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# EFFECTS OF OCCUPATIONAL EXPOSURE TO ALUMINUM ON NERVOUS SYSTEM: CLINICAL AND ELECTROENCEPHALOGRAPHIC FINDINGS

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**Abstract**
**Objectives:** The aim of the present study was to assess the effects of aluminum (Al) on the nervous system functions in workers chronically exposed to Al. **Materials and Methods:** The study covered a selected group of 67 male workers (mean age, 38.7 SD 10.3 years; range 23–55 years) involved in the Al production. Their employment duration ranged between 2 and 34 years (mean, 14.6 SD 8.9 years). Aluminum oxide ($Al_20_3$) concentrations varied from 0.13 to 1.95 mg/m$^3$ (arithmetic mean, 0.40 mg/m$^3$, geometric mean, 0.35 mg/m$^3$ SD 0.29). Urine Al concentrations found in smelters ranged from 8.5 to 93.0 µg/l (mean, 42.9 SD 20.5 µg/l). The control group consisted of 57 men non-occupationally exposed to Al, matched by gender, age and work shifts. **Results:** Clinically, headache (41.8%), increased emotional irritability (56.7%), concentration difficulty (22.4%), insomnia (22.4%) and mood lability (14.9%) predominated among functional disorders of the nervous system in workers chronically exposed to Al. Objective neurological examinations did not reveal organic lesions in the central or peripheral nervous system. In the EEGs classified as abnormal, generalized and paroxysmal changes were most common. **Conclusions:** The results of this study suggest that exposure to $Al_20_3$ at concentrations below MAC values induces subclinical effect in the nervous system.

**Key words:**
**Aluminum, Occupational exposure, Nervous system, Electroencephalography**

## INTRODUCTION

A growing interest in toxic effects of aluminum (Al) on the environment and humans has been observed over the recent years. Al is one of the most common metals in nature, it makes 7.5% of all elements the lithosphere is composed of [1]. Bauxite is the most important raw material used to produce Al. It contains about 55% of Al in the form of aluminum oxide ($Al_2O_3$). Al production is kept at a rather stable level; in 1992 it accounted for 15 million tons [2]. Recently (June 2002 – July 2003),

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Al production was slightly reduced to about 13 million tons [3].

Production of Al is associated with its emission to the environment, which may become a potential threat to the whole ecosystem. Man-generated activities, for example, fertilization or application of aluminum salts in coagulation treatment of water, increase Al contents in the soil and water. Food and administration of drugs containing Al compounds additionally contribute to this hazard.

Aluminum has been traditionally regarded as non-toxic metal that induces pathological changes only in very specific conditions, e.g., long-term dialysis due to renal failure or occupational exposure to Al dusts, fumes and its oxides [4–6].

Owing to the advanced knowledge and development of research methods, scientists have drawn their attention to aluminum assuming that it is an important etiopathogenetic agent responsible for the incidence of numerous degenerative diseases of the nervous system. At present, the interest of researchers is mainly focused on the role of Al in etiopathogenesis of Alzheimer's disease and dementia. In the opinion of some authors it contributes to the development of these diseases [7].

Toxic effects of environmental agents, including Al, are taken into account when considering the development of such nervous diseases as endemic amyotrophic lateral sclerosis, parkinsonism and senile dementia occurring in certain geographical areas [8].

Aluminum and its compounds have a variety of applications in different branches of industry, particularly in the aircraft, motor car and electrical industries. Al compounds are used in manufacturing glass, ceramic products, rubber, wood preservatives or pharmaceuticals. Welders and workers employed in electrolytic heat and aluminum casting, or in the production of abrasive materials are among those who are mostly exposed to Al dusts and fumes.

Blood serum Al (S-Al) and urinary Al (U-Al) concentrations are indicators of Al absorption. To assess occupational exposure of workers, it is recommended to determine Al concentrations in urine. The mean values of U-Al concentrations in non-exposed persons fall within the range of 4–11 µg/l. The upper reference limit for aluminum is about 16 µg/l. Bearing in mind that the Polish maximum allowable concentration (MAC) [9] value for $Al_2O_3$ is 2 mg/m$^3$, which corresponds with Al concentration of 1.05 mg/m$^3$, the allowable biological concentration, namely the biological exposure index (BEI) would be 56 µg/l according to the following formula [10]:

$$\text{BEI U-Al} = 29.6 + 25 \bullet 1.05 \text{ mg/m}^3 = 56 \text{ µg/l}.$$

Despite growing interest in Al neurotoxicity, the published findings on occupational exposure to Al and its compounds are rather scarce. The available reports provide evidence that occupational exposure to Al and its components generates harmful effects on the workers' nervous system as well as induces disorders of mental processes and motor actvities [11]. However, no single finding supports a hypothesis that occupational exposure to Al affects cognitive mechanisms [12].

