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**DISCUSSION**

# Psychophysiological Features of Somatosensory Disorders in Victims of the Chernobyl Accident

**K. N. Loganovsky**
*Center for Radiation Medicine, Academy of Medical Sciences of Ukraine*
*WHO Collaborating Center, Kiev, Ukraine*
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**Abstract**—Participants of the Chernobyl clean-up ($n$ = 145) teams exposed to radiation doses from 0.05 to 3.5 Gy who had for the first time complained of pathologic somatosensory sensations (ostealgic syndrome), 20 healthy subjects, and 50 veterans of the war in Afghanistan with posttraumatic stress disorder (PTSD) were examined by a neuropsychiatrist and presented with the MMPI test. Somatosensory evoked potentials (SSEPs) were recorded. Paresthesia and cenesthopathy were characteristic of the participants of the Chernobyl clean-up. Sensation disorders of the cerebral type, kinesthetic illusions, cenesthopathic hypochondriac disorders, and paroxysmal psychosensory states predominated in this group of subjects. They differed significantly from the veterans with PTSD in markedly increased scores on MMPI scales (hypochondriasis, schizophrenia, pure hypochondriasis, pure schizophrenia, emotional exclusion, and perception oddity), which closely correlated with clinical somatosensory symptoms. In clean-up workers, somatosensory disorders were significantly associated with hypochondriac and schizophrenic-like symptoms. The latencies (LPs) of main SSEP components—$N_{20}$, $P_{25}$, $N_{140}$, $P_{300}$, and $N_{400}$—were increased and their amplitudes decreased in subjects exposed to radiation. Their SSEPs had significant topographical deviations in the left temporoparietal area: the contralateral LPs were increased, whereas the contralateral amplitudes of the thalamocortical $N_{20}$ component and the cortical $P_{25}$ component were decreased as compared to normal values. Somatosensory disorders and hypochondriac and schizophrenic symptoms were significantly correlated with changes in the SSEPs. The decrease in the $N_{20}$ amplitude and increase in the $P_{25}$ latency in the left temporoparietal area were dose-dependent. The results suggest cerebral rather than peripheral origin of ostealgic syndrome and other somatosensory disorders in the participants of the Chernobyl clean-up. These disorders are associated with radiation-induced dysfunction of the corticolimbic structures of the left—dominant—hemisphere. It is suggested that somatosensory disorders in patients exposed to low doses of radiation can be considered as manifestations of chronic fatigue syndrome /fibromyalgia, whereas schizoform organic brain lesions manifest themselves after exposure to a radiation dose of 0.3–0.5 Gy.

Ostealgic syndrome is a characteristic manifestation of chronic radiation sickness after incorporation of osteotropic radionuclides (radium, strontium, plutonium, uranium, americium, etc.) [1–3]. This syndrome has been described in persons exposed to radiation as a result of accidents that took place in the period from 1949 to 1967 in the south Ural region at the Mayak military radiochemical production facility. Ostealgic syndrome developed from 5 to 8 years after the inflow of products of uranium division in doses equal to or higher than 1.87 Sv per bony surface. Loci of hypo- and hyperesthesia, periosteal tenderness to palpation, and a decrease in vibration sensation were noted in algesic zones. X-ray examination did not reveal any structural changes in the bones; however, trepanobiopsy showed dystrophic changes in the bone tissue after exposure to doses from 1 to 4 Sv per bony surface [4]. In this case, the ostealgic syndrome was considered as a peripheral disorder resulting from the exposure of the nerve endings to incorporated radionuclides. Gus'kova and Baisogolov [1] related postradiation ostealgic syndrome to regional circulation disorders.

Pathologic somatosensory sensations such as ostealgia, polyarthralgia, myalgia, paresthesia, cenesthopathy, headache, and heart pain are rather common in victims of the Chernobyl accident [5–10].

Cesium isotopes are largely responsible for internal irradiation over the whole course of action of the Chernobyl accident source. During the first decade after the accident, strontium provided irradiation from seven to ten times lower than cesium, and the irradiation from transuranic elements was tens of times lower both with respect to the annual average dose and in the total dose accumulated over different periods [11]. The maximal accumulated doses of irradiation received from $^{90}$Sr during the whole postaccident period are only 2.9–4 mSv. The absolute value of the annual weighted effective doses received from natural radioactivity is 4.88 mSv [12]. Consequently, the doses of internal irradiation from osteotropic radionuclides of Chernobyl origin are times less than the doses for which radiation-induced 500 and more ostealgic syndrome from incorporated radionuclides was described.

Some authors consider pathologic somatosensory sensations in victims of the Chernobyl nuclear power

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plant accident to be manifestations of somatoform disorders accompanying psychological and social stress [13–15].

