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Original Article

Trace element status of populations living in areas with anthropogenic anomalies and methods of correction

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Abstract

The trace element composition of hair is an integral indicator that can be used to assess the state of an individual's health, after which an optimal diet can be selected. The trace element status of volunteers of the South Ural region of Russia was investigated to determine a means of correction. The upper limit of the permissible level of nickel was found in the hair of all age groups of volunteers. Most volunteers aged ≥30 years experienced a high load of heavy metals that included cadmium, lead, mercury, chromium, and trace amounts of iron and manganese alongside significant selenium and iodine deficiency. The average values of zinc and copper concentrations in the hair of volunteers of all age groups were found to be within the permissible levels but with aging the risk of developing trace element deficiency increased slightly.

Keywords: heavy metals, trace elements, ecology, elemental status, enriched foods

1. Introduction

The Ural region has historically been one of the centers of the Russian metallurgical industry and its capital, Chelyabinsk, is one of the largest producers of high-quality alloys, heat-resistant and stainless steels, and long and flat products. Chelyabinsk enterprises produce 43% of all Russian ferroalloys, over 60% of all zinc produced in the country, and 25% of pipe production (Zyryanov *et al.*, 2013). However, the concentration of metallurgical enterprises in the region has a number of negative aspects that are manifested by the sharp deterioration in environmental health (Gudim & Golubev, 2008). The formation of anthropogenic anomalies adversely affects human health; in particular, mineral metabolism is violated due to a change in the content and ratio of elements in the environment, drinking water, and food products (Dubovoi, 2009; Oberlis, Harland, & Skalny, 2008).

The primarily route of carcinogens into the human body for the populations of Magnitogorsk, Chelyabinsk, and Karabash was oral at 95.7%, 95.1%, and 92.4%, respectively. The percentages of oral intake via food products of xenobiotics for these 3 cities were 93.2%, 73.2%, and 83.0%, respectively, followed by drinking water at 2.9%, 20.1%, and 1.8%, respectively, and soil at 0.027%, 1.80%, and 7.55%, respectively. For the entire population of the Chelyabinsk region, chemical substances, which are pollutants of the highest class of danger, are of particular concern. For Magnitogorsk inhabitants, the leading substance among all carcinogens entering the body was arsenic (As) (82.6%) followed by lead (Pb) (6.69%), and cadmium (Cd) (6.36%). For the population of Chelyabinsk, the main contributions to multi-environment carcinogenic risk were As (81.4 %), hexavalent chromium (8.7%), and bromodichloromethane and carbon tetrachloride at 3.4% each. For Karabash residents, As (91.5%) that comes from local agricultural products was the main food carcinogen (Kurchanov, Lim, Voetsky, & Golovanin, 2015; Uralshin, Valeullina, & Brylina, 2012).

At present, the science of trace element deficiency is actively developing in medicine. Deviations in the content of chemical elements caused by environmental, professional, and climatogeographic factors that lead to a wide range of disorders in the state of health are being more carefully studied. At the same time, technogenic trace element

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deficiencies are becoming increasingly important (Avtsyn, Zhavoronkov, Rish, & Strochkova, 1991; Skalnaya, 2005). The elemental status of a person is reflected in the elemental composition of their hair, which is a kind of integral indicator used to map the prevalence of diseases of environmental etiology among a population. An assessment of the hair gives information on the adequacy of human nutrition which gives the basis for selection of an optimal diet (Skalnaya, 2005; Skalny *et al.,* 2014). The purpose of this research was to study and establish means of correcting the elemental status of individuals living in an anthropogenically anomalous area.

2. Materials and Methods

Concentrations of certain elements in various biosubstrates (hair, blood, saliva) are interrelated. However, the determination of these concentrations in the hair has several advantages. The content of all chemical elements in the hair is many times higher, which predetermines a higher accuracy of measurements and the method of obtaining the biosubstrate is the simplest, i.e. non-invasive (without traumatizing the patient while avoiding the risk of infection). The chemical composition of hair, compared with biological fluids of the human body, is less susceptible to fluctuations, which makes it possible to conduct retrospective analyzes at certain intervals. (Aghajanyan *et al.,* 2016; Dubovoi, 2009).

Hair samples were taken from 638 male volunteers who were original residents of Chelyabinsk. The number of subjects was selected in accordance with the related quotas for sex and age on the basis of statistical data provided by the State Statistics Committee of the Chelyabinsk region on socio-demographic characteristics of the city's population. All volunteers were divided into five age groups: (1) 18-29 years old (158 volunteers); (2) 30-39 years old (117 volunteers); (3) 40-49 years old (135 volunteers); (4) 50-59 years old (103 volunteers); and (5) over 60 years old (125 volunteers). The statistical error of the data did not exceed 5% (95% confidence level).

The hair was sheared off from 3-5 places from the occipital part of the head to the entire length in an amount not less than 0.1 g and placed in special bags and then in envelopes with identification records. The hair was initially treated with acetone for 10-15 min to remove surface contamination and grease. The hair was then washed three times with deionized water and held at 60 °C until air dry. Sample weights of ~0.05 g were mineralized in Teflon-lined vessels with 5 mL of nitric acid in a Multiwave 3000 microwave digestion system (Perkin Elmer/Anton Paar, Austria) using the following mode: 5 min rise in temperature to 200 °C, 5 min at 200 °C, and then cooling to 45 °C. The resultant solutions were quantitatively transferred to 15 mL polypropylene tubes. The Teflon-lined vessels and covers were washed three times with deionized water and the wash liquid was transferred to the appropriate test tubes. The solutions were then adjusted to a volume of 15 mL with deionized water and thoroughly mixed by shaking in closed tubes.

The elemental composition for each sample was analyzed using mass spectrometry and atomic emission spectrometry with inductively-coupled argon plasma using