The aim of the present study was to assess the condition of the nervous system in workers exposed to Al during its production and to define the health effects of occupational exposure related to exposure duration, cumulative exposure index and U-Al concentrations. The survey was based on clinical neurological examinations and electroencephalographic (EEG) findings*.

## MATERIALS AND METHODS

### Study population: criteria for eligibility

The study covered a selected group of 67 male workers, aged 23–55 years (mean, 38.7 SD 10.3 years), employed in an Al foundry and exposed to aluminum oxide ($Al_20_3$) (Table 1). The employment duration ranged from 2 to 34 years (mean, 14.6 SD 8.9 years) (Table 2).

As depicted in Table 2, the employment duration of 11–20 years and below 10 years applied to the largest group of workers.

Persons with suspected or past diseases of the nervous system, especially cranio-cerebral traumas, neuroinfections, brain tumors, cerebrovascular disease and migraine, persons with diabetes or hypertension and those suspected of alcoholism and drug abuse were excluded from the study group.

* Results of EEG and evoked potentials as well as their comparisons are the subject of another work.

**Table 1.** Age characteristics of the study and control groups

| Age | Study group | | | | | Control group | | | | | P* |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | No. of persons | min | max | $\bar{x}$ | SD | No. of persons | min | max | $\bar{x}$ | SD | |
| ≤ 29 | 15 | | | 25.2 | 1.6 | 15 | | | 24.4 | 2.1 | 0.16 |
| 30–39 | 22 | | | 33.3 | 3.0 | 17 | | | 34.2 | 3.3 | 0.41 |
| 40–49 | 16 | | | 45.5 | 3.2 | 11 | | | 45.5 | 2.8 | 0.97 |
| ≥ 50 | 14 | | | 52.9 | 1.6 | 14 | | | 52.8 | 2.4 | 0.93 |
| Total | 67 | 23 | 55 | 38.7 | 10.3 | 57 | 20 | 58 | 38.3 | 11.3 | 0.86 |

* Probability in the t-test in age groups.

**Table 2.** Characteristics of the study group by exposure duration

| | No. of persons | Exposure duration (years) | | | | Number of persons (%) by exposure duration | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | min | max | $\bar{x}$ | SD | ≤ 10 | 11–20 | 21–30 | ≥ 31 | Total (%) |
| Study group | 67 | 2 | 34 | 14.6 | 8.9 | 26 (38.8) | 25 (37.3) | 13 (19.4) | 3 (4.5) | 67 (100.0) |

The latter factor was essential because of a known impact of drugs on bioelectric cerebral activity and EEG patterns.

The control group consisted of 57 persons, aged 20–58 years (mean, 38.3 SD 11.3 years), without contact with Al or other chemical agents matched by gender, age and work shifts. They worked at the same foundry, but were employed as operators of transport vehicles and wiremen or in wood-workshops. Identification of the study and control groups was preceded by a very careful selection of subjects in view of possible specific changes in their health condition.

**Neurological examinations and EEG recordings**

The out-patient neurological examinations included subjective and objective survey performed in accordance with common clinical procedures. Medical history was extended to include a permanent set of questions on symptoms possibly associated with Al exposure. The data obtained were documented in a neurological examination form standardized for all subjects.

Electroencephalography was performed using Digital EEG Pegasus units with the international system of 10–20 electrodes. After EEG recorded at rest, and checking the reaction retention, a 3-min hyperventilation was employed, followed by rhythmical flash activation. During the final trial, a 10-s flash series at the frequency of 1–25 Hz was applied.

EEG recordings were assessed on the basis of the generally recognized criteria, including frequency, amplitude, morphology, localization rhythms and their reaction to stimuli. The results were divided into three groups: normal, borderline and abnormal, according to the classification of Majkowski [13].