The incidence of pathologic somatosensory sensations in survivors after the atom-bomb explosions in Hiroshima and Nagasaki is 3.6–4.7 times higher than in the population on the whole. Moreover, this incidence is higher in atom-bomb victims who had acute radiation sickness [16]. These symptoms were classified as nonspecific manifestations of an "atom-bomb neurosis" [17–19]. However, Furitsu *et al.* [16] do not share this viewpoint. They consider that such an approach leads to underestimation of the radiation effects of both the atom-bombs in Japan and the Chernobyl accident. The pathologic somatosensory sensations and other symptoms were unified into "genbaku bura bura disease" a chronic atom-bomb sickness of the radiational rather than psychogenic origin [16, 20, 21].

This study was aimed at psychophysiological assessment of ostealgic syndrome and other pathologic somatosensory sensations in Chernobyl victims and examination of a possible dependence on the radiation dose.

## METHODS

We examined 145 participants of the Chernobyl clean-up (1986–1990) teams who had for the first time after work in the exclusion zone complained of pathologic somatosensory sensations (the main group). None of them had a somatic disease that would explain these sensations. All the examined subjects were right-handed men aged from 32 to 57 years at the moment of the examination. The absorbed radiation doses were 0.05–3.5 Gy (0.58 ± 0.46 Gy, $M \pm \sigma$).

Twenty virtually healthy right-handed men and 50 veterans of the war in Afghanistan with posttraumatic stress disorder (PTSD) (a control group by the factor of psychological stress) took part in the examination as groups of comparison.

All the subjects were subjected to neuropsychiatric examination and pathopsychological testing using an adapted variant of the MMPI test [22]. Somatosensory evoked potentials (SSEPs) were recorded.

SSEPs to 40 electrodermal stimuli at the level of the pain threshold were recorded using a Brain Surveyor 19-channel brain potential analyzer (SAICO, Italy). The right median nerve was stimulated with rectangular pulses (0.1 ms, 0.5 Hz) applied to the skin on the lower third of the arm via a bipolar electrode (with a proximal cathode). Analysis epochs were 50 and 1000 ms for short- and long-latency SSEPs, respectively. Peak-to-peak amplitudes (μV) and peak latencies (ms) were measured.

The results were subjected to correlation and regression analysis on the basis of Microsoft Excel 97 electronic tables and the Statistica 5.0 software package. A normalized $z$ transformation and the $\chi^2$ test were used in the statistical analysis.

**Table 1.** Subjective somatosensory symptoms in patients exposed to radiation and veterans of the war in Afghanistan with PTSD

| Symptom | Clean-up workers ($n$ = 145) | $\chi^2$ | $p$ | Veterans ($n$ = 50) |
|---|---|---|---|---|
| Ostealgia | 88 | 2.45 | >0.05 | 24 |
| Arthralgia | 84 | 2.91 | >0.05 | 22 |
| Myalgia | 83 | 1.31 | >0.05 | 26 |
| Low-back pain | 71 | 0.72 | >0.05 | 21 |
| Headache | 129 | 1.11 | >0.05 | 42 |
| Heart pain | 63 | 0.27 | >0.05 | 24 |
| Paresthesia | 113 | 12.21 | <0.001 | 26 |
| Cenesthopathy | 104 | 19.71 | <0.001 | 21 |

## RESULTS

Subjective somatosensory symptoms were revealed in all clean-up workers and 39 (78%) veterans with PTSD ($\chi^2 = 33.81$, $p < 0.001$). No such symptoms were revealed in healthy subjects. The symptoms included ostealgia, arthralgia, myalgia, low-back pain, headache, heart pain, paresthesia, and cenesthopathy (Table 1). Both Chernobyl victims and veterans complained of various chronic pains, but the incidence of paresthesias and cenesthopathies was higher in irradiated subjects.

Objective neuropsychiatric symptoms were scored in the following way: 0 (asymptomatic), 1 (mild), 2 (moderate), and 3 (severe) (Table 2). In patients exposed to radiation, disorders of all types of somatosensory sensitivity were more pronounced, but disorders of the surface (touch and pain) sensitivity predominated.

The clean-up workers did not differ significantly from the comparison groups in peripheral and segmental sensitive disorders. However, they had significantly more disorders of the cerebral type: disorders of afferent synthesis (synthetic) and so-called maculomosaic (extralemniscal) disorders. Clinical manifestations of the latter were spots, ribbons, circles, and points of tactile hypoesthesia mosaically distributed over the body and showing lack of correspondence with classical neuroanatomic schemes.

Psychopathologic manifestations of somatosensory afferent disorders consisted in kinesthetic illusions, cenesthopathies with fixed and sometimes delusional hypochondriac ideas, paroxysmal psychosensory states, and, from time to time, somatosensory hallucinatory feelings. Such psychopathology was also significantly more frequent in clean-up workers as compared to veterans with PTSD.

