cells of origin, course, and termination patterns of the ventral, uncrossed component of the mature rat corticospinal tract. J. Comp. Neurol. 1997; 386: 293-303.
4. *Brown L.T.* Corticorubral projections in the cat. J. Comp. Neurol. 1974; 154: 149-168.
5. *Burke R.E., Jankowska E., ten Bruggencate G.* A comparison of peripheral and rubrospinal synaptic input to slow and fast twitch motor units of triceps surae. J. Physiol. (Gr. Brit.) 1970; 207: 709-732.
6. *Eccles J.C., Rantucci T., Scheid P., Taborikova H.* Somatotopical studies on the red nucleus: Spinal projection level and respective receptive fields. J. Neurophysiology 1975*a*; 38: 965-980.
7. *Eccles J.C., Scheid P., Taborikova H.* Responses of red nucleus neurons to antidromic and synaptic activation. J. Neurophysiol. 1975b; 38: 947-964.
8. *Fanardjian V.V., Sarkissian J.S* . [Neuron mechanisms of nucleus ruber] [published in Russian] Nauka Publishers. Moscow. 1992; 270p.
9. *Fujito Y., Imai T., Aoki M.* Monosynaptic excitation of motoneurons innervating forelimb muscles following stimulation of the red nucleus in cats. Neurosci. Lett. 1991; 127: 137-140.
10. *Ghez C.* Input-output relations of the red nucleus in the cat. Brain Res. 1975; 98: 93-108.
11. *Hongo T., Jankowska E., Lundberg A.* The rubrospinal tract. 3. Effects of primary afferent terminals. Exp. Brain Res. 1972; 15: 39-53.
12. *Humphrey D.R., Gold R., Reed D.J.* Sizes, laminar and topographic origins of cortical projections to the major divisions of the red nucleus in the monkey. J. Comp. Neurol. 1984; 225: 75-94.
13. *Jankowska E.* Target cells of rubrospinal tract fibers within the lumbar spinal cord. Behav. Brain Res. 1988; 28: 91-96.
14. *Jankowska E., Krutki P., Matsuyama K.* Relative contribution of Ia inhibitory interneurones to inhibition of feline contralateral motoneurones evoked via commissural interneurones. J. Physiol. 2005; 568: 617-628.
15. *Krutki P., Jankowska E., Edgley S.A.* Are crossed actions of reticulospinal and vestibulospinal neurons on feline motoneurons mediated by the same or separate commissural neurons. J. Neurosci., 2003; 23: 8041-8050.
16. *Kuypers H.G.J.M., Lawrence D.G.* Cortical projections to the red nucleus and the brainstem in the rhesus monkey. Brain Res. 1967; 4: 151-188.
17. *Lemon R.N., Baker S.N., Davis J.A., Kirkwood P.A., Maier M.A., Yang H.S.* The importance of the cortico-motoneuronal system for control of grasp. Novartis Found Symp. 1998; 218: 202-215.
18. *Lundberg A.* Multisensory control of spinal reflex pathways. Progr. Brain Res. 1979; 50: 11-28.
19. *Markham C.H.* Vestibular control of muscular tone and posture. Can. J. Neurol. Sci. 1987; 14: 493-496.
20. *Martin G.F.* The pattern of neocortical projections to the mesencephalic of the opossum, Didelphis Virginiana. Brain Res.1968: 11: 593-610.

21. *Martin J.N., Ghez C.* Red nucleus and motor cortex: Parallel motor systems for the initiation and control of skilled movement. Behav. Brain Res. 1988; 28: 217-223.

22. *McCrea D.A., Rybak I.A*. Organization of mammalian locomotor rhythm and pattern generation. Brain Res. Rev. 2008; 57: 134-146.

23. *Mugnaini E., Walberg F., Brodal A.* Mode of termination of primary vestibular fibers in the lateral vestibular nucleus. An electron microscopical study in the cat. Exp. Brain Res. 1967; 4(3): 187-211.

24. *Paxinos G., Watson C.* The rat brain in stereotaxic coordinates. Elsevier Academic Press. 5th ed. 2005. 367p.

25. *Porter R.* Functional studies of motor cortex. Ciba Found. Symp. 1987; 132: 83-97.

26. *Ralston D.D., Ralston H.J.* The terminations of corticospinal tract axons in the macaque monkey. J. Comp. Neurol. 1985; 242: 325-337.

27. *Rinvik E., Walberg E.* Demonstration of somato-topically arranged corticorubral projections in the cat: An experimental study with silver method. J. Comp. Neurol. 1963; 120: 393-407.

28. *Schieber M.H.* Comparative anatomy and physiology of the corticospinal system. Chapter 2. Handb. Clin. Neurol. 2007; 82: 15-37.

29. *Yang H.W., Lemon R.N.* An electron microscopic examination of the corticospinal projection to the cervical spinal cord in the rat: lack of evidence for cortico-motoneuronal synapses. Exp. Brain Res. 2003; 149: 458-469.