Abnormal EEG recordings were classified in line with the nature of pathologies and their intensity; the following four sub-groups of changes were distinguished: generalized, focal, paroxysmal, and asymmetrical.

**Method used for assessing work environment**

Personal air samples (1 sample per shift) to assess time-weighted average (TWA) Al concentrations were continuously collected from the workers' breathing zone. All the samples covered 6–7 h of an 8-h work shift (according to norm PN-Z-04008-7-2002) [14].

Casella AFC-123 personal air samplers equipped with membrane filters (Sartorius 11304, 0.8 μm, ⌀ 37 mm) were used to collect total dust at an air flow rate of 2.0 1/min.

After the gravimetric determination of dust concentration, the filter with collected sample was melted with sodium carbonate/sodium borate 2:1 (by weight) mixture, and the re-

**Table 3.** Characteristics of the study group by current exposure and cumulative exposure index

| | No. of persons | Current $Al_2O_3$ exposure ($mg/m^3$) | | | |
|---|---|---|---|---|---|
| | | min | max | $\bar{x}$ | SD |
| Study group | 67 | 0.13 | 1.95 | 0.40 | 0.29 |
| | | Cumulative exposure index ($mg/m^3$ • years) | | | |
| | | min | max | $\bar{x}$ | SD |
| | | 0.6 | 17.4 | 4.8 | 3.4 |

sultant melt was dissolved in 10 ml of 10% $HNO_3$ with added 1 mg/ml of La and Cs. A flame atomic absorption spectrophotometer (Varian, Spectr AA-250) was used to determine Al concentration. In Poland, MAC value for $Al_2O_3$ is 2 $mg/m^3$ and for short term exposure limit (STEL) 16 $mg/m^3$ [9].

In the breathing zone of the foundry workers, the concentrations of Al dust and $Al_2O_3$ ranged from 0.3 to 8.3 $mg/m^3$ ($\bar{x}_a$ = 1.5; $\bar{x}_g$ = 1.3; SD = 1; n = 67) and from 0.13 to 1.95 $\bar{x}_a$ = 0.40; $\bar{x}_g$ = 0.35; SD = 0.29; n = 67), respectively. Mean proportion of $Al_2O_3$ in dusts was $\bar{x}_a$ = 28%; $\bar{x}_g$ = 26,9%; SD = 12.3. The highest air $Al_2O_3$ concentrations were found at workposts of workers responsible for metallic charge ($\bar{x}_a$ = 1.2; n = 2), smelters and foremen ($\bar{x}_g$ = 0.36; n = 59). $Al_2O_3$ concentrations in the foundry workers' breathing zone did not exceed the Polish MAC value of 2 $mg/m^3$ [9]. For each subject a cumulative exposure index (a product of current exposure to $Al_2O_3$ ($mg/m^3$) and exposure duration (years)) was calculated. It fell within the range between 0.6 and 17.4 ($\bar{x}$ = 4.8; SD = 3.4).

Table 3 gives the characteristics of the exposed group by the values of current $Al_2O_3$ exposure and cumulative exposure index.

### Urine aluminum determination

Graphite atomic absorption spectrophotometry (GF-AAS) was used to determine urine Al concentration, employing an atomic absorption spectrometer (Unicam, Model 989 QZ Sollar) with Zeeman background correction. Diluted nitric acid solution was applied as a matrix modifier for U-Al determination [15]. The method was validated to define linearity, precision, repeatability, detectability, determinability and accuracy (expressed as a relative load). U-AL concentrations were determined in a group of randomly selected 34 foundry workers, aged $\bar{x}$ = 39.7 SD 10.2 years and in 30 subjects eligible for the control group, matched by age ($\bar{x}$ = 39.4 SD 10.8 years). In the study and control groups, U-AL concentrations ranged from 8.5 to 93.0 µg/l ($\bar{x}$ = 42.9 SD 20.5 µg/l), and from 0.3 to 76.1 µg/l ($\bar{x}$ = 20.3 SD 17.6 µg/l), respectively. A comparison of results showed statistically significant difference ($p < 0.0001$) (Table 4).

**Table 4.** Urine Al concentrations (µg/l) in the study and control groups

| Group | No. of persons | Age (years) | | P* | Al concentration in urine | | | | P* |
|---|---|---|---|---|---|---|---|---|---|
| | | $\bar{x}$ | SD | | min | max | $\bar{x}$ | SD | |
| Study | 34 | 39.7 | 10.2 | 0.93 | 8.5 | 93.0 | 42.9 | 20.5 | 0.0001 |
| Control | 30 | 39.4 | 10.8 | | 0.3 | 76.1 | 20.3 | 17.6 | |

* Probability in the t-test in age groups.