**Table 2.** Objective somatosensory symptoms in patients exposed to radiation and veterans of the war in Afghanistan with PTSD

| Disorder | Clean-up workers ($n$ = 145) $M \pm \sigma$ | $z$ | $p$ | Veterans ($n$ = 50) $M \pm \sigma$ |
|---|---|---|---|---|
| Surface sensibility | 1.35 ± 0.61 | 9.84 | <0.001 | 0.46 ± 0.53 |
| Deep sensibility | 0.87 ± 0.78 | 5.8 | <0.001 | 0.43 ± 0.28 |
| Complex sensibility | 0.52 ± 0.69 | 5.74 | <0.001 | 0.12 ± 0.28 |
| Mononeural type | 0.04 ± 0.22 | 2.19 | <0.05 | 0 |
| Polyneural type | 0.61 ± 0.64 | 2.77 | <0.01 | 0.38 ± 0.45 |
| Radicular type | 0.22 ± 0.57 | 2.29 | <0.05 | 0.09 ± 0.22 |
| Segmental type | 0 | – | – | 0 |
| Conductive type | 0.12 ± 0.32 | 4.52 | <0.001 | 0 |
| Cortical type | 0.01 ± 0.10 | 1.2 | >0.05 | 0 |
| Synthetic type | 1.11 ± 0.61 | 8.07 | <0.001 | 0.38 ± 0.53 |
| Maculomosaic (extralemniscal) type | 1.78 ± 0.77 | 10.72 | <0.001 | 0.58 ± 0.65 |
| Hypoesthesia | 1.33 ± 0.68 | 10.59 | <0.001 | 0.36 ± 0.51 |
| Hyperesthesia | 0.45 ± 0.61 | 1.34 | >0.05 | 0.33 ± 0.52 |
| Somatosensory illusions | 0.95 ± 0.68 | 5.5 | <0.001 | 0.44 ± 0.52 |
| Psychosensory paroxysms | 1.57 ± 0.71 | 13.63 | <0.001 | 0.33 ± 0.49 |
| Somatosensory hallucinations | 0.24 ± 0.47 | 6.15 | <0.001 | 0 |

The MMPI personality profile of the exposed subjects significantly differed from the profiles of both comparison groups (Table 3). The characteristic pathologic averaged profile of clean-up workers was "swimming" with a simultaneous increase in scores on the "neurotic" and "psychotic" scales. Such a profile testifies to personality dysadaptation with intellectual and emotional disintegration. Hypochondriac and depressive symptoms were associated with inertia of thinking, dogmatism, suspiciousness, and even hostility in interpersonal contacts. A chronic feeling of mental discomfort and decrease in general productivity was complicated by apathic manifestations, introversion, and cenesthohypochondriasis.

The MMPI profile of exposed patients corresponded to a clearly asthenic type of reactions with hypochondriac and schizophrenic-like manifestations. The exposed subjects sharply differed from the veterans with PTSD in a substantial increase in scores on the following scales: 1Hs, hypochondriasis (88.62 ± 13.69 and 71.2 ± 15.43, respectively, $z = 7.08$, $p < 0.001$), 8Sch, schizophrenia (79.9 ± 16.53 and 71.15 ± 8.95, respectively, $z = 4.69$, $p < 0.001$), HS'80, pure hypochondriasis (85.26 ± 18.83 and 70.25 ± 13.15, $z = 6.18$, $p < 0.001$), Sc'181, pure schizophrenia (67.89 ± 12.45 and 54.45 ± 7.89, $z = 8.84$, $p < 0.001$), $Sc_{1B}$183, emotional exclusion (68.56 ± 14.25 and 54.28 ± 8.95, $z = 8.24$, $p < 0.001$), and $Sc_B$187, sensory perception oddity (74.12 ± 18.2 and 54.68 ± 17.29, $z = 6.76$, $p < 0.001$) (Table 3).

Scores on the indicated MMPI scales in clean-up workers were closely correlated with each other: the scale 1Hs, hypochondriasis, was correlated with the scales 8Sch, schizophrenia ($r = 0.61$, $p < 0.001$), HS'80, pure hypochondriasis ($r = 0.70$, $p < 0.001$), Sc'181, pure schizophrenia ($r = 0.37$, $p < 0.001$), $Sc_{1B}$183, emotional exclusion ($r = 0.38$, $p < 0.001$), and $Sc_B$187, sensory perception oddity ($r = 0.63$, $p < 0.001$). Scores on the scale 8Sch, schizophrenia, were correlated with the scales HS'80, pure hypochondriasis ($r = 0.39$, $p < 0.001$), Sc'181, pure schizophrenia ($r = 0.63$, $p < 0.001$), $Sc_{1B}$183, emotional exclusion ($r = 0.53$, $p < 0.001$), and $Sc_B$187, sensory perception oddity ($r = 0.82$, $p < 0.001$). Consequently, hypochondriac symptoms were associated with schizophrenic-like symptoms.