### Statistical analysis

The results were analyzed with use of Fisher's exact test, t-test to compare the mean values, and one-way ANOVA. For all applied tests significance level $\alpha$ = 0.05 was adopted.

## RESULTS

### Neurological examinations and EEG findings

The most frequent complaints reported by the workers included: increased emotional irritability (56.7%), headache (41.8%), concentration difficulty (22.4%), insomnia (22.4%), vertigo (16.4%), sleepiness (14.9%), mood lability (14.9%), dysmnesia (11.9%), anxiety and fear (10.4%) (Table 5).

Headache reported by the subjects were not characterized by any specific feature, it differed in localization, duration and time of its occurrence. As reported by the workers, it was sometimes provoked by physical strain and

**Table 5.** Frequency of subjective symptoms in the study and control groups

| Subjective symptoms | Study group | Control group | P* |
|---|---|---|---|
| | n = 67 (%) | n = 57 (%) | |
| Headache | 28 (41.8) | 4 (7.0) | 0.01 |
| Vertigo | 11 (16.4) | 1 (1.8) | 0.01 |
| Increased emotional irritability | 38 (56.7) | 3 (5.3) | 0.01 |
| Dysmnesia | 8 (11.9 | 0 (-) | 0.01 |
| Concentration difficulty | 15 (22.4) | 2 (3.5) | 0.01 |
| Insomnia | 15 (22.4) | 4 (7.0) | 0.01 |
| Sleepiness | 10 (14.9) | 0 (-) | 0.01 |
| Mood lability | 10 (14.9) | 1 (1.8) | 0.01 |
| Anxiety and fear | 7 (10.4) | 0 (-) | 0.01 |
| Myospasm | 1 (1.5) | 0 (-) | 1.00 |
| Muscular fatigue | 2 (3.0) | 0 (-) | 0.50 |
| Extremity pains | 2 (3.0) | 0 (-) | 0.50 |
| Paresthesia | 2 (3.0) | 0 (-) | 0.50 |

* Probability in Fisher's exact test.

high temperature. In many cases, headache assumed the form of vasomotor pains, or was accompanied by vertigo. The changed position of the body sometimes increased its intensity, but in general, it was not so acute as to lead to difficulties in walking or collapse.

The state of increased emotional irritability with symptoms of impatience and lack of self-control was reported by 38 (56.7%) persons. Concentration difficulty was usually temporary. Sleeping disturbances were manifested by insomnia or difficulties in falling asleep, sleepiness during the day was less frequent. Mood lability was characterized by a rapid change from a cheerful to a depressive mood. No regular sequence of the particular mood occurrence could be identified, and the subjects themselves did not regard this symptom as a morbid one.

Dysmnesia mainly applied to recent events, whereas past events were very well remembered. Anxiety and fear were demonstrated by inner unrest and irrational distress. The reported complaints did not originate from psychotic experiences and were not similar to those observed in endogenic depression.

In the study group, 21% of workers reported no complaints. A comparison indicated more frequent subjective symptoms in the central nervous system (CNS) in the exposed workers than in controls, and in those exposed to U-Al concentration above and below 56 µg/l (BEI), the associations were statistically insignificant*. A comparison between Al exposure duration and CNS subjective symptoms revealed statistical significance for headache ($p = 0.04$), and insomnia ($p = 0.05$) (Table 6).

The relationship between the cumulative exposure index and subjective CNS symptoms also showed statistical significance for headache ($p = 0.02$) and insomnia ($p = 0.04$) (Table 6). There were no statistically significant associations between U-Al concentration and current exposure to $Al_2O_3$ and subjective CNS symptoms (Table 7). The objective neurological examination did not reveal focal symptoms of organic lesions in the central or peripheral nervous system that could be attributed to occupational exposure. Clinical neurological examination provided no grounds for diagnosing toxic encephalopathy or polyneuropathy.