In the clean-up workers, scores on the scale 1Hs, hypochondriasis, were correlated with somatosensory symptoms: disorders of surface ($r = 0.21$, $p = 0.039$) and deep sensibility ($r = 0.27$, $p = 0.007$), maculomosaic sensory disorders ($r = 0.2$, $p = 0.047$), somatosensory illusions ($r = 0.25$, $p = 0.012$), psychosensory paroxysmal states ($r = 0.37$, $p < 0.001$), and somatosensory hallucinations ($r = 0.22$, $p = 0.031$). Scores on the scale 8Sch, schizophrenia, in clean-up workers were also correlated with a number of somatosensory symptoms: disorders of surface ($r = 0.3$, $p = 0.002$), deep ($r = 0.24$, $p = 0.017$), and complex ($r = 0.22$, $p = 0.027$) sensibility; synthetic ($r = 0.33$, $p = 0.001$) and maculomosaic ($r = 0.25$, $p = 0.012$); sensory disorders somatosensory illusions ($r = 0.28$, $p = 0.005$); psychosensory paroxysmal states ($r = 0.36$, $p < 0.001$); and somatosensory hallucinations ($r = 0.22$, $p = 0.029$). Thus, in the clean-up workers, somatosensory disorders were significantly associated with hypochondriac and schizophrenic-like

**Table 3.** Scores on the main and supplementary MMPI scales in Chernobyl clean-up workers and groups of comparison

| MMPI scale | Clean-up workers (1) ($n$ = 145) $M \pm \sigma$ | $z_{1-2}$ | $p_{1-2}$ | $z_{1-3}$ | $p_{1-3}$ | Normals (2) ($n$ = 20) $M \pm \sigma$ | $z_{2-3}$ | $p_{2-3}$ | Veterans (3) ($n$ = 50) $M \pm \sigma$ |
|---|---|---|---|---|---|---|---|---|---|
| L, lie | 51.29 ± 7.59 | 1.19 | >0.05 | 0.87 | >0.05 | 49.43 ± 6.4 | –0.53 | >0.05 | 50.33 ± 6.42 |
| F, fidelity | 65.12 ± 12.44 | 6.3 | <0.001 | –3.1 | <0.01 | 55.67 ± 4.86 | –9.51 | <0.001 | 69.51 ± 6.84 |
| K, correction | 51.01 ± 7.35 | 0.81 | >0.05 | 1.39 | >0.05 | 50.1 ± 4.21 | 0.4 | >0.05 | 49.52 ± 6.23 |
| 1Hs, hypochondriasis | 88.62 ± 13.69 | 23.87 | <0.001 | 7.08 | <0.001 | 50.1 ± 5.12 | –8.56 | <0.001 | 71.2 ± 15.43 |
| 2D, depression | 86.23 ± 13.78 | 15.86 | <0.001 | 1.68 | >0.05 | 54.23 ± 7.43 | –11.33 | <0.001 | 82.56 ± 13.21 |
| 3Hy, hysteria | 77.21 ± 10.75 | 22.94 | <0.001 | 2.86 | <0.01 | 51.22 ± 3.12 | –10.12 | <0.001 | 71.32 ± 13.15 |
| 4Pd, psychopathy | 71.12 ± 10.34 | 9.57 | <0.001 | 3.41 | <0.01 | 51.12 ± 8.52 | –7.14 | <0.001 | 66.56 ± 7.24 |
| 5MF, masculinity–femininity | 57.28 ± 9.53 | 0.99 | >0.05 | –0.59 | >0.05 | 55.89 ± 5.16 | –1.48 | >0.05 | 57.91 ± 5.16 |
| 6Pa, paranoia | 68.34 ± 11.85 | 8.64 | <0.001 | 4.92 | <0.001 | 53.12 ± 6.53 | –4.04 | <0.001 | 60.74 ± 8.43 |
| 7Pt, psychasthenia | 72.25 ± 12.53 | 9.78 | <0.001 | 0.09 | >0.05 | 51.64 ± 8.2 | –9.13 | <0.001 | 72.1 ± 9.12 |
| 8Sch, schizophrenia | 79.9 ± 16.53 | 16.5 | <0.001 | 4.69 | <0.001 | 53.12 ± 3.87 | –11.76 | <0.001 | 71.15 ± 8.95 |
| 9Ma, mania | 58.53 ± 13.68 | 0.42 | >0.05 | –0.87 | >0.05 | 57.84 ± 5.42 | –1.25 | >0.05 | 59.96 ± 8.36 |
| 0Si, introversion | 64.82 ± 8.24 | 8.93 | <0.001 | 1.8 | >0.05 | 54.57 ± 4.12 | –5.9 | <0.001 | 62.63 ± 7.13 |
| HS'80, pure hypochondriasis | 85.26 ± 18.83 | 20.17 | <0.001 | 6.18 | <0.001 | 52.28 ± 2.14 | –9.36 | <0.001 | 70.25 ± 13.15 |
| Sc'181, pure schizophrenia | 67.89 ± 12.45 | 13.54 | <0.001 | 8.84 | <0.001 | 46.92 ± 5.16 | –4.69 | <0.05 | 54.45 ± 7.89 |
| $Sc_{1B}$183, emotional exclusion | 68.56 ± 14.25 | 11.16 | <0.001 | 8.24 | <0.001 | 52.22 ± 3.86 | –1.34 | >0.05 | 54.28 ± 8.95 |
| $Sc_B$187, sensory perception oddity | 74.12 ± 18.2 | 13.61 | <0.001 | 6.76 | <0.001 | 49.9 ± 4.2 | –1.82 | >0.05 | 54.68 ± 17.29 |

symptoms. Moreover, the more close association of somatosensory disorders with schizophrenic-like symptoms testifies to cerebral rather than peripheral origin of these disorders.

In subjects exposed to radiation, the LPs of the main SSEP components ($N_{20}$, $P_{25}$, $N_{140}$, $P_{300}$, and $N_{400}$) to stimulation of the right median nerve were increased and the amplitudes were decreased (Table 4) in the projection area (the left temporoparietal area, $C_3$). The SSEPs of the clean-up workers exhibited significant topographic deviations in the left temporoparietal area as compared to both control groups. Under conditions of right-side stimulation of the median nerve, in the $C_3$ lead, the latencies of the contralateral thalamocortical $N_{20}$ and cortical $P_{25}$ components were increased ($p$ < 0.001), and their amplitudes decreased (Table 4).

The amplitudes of the $P_{300}$ and $N_{400}$ SSEP components in $C_3$ the lead were correlated with psychosensory paroxysmal states ($r$ = –0.21, $p$ = 0.037 and $r$ = –0.23, $p$ = 0.02, respectively). This means that the decrease in the $P_{300}$ and $N_{400}$ amplitudes in the left temporoparietal area is associated with increased risk of the development of paroxysmal psychosensory states in a remote period after the exposure. The LP of the $N_{400}$ in $C_3$ lead in the clean-up workers was correlated with the strength of subjective somatosensory disorders ($r$ = 0.2, $p$ = 0.046). Consequently, the increase in the LP of $N_{400}$ in the left temporo-parietal area is associated with the growth of risk of the development of spontaneous sensory phenomena in a remote period after the exposure.

In the exposed subjects, the following correlations were revealed between the SSEPs and the MMPI scores. The $N_{20}$ amplitude in the $C_3$ lead was correlated with the score on the scale HS'80, pure hypochondriasis ($r$ = –0.22, $p$ = 0.032); the $P_{300}$ amplitude was correlated with the scores on the scales 1Hs, hypochondriasis ($r$ = –0.33, $p$ < 0.001) and HS'80, pure hypochondriasis ($r$ = –0.33, $p$ < 0.001) and; the $N_{400}$ amplitude was correlated with the scores on the scales 1Hs, hypochondriasis ($r$ = –0.29, $p$ = 0.004), HS'80, pure hypochondriasis ($r$ = –0.21, $p$ = 0.039), and $Sc_B$187, sensory perception oddity ($r$ = –0.23, $p$ = 0.024). This testifies to an association between hypochondriac and schizophrenic-like psychopathology and decrease in the SSEP amplitude, especially the "smoothness" of $P_{300}$ in the subjects exposed to radiation. The increase in the scores on the MMPI scale 1Hs, hypochondriasis, as a function of the decrease in the $P_{300}$ amplitude is described by the equation 1Hs = 107.53 – 1.148 × $P_{300}$ ($r$ = –0.3335; $t$ = –3.4659; $p$ = 0.000792) amplitude.

The LP of the $P_{300}$ SSEP component in the $C_3$ lead was correlated with scores on the MMPI scales 1Hs, hypochondriasis ($r$ = 0.2, $p$ = 0.048); 8Sch, schizophrenia ($r$ = 0.26, $p$ = 0.01); Sc'181, pure schizophrenia ($r$ = 0.24, $p$ = 0.017); and $Sc_B$187, sensory perception oddity ($r$ = 0.21, $p$ = 0.041). This testifies to an association between the hypochondriac and schizophrenic-like