The characteristics of EEG recordings is summarized in Table 8. Normal EEG was characterized by the presence of alpha and beta rhythms as well as by the alpha rhythm blockade. The alpha rhythm frequency range was 9–11 Hz, and the alpha waves amplitude was usually 40–60 µV. Beta activity at the frequency above 14 Hz and amplitude below 25 µV was another background rhythm. EEG with 5% of symmetric slow theta waves, frequency of 6–7 Hz in parietal leads, and 4–6 Hz in anterior-temporal leads was also classified as normal. Borderline EEG was characterized by one of the normal background rhythms, usually alpha waves rhythm and theta waves in 5–15% of recordings. Ac-

* As it was rather not feasible to include a complete statistical assessment, data are not given, but they can be obtained from the first author.

**Table 6.** Comparison of exposure duration and cumulative exposure index in the study group between subjects without and with symptoms

| Subjective symptoms | Exposure duration (yr) (mean value of exposure duration (yr)) in the study group | | P* | Cumulative exposure index ($mg/m^3$ • years) in the study group | | P* |
|---|---|---|---|---|---|---|
| | Without symptoms | With symptoms | | Without symptoms | With symptoms | |
| Headache | 12.7 | 17.2 | 0.04 | 3.9 | 5.9 | 0.02 |
| Vertigo | 13.9 | 17.7 | 0.20 | 4.6 | 5.9 | 0.21 |
| Increased emotional irritability | 12.4 | 16.2 | 0.08 | 4.1 | 5.3 | 0.17 |
| Dysmnesia | 14.3 | 16.4 | 0.54 | 4.7 | 5.3 | 0.68 |
| Concentration difficulty | 14.3 | 15.4 | 0.68 | 4.8 | 4.9 | 0.90 |
| Insomnia | 13.5 | 18.4 | 0.05 | 4.4 | 6.5 | 0.04 |
| Sleepiness | 14.2 | 16.8 | 0.39 | 4.5 | 6.3 | 0.10 |
| Mood lability | 13.9 | 18.0 | 0.19 | 4.7 | 5.5 | 0.49 |
| Anxiety and fear | 14.6 | 14.0 | 0.86 | 4.8 | 4.4 | 0.77 |

* Probability in the t-test.

**Table 7.** Comparison of urine Al concentrations and $Al_2O_3$ concentrations in the air at workposts in the study group between subjects without and with symptoms

| Subjective symptoms | Al concentration in urine | | P* | $Al_2O_3$ concentration in the air at workposts | | P* |
|---|---|---|---|---|---|---|
| | Without symptoms | With symptoms | | Without symptoms | With symptoms | |
| Headache | 42.7 | 43.2 | 0.94 | 0.35 | 0.33 | 0.75 |
| Vertigo | 43.3 | 40.9 | 0.80 | 0.35 | 0.32 | 0.51 |
| Increased emotional irritability | 40.3 | 44.5 | 0.58 | 0.35 | 0.34 | 0.74 |
| Dysmnesia | 42.1 | 49.1 | 0.53 | 0.34 | 0.31 | 0.54 |
| Concentration difficulty | 44.0 | 38.4 | 0.52 | 0.35 | 0.30 | 0.26 |
| Insomnia | 43.9 | 39.8 | 0.61 | 0.33 | 0.35 | 0.80 |
| Sleepiness | 42.6 | 44.1 | 0.88 | 0.34 | 0.36 | 0.68 |
| Mood lability | 41.4 | 49.7 | 0.38 | 0.35 | 0.31 | 0.38 |
| Anxiety and fear | 42.0 | 47.9 | 0.56 | 0.34 | 0.33 | 0.76 |

*Probability in the t-test.

**Table 8.** Frequency of EEG findings in the study and control groups

| Group | No. of persons (%) | Electroencephalography (EEG) | | | P* | Abnormal EEG | | | | P* |
|---|---|---|---|---|---|---|---|---|---|---|
| | | Normal | Borderline | Abnormal | | Generalized | Focal | Paroxysmal | Asymmetrical | |
| Study | 67 (100.0) | 29 (43.3) | 13 (19.4) | 25 (37.3) | 0.05 | 12 (17.9) | 5 (7.5) | 7 (10.4) | 1 (1.5) | 0.01 |
| Control | 57 (100.0) | 38 (66.7) | 7 (12.3) | 12 (21.1) | | 6 (10.5) | 3 (5.3) | 2 (3.5) | 1 (1.8) | |

* Probability in Fisher's exact test.

tivity of slow theta waves at frequency of 4–7 Hz occurred in the form of a shorter or a longer series, usually in central leads at background activity amplitude. In abnormal EEG recordings, those with generalized changes predominated (17.9% of all recordings) in the study group. They were characterized by irregular background, decreased alpha waves and excess of slow theta waves at different frequencies (from 4 to 7 Hz) and amplitudes. Sometimes single slower waves of delta type (3 Hz) or single sharp waves with duration below 200 ms could be observed. In a part of examinations, the changes were intensified during or after hyperventilation.

More serious abnormalities involved paroxysmal changes, found in 7 (10.4%) exposed subjects. Paroxysmal changes assumed the form of generalized slow dysrhythmic theta wave discharges usually at the unchanged background activity. Focal changes, pronounced by theta waves and sometimes by sharp waves localized mostly in the left temporal or frontal-temporal leads, were registered in 5 (7.5%) subjects. Asymmetric recordings with left lateralization associated with the asymmetry of dominant alpha rhythm were observed in one subject.

Normal EEG was more frequent (66.7%) in the control than in the study group (43.3%). In the study group, abnormal (37.3%) and borderline (19.4%) recordings were also more common. The comparison of these values proved to be statistically significant ($p = 0.05$). A comparison of abnormal EEG recordings between the study group and controls yielded statistically significant difference ($p = 0.01$). In abnormal EEG, generalized, focal, and paroxysmal changes were more frequent in the study group (Table 8).

When comparing the frequency of subjective CNS symptoms with the type of EEG changes, abnormal or borderline EEG was significantly more frequent in the subjects reporting sleepiness ($p = 0.01$), whereas generalized changes in EEG were significantly more frequent in subjects reporting vertigo ($p = 0.05$) (Table 9).

**Table 9.** Types of EEG findings and their frequency compared with CNS subjective symptoms in the study group

| Subjective symptoms | Electroencephalography (EEG) | | | P* | Abnormal EEG | | | | P* |
|---|---|---|---|---|---|---|---|---|---|
| | Normal | Borderline | Abnormal | | Generalized | Focal | Paroxysmal | Asymmetrical | |
| | n = 29 (%) | n = 13 (%) | n = 25 (%) | | n = 12 (%) | n = 5 (%) | n = 7 (%) | n = 1 (%) | |
| Headache | 10 (35.7) | 8 (28.6) | 10 (35.7) | 0.25 | 6 (60.0) | 1 (10.0) | 2 (20.0) | 1 (10.0) | 0.52 |
| Vertigo | 2 (18.2) | 2 (18.2) | 7 (63.6) | 0.11 | 4 (57.1) | 1 (14.3) | 1 (14.3) | 1 (14.3) | 0.05 |
| Increased emotional irritability | 16 (42.1) | 10 (26.3) | 12 (31.6) | 0.22 | 7 (58.3) | 2 (16.7) | 2 (16.7) | 1 (8.3) | 0.39 |
| Dysmnesia | 3 (37.5) | 3 (37.5) | 2 (25.0) | 0.37 | 1 (50.0) | 1 (50.0) | 0 (-) | 0 (-) | 0.77 |
| Concentration difficulty | 5 (33.3) | 3 (20.0) | 7 (46.7) | 0.63 | 5 71.4) | 1 (14.3) | 1 (14.3) | 0 (-) | 0.49 |
| Insomnia | 5 (33.3) | 5 (33.3) | 5 (33.3) | 0.29 | 3 (60.0) | 2 (40.0) | 0 (-) | 0 (-) | 0.50 |
| Sleepiness | 1 (10.0) | 5 (50.0) | 4 (40.0) | 0.01 | 2 (50.0) | 2 (50.0) | 0 (-) | 0 (-) | 0.41 |
| Mood lability | 3 (30.0) | 2 (20.0) | 5 (50.0) | 0.61 | 3 (60.0) | 1 (20.0) | 0 (-) | 1 (20.0) | 0.08 |
| Anxiety and fear | 2 (28.6) | 2 (28.6) | 3 (42.8) | 0.67 | 2 (75.0) | 0 (-) | 1 (25.0) | 0 (-) | 0.85 |

* Probability in Fisher's exact test.