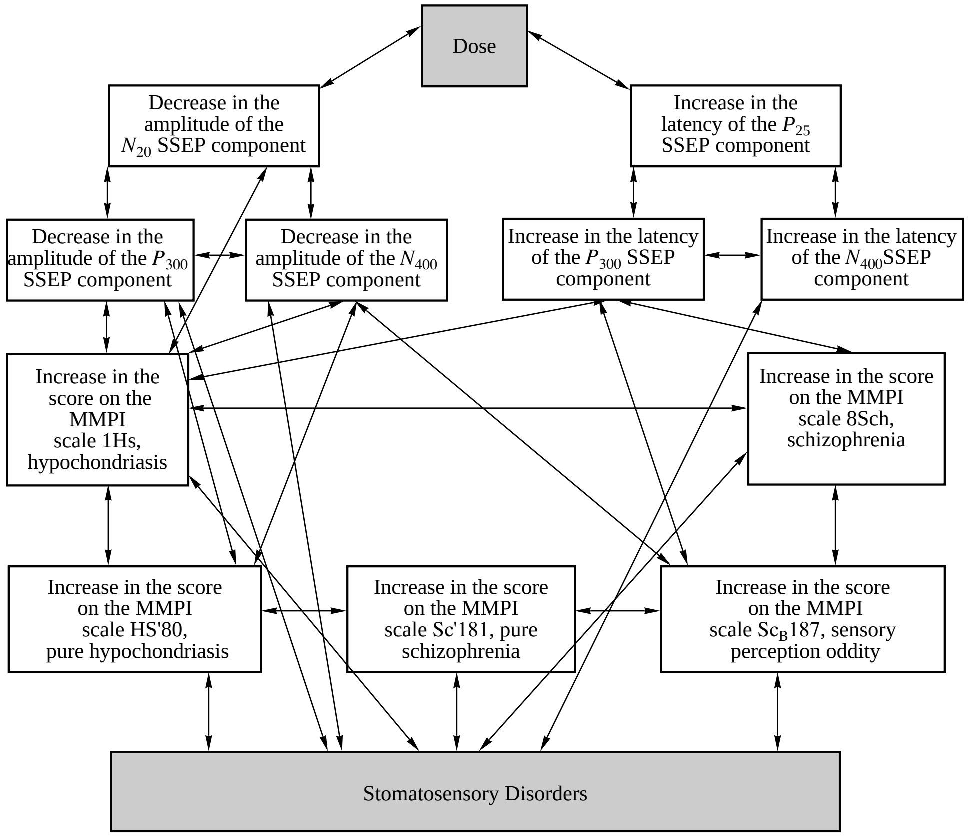
**Table 4.** Amplitude–time parameters of SSEPs in Chernobyl clean-up workers and groups of comparison