**Table 10.** Comparison of exposure duration and cumulative exposure index in the study group with different changes in EEG*

| Type of EEG findings | Exposure duration (year) | | | Cumulative exposure index | | |
|---|---|---|---|---|---|---|
| | n | $\bar{x}$ | SD | n | $\bar{x}$ | SD |
| Generalized | 12 | 17.8 | 9.9 | 12 | 6.7 | 5.2 |
| Focal | 5 | 16.4 | 7.7 | 5 | 5.9 | 2.8 |
| Paroxysmal | 7 | 9.4 | 7.7 | 7 | 3.3 | 2.6 |
| P | | 0.15 | | | 0.23 | |

One-way ANOVA.
* Asymmetrical EEG excluded from the analysis because of a small number of recordings.

**Table 11.** Comparison of urine Al concentration and $Al_2O_3$ concentration in the workpost air with different changes in EEG* in the study group

| Type of EEG findings | Al concentration in urine | | | $Al_2O_3$ concentration in the ambient air at workposts | | |
|---|---|---|---|---|---|---|
| | n | $\bar{x}$ | SD | n | $\bar{x}$ | SD |
| Generalized | 4 | 49.3 | 23.2 | 12 | 0.35 | 0.1 |
| Focal | – | – | – | 5 | 0.36 | 0.0 |
| Paroxysmal | 6 | 41.4 | 15.8 | 7 | 0.38 | 0.3 |
| P | | 0.54 | | | 0.93 | |

One-way ANOVA.
* Asymmetrical EEG excluded from the analysis because of a small number of recordings.

A comparison between Al exposure duration (in years) and the cumulative exposure index and different types of EEG changes did not reveal any statistically significant associations (Table 10). A comparison of U-Al concentration and $Al_2O_3$ concentration in the ambient air with different types of EEG changes neither revealed statistically significant associations (Table 11).

## DISCUSSION

In the clinical picture of the nervous system disorders observed in the foundry workers exposed to $Al_2O_3$ in concentrations ranging from 0.13 to 19.5 mg/m$^3$ during Al production, subjective CNS symptoms pronounced by the increased emotional irritability, headache, concentration difficulty, sleep disorders, vertigo, mood lability, anxiety and fear were in the majority. Some of these symptoms were significantly associated with Al exposure duration, but there were no significant associations between U-Al concentrations and current exposure to $Al_2O_3$ in the ambient air of the work environment.

In the study group of smelters exposed to $Al_2O_3$ below MAC values who reported subjective symptoms, no CNS changes were found that could provide grounds for clinical diagnosis of encephalopathy. Severe CNS damages manifested by paroxysmal convulsions, growing dementia and pathological EEG recordings, reported many years ago [16], do not occur any longer. Microsymptomatology that predominates in the clinical picture imposes the need to use neurophysiological methods for exploring the condition of the nervous system, which render it possible to assess noxious effects of neurotoxins already at the preclinical level.

A comparison between our own results of the study in a group of foundry workers and the literature data is rather difficult because of different methods used for assessing occupational exposure, sometimes combined exposure, and different neurological examinations performed for testing the neurological condition of persons representing different occupations involving Al exposure.

Results similar to ours were obtained by Hošovski et al. [17] who carried out neurological examinations expanded by psychological tests in a group of 87 founders occupationally exposed to Al contained in fumes and dusts at concentrations ranging from 4.6 to 11.5 mg/m$^3$. The results obtained in the study group and in the control group consisted of 60 non-exposed subjects were compared. They did not find clinical symptoms of the damage to the nervous system, but they observed memory difficulty, emotional lability, slowing down of psychomotoric functions, and disorders of visual and motor coordination.

Symptoms of the damage to the nervous system were described by White et al. [18] in 25 Al smelters (mean age, 47.0 SD 6.6 years; mean employment duration, 18.7 SD 3.6 years). In this study, the level of Al exposure was not defined. In the clinical picture, ataxia, memory difficulty, impairment of abstractive thinking, and depression were most pronounced.

Hänninen et al. [19] and Sjögren et al. [20] found in welders disorders of CNS functions such as memory, concentration and mood.

Symptoms of neuropsychiatric profile like those observed in our study, in similar conditions of Al occupational

exposure, were reported by Bast-Pettersen et al. [21] in welders exposed for about 8 years; Al concentration in the ambient air at work posts ranged from 0.6 to 3.8 mg/m$^3$ ($\bar{x}$ = 1.18 mg/m$^3$). U-Al in study subjects accounted for 50.3 µg/l on average.

Reports on EEG examinations in persons exposed to aluminum are scarce, but those available point out to the presence of bioelectric disorders of cerebral functions. A significant role of EEG examinations in the diagnosis of dialysis encephalopathy syndrome was indicated in the literature published some time ago. Disorders in the brain bioelectric activity could sometimes outpace the occurrence of clinical pathologies [6].

In our study group, abnormal EEG was observed more frequently (in 37.3% of examinations) than in controls, and markedly exceeded so called population standard [13]. In abnormal EEG, generalized changes dominated (17.9%), paroxysmal and epilepsy-like changes were observed less frequently (10.4%) and usually against the background of unchanged basic function.

Our observations are in agreement with those made by Riihimäki et al. [22] who described generalized changes in EEG performed in a group of welders; 17% of these changes occurred at low exposure (Al-sum $\bar{x}$ = 5.7 µmol/l) and 27% at high exposure (Al-sum $\bar{x}$ = 12.8 µmol/l). Paroxysmal and epilepsy-like changes of moderate intensity were found in 7% and 17% of EEG findings, respectively [22].

A qualitative analysis performed by Hänninen et al. [19] in a group of 17 welders (without the control group) showed in EEG findings the presence of pathological changes in the form of slow theta and delta waves localized in the frontal area, which positively correlated with Al determinations in blood serum ($\bar{x}$ = 0.21 µmol/l). Similar localization of EEG changes was noted in our own studies.

Iregren et al. [23] assessing the results, visually and quantitatively, in three different groups of Al exposed workers (smelters, flake powder workers, welders) and in the control group did not find statistically significant differences.

An analysis of our own results demonstrated more frequent abnormalities in EEG recordings in the exposed subjects who reported sleepiness and vertigo. Having compared the Al exposure duration, cumulative exposure index, current exposure to $Al_2O_3$ in the ambient air at workposts, and U-Al with different types of pathological EEG changes, no statistically significant associations were found.

The absence of parallelism between EEG abnormalities and evaluation parameters of occupational exposure to Al, observed in our study, may suggest that the used method is more sensitive and thus more useful in the evaluation of occupational hazards.

A review of issues related to Al neurotoxicity indicate that occupational exposure to Al compounds induces adverse effects on functions of the nervous system. Mechanisms responsible for Al toxic effects has not as yet been fully elucidated, despite numerous attempts [24]. The presence of confounding factors, difficulties in exposure assessment, and possible combined exposure render it difficult to evaluate the effect of exposure on the nervous system condition [25].

The need to identify harmful effects of occupational exposure to Al and its compounds was highlighted during the 7th International Symposium on Neurobehavioral Methods and Effects in Occupational and Environmental Health (Stockholm, Sweden, 20–23 June, 1999).

## CONCLUSIONS

1. Neurological and electroencephalographic studies reveal that occupational exposure to Al present in the ambient air at workposts of smelters, founders and auxiliary workers, employed in the Al production with $Al_20_3$ concentrations, ranging between 0.13 and 1.95 mg/m$^3$ ($\bar{x}_a$ = 0.40; $\bar{x}_g$ = 0.35; SD – 0.29), does not induce organic lesions in the central or peripheral nervous system that could provide grounds for clinical diagnosis of encephalopathy or polyneuropathy, however, it is responsible for sub-clinical effects on the nervous system.

2. Functional disorders of the nervous system are pronounced in the form of a subjective syndrome consisted of headache, vertigo, increased emotional irritability, dysmnesia, concentration difficulties, sleep disturbance (insomnia and sleepiness), mood lability, anxiety and fear. Of these symptoms, headache and sleep disturbance

showed statistically significant association with duration of Al exposure and a cumulative exposure index, however, there were no relations with urine Al concentrations.

3. The presence of bioelectric disorders of cerebral functions in EEG recordings was found in 37.3% of Al-exposed workers. They occurred more frequently in the study group then in controls and exceeded population standard. Abnormalities in EEG assumed the form of generalized and paroxysmal changes. A comparison of Al exposure duration, cumulative exposure index, current exposure to $Al_2O_3$ in the ambient air at workposts and urine Al concentrations with different types of abnormalities in EEG recording did not reveal statistically significant associations.

4. It is recommended that neurological examination and EEG become a compulsory component of preventive examinations in Al-exposed workers.

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