| SSEP parameter | Clean-up workers (1) ($n$ = 145) $M \pm \sigma$ | $z_{1-2}$ | $p_{1-2}$ | $z_{1-3}$ | $p_{1-3}$ | Normals (2) ($n$ = 20) $M \pm \sigma$ | $z_{2-3}$ | $p_{2-3}$ | Veterans (3) ($n$ = 50) $M \pm \sigma$ |
|---|---|---|---|---|---|---|---|---|---|
| Amplitude, μV | | | | | | | | | |
| $N_{20}C_3$ | 2.15 ± 0.8 | –9.6 | <0.001 | –9.78 | <0.001 | 3.29 ± 0.44 | –0.81 | >0.05 | 3.41 ± 0.78 |
| $C_4$ | 2.99 ± 0.75 | –0.17 | >0.05 | –0.97 | >0.05 | 3.01 ± 0.45 | –0.71 | >0.05 | 3.12 ± 0.84 |
| Laterality ($C_3$–$C_4$) ($M \pm \sigma$) | –0.75 ± 0.93 | | | | | 0.25 ± 0.43 | | | 0.23 ± 1.06 |
| Paired *t*-test | $t$ = –9.71 | | | | | $t$ = 2.62 | | | $t$ = 1.84 |
| | $p$ < 0.001 | | | | | $p$ < 0.05 | | | $p$ > 0.05 |
| $P_{25}C_3$ | 2.35 ± 0.72 | –17.31 | <0.001 | –11.69 | <0.001 | 4.15 ± 0.37 | 1.58 | >0.05 | 3.92 ± 0.85 |
| $C_4$ | 3.17 ± 0.98 | –6.11 | <0.001 | –2.26 | <0.05 | 3.95 ± 0.44 | 2.62 | <0.05 | 3.52 ± 0.93 |
| Laterality ($C_3$–$C_4$) ($M \pm \sigma$) | –0.71 ± 0.85 | | | | | 0.21 ± 0.45 | | | 0.17 ± 0.84 |
| Paired *t*-test | $t$ = –10.06 | | | | | $t$ = 2.09 | | | $t$ = 1.43 |
| | $p$ < 0.001 | | | | | $p$ < 0.05 | | | $p$ > 0.05 |
| $N_{140}C_3$ | 6.97 ± 3.12 | –9.3 | <0.001 | –6.62 | <0.001 | 12.05 ± 2.15 | 3.87 | <0.001 | 9.78 ± 2.38 |
| $P_{300}C_3$ | 15.51 ± 3.78 | –6.08 | <0.001 | –6.62 | <0.001 | 22.55 ± 4.98 | 1.35 | >0.05 | 20.76 ± 5.15 |
| $N_{400}C_3$ | 17.02 ± 5.15 | –3.96 | <0.001 | –2.93 | <0.01 | 21.79 ± 5.04 | 1.85 | >0.05 | 19.36 ± 4.78 |
| Latency, ms | | | | | | | | | |
| $N_{20}C_3$ | 19.97 ± 1.45 | 4.88 | <0.001 | 6.25 | <0.001 | 18.75 ± 0.98 | –0.31 | >0.05 | 18.83 ± 0.97 |
| $C_4$ | 18.78 ± 1.12 | –3.21 | <0.01 | –3.23 | <0.01 | 19.57 ± 1.02 | 0.16 | >0.05 | 19.52 ± 1.48 |
| Laterality ($C_3$–$C_4$) ($M \pm \sigma$) | 0.99 ± 1.01 | | | | | –0.3 ± 0.76 | | | –0.27 ± 0.67 |
| Paired *t*-test | $t$ = 11.8 | | | | | $t$ = –1.77 | | | $t$ = –2.85 |
| | $p$ < 0.001 | | | | | $p$ > 0.05 | | | $p$ < 0.01 |
| $P_{25}C_3$ | 25.96 ± 1.35 | 10.69 | <0.001 | 4.43 | <0.001 | 24.11 ± 0.59 | –4.51 | <0.001 | 25.07 ± 1.18 |
| $C_4$ | 23.78 ± 1.42 | –5.45 | <0.001 | –8.07 | <0.001 | 24.79 ± 0.64 | –2.88 | <0.01 | 25.42 ± 1.17 |
| Laterality ($C_3$–$C_4$) ($M \pm \sigma$) | 1.35 ± 1.98 | | | | | –0.15 ± 0.69 | | | –0.11 ± 0.75 |
| Paired *t*-test | $t$ = 8.21 | | | | | $t$ = –0.97 | | | $t$ = –1.04 |
| | $p$ < 0.001 | | | | | $p$ > 0.05 | | | $p$ > 0.05 |
| $N_{140}C_3$ | 152.17 ± 15.24 | 6.2 | <0.001 | 2.97 | <0.01 | 139.74 ± 6.95 | –1.88 | >0.05 | 146.75 ± 15.25 |
| $P_{300}C_3$ | 269.43 ± 23.15 | 12.59 | <0.001 | 1.82 | >0.05 | 242.17 ± 4.45 | –4.45 | <0.001 | 261.13 ± 29.27 |
| $N_{400}C_3$ | 415.12 ± 20.17 | 8.16 | <0.001 | 2.41 | <0.05 | 383.95 ± 15.36 | –4.35 | <0.001 | 405.56 ± 25.43 |

psychopathology and the increase in the LP of $P_{300}$ component. The increase in the scores on the MMPI scale 8Sch, schizophrenia, as a function of the increase in the $P_{300}$ latency is described by the equation 8Sch = 32.916 + 0.17658 × $P_{300}$ latency ($r$ = 0.258, $t$ = 2.6165, $p$ = 0.01032).

No statistically significant correlation was found between the amplitude–time SSEP characteristics and the MMPI scores in the healthy subjects. Only one significant correlation between the SSEPs and MMPI scores was established in the veterans: the $N_{140}$ latency in the $C_3$ lead was correlated with the scores on 1Hs, hypochondriasis ($r$ = 0.51, $p$ = 0.024).

A dose–response relationship was revealed between the dose of absorbed radiation and the decrease in the $N_{20}$ amplitude in the left parietotemporal area. This relationship is described by the equation amplitude $N_{20}$ = 2.2865 – 0.3135 × dose (Gy) ($r$ = –0.2106, $t$ = –2.11107, $p$ = 0.037365). Also revealed was a dose–response relationship between the absorbed radiation dose and the increase in the $P_{25}$ latency in the left temporoparietal area, which is described by the equation $P_{25}$ latency = 25.352 + 0.85769 × dose (Gy)




Significant correlations (shown by arrows; $p < 0.05$) between the strength of somatosensory sensations, psychophysiological indices (SSEP and MMPI scores), and radiation dose.

($r = 0.26648$, $t = 2.7089$, $p = 0.007995$). Consequently, exposure to ionizing radiation can be responsible for the topographic deviations in the SSEPs in the left temporoparietal area—a decrease in the contralateral amplitudes ($p < 0.001$) and an increase in the contralateral LPs ($p < 0.001$) of the thalamocortical $N_{20}$ component and the cortical $P_{25}$ component in the $C_3$ lead.

Correlations between the radiation dose, SSEPs, scores on the MMPI, and somatosensory disorders are shown in the figure, which reflects the psychophysiological mechanism of development of ostealgic syndrome after general exposure. The results obtained testifies to cerebral rather than peripheral origin of ostealgic syndrome and other somatosensory disorders in victims of the Chernobyl accident. These disorders are associated with radiation-induced dysfunction of corticolimbic structures of the left (dominant) hemisphere.

## DISCUSSION

The above interpretation of ostealgic syndrome in victims of Chernobyl accident as having cerebral rather than peripheral origin is consistent with the so-called law of sensation projection [23]. According to this law, a painful sensation formed in the higher parts of the central nervous system is always assigned to the primary receptor field of a certain sensory pathway, independently of the point of irritation.

The maculomosaic somatosensory disorders that are common in subjects exposed to radiation reflect disorders of the extralemniscal system, to which, first of all, the corticolimbic-reticular structures are referred [5, 24].

Somatosensory disorders in victims of radiation exposure can be classified as chronic fatigue syndrome/fibromyalgia, whose diagnosis is widespread in the countries of Western Europe and North America. Actually, clinical manifestations referred to chronic fatigue syndrome (unaccountable constant fatigue, which does not disappear after rest and produces a substantial decrease in occupational, social, and personal activity; impairment of the short-term memory and concentration of attention; myalgia; ostealgia; polyarthralgia; headache; sleep disorders; and overexhaustion after exercises) [25, 26] match the disorders observed in both Chernobyl victims [8, 27, 28] and atom-bomb survivors in Hiroshima and Nagasaki [16, 21].

It is evident that chronic fatigue syndrome is close, if not identical, to the states traditionally diagnosed in victims as autonomic “vascular dystonia” or “neurocirculatory dystonia,” “asthenoneurotic syndrome,” and, possibly, etiologically unclear encephalomyelopathy and encephalomyelitis. However, these diagnoses are not used by Western researchers and clinicians. This results in misunderstanding and underestimation of the medical consequences of the Chernobyl accident by Western experts, who largely attribute these consequences to psychosocial stress and psychogenic somatoform disorders [15].

Chronic fatigue syndrome is a “limbic encephalopathy,” in which of the main adaptation systems of the body (the nervous, endocrine, and immune systems) are disordered, with predominance of lesions in the corticolimbic structures and the hypothalamo–hypophyseal–adrenal axis. Infections, injuries, intoxications, stress, etc., are trigger factors [29, 30]. However, a diagnosis of chronic fatigue syndrome requires that other known diseases and exogenic lesions be excluded. Thus, the diagnosis of chronic fatigue syndrome in Chernobyl accident victims is reasonable in cases of exposure to low and very low radiation doses [8, 27, 28]. Because the radiation doses are not well defined, the doses which cause no deterministic radiation effects should be taken into account in practice. According to our data, doses of 0.3–0.5 Gy of general exposure are threshold radiation doses provoking psychophysiological effects [31].

Somatosensory disorders in clean-up workers exposed to doses higher than 0.3–0.5 Gy are manifestations of an organic brain lesion (of a polyetiologic character with account of the radiation factor) with dysfunction of the corticolimbic structures predominantly in the left (dominant) hemisphere. In a number of cases (in the presence of negative psychopathologic symptoms, cenestohypochondriasis, paranoiac and paranoid ideas), the disorders acquire the character of schizoform syndrome. An association has been established between left-hemispheric frontotemporal dysfunctions and schizophrenic symptoms [32–34]. We are aware of a increase in the incidence of schizophrenia among the staff of the Chernobyl exclusion zone and an increase in the incidence of disorders of the schizophrenic spectrum among subjects exposed to doses of 0.3–0.5 Gy and higher as a result of the radiation-induced dysfunction of the fronto-temporal–limbic structures of the left (dominant) hemisphere [7, 9, 10, 31]. Involvement of the mediobasal cortical structures of the left hemisphere in a remote period after exposure has been demonstrated in a number of studies [35–37].

The limbico–reticular complex ensures sensory filtration and a sharp decrease in the volume of conscious sensory perception: the information flow at the input of the somatosensory afferent system is 1 million bits per second, but normally only 5 bits per second is realized [38]. Exposure to ionizing radiation causes a dysfunction of the cortico-limbico–reticular complex and possibly breaks the “sensory gates,” which can result in the development of cenesthopathies and their hypochondriac interpretation. Disorder of sensorimotor gating is considered a key psychophysiological mechanism of schizophrenia [39, 40]. These data are also in agreement with the correlation found by us between changes in the SSEPs and schizophrenic and hypochondriac psychopathology in subjects exposed to radiation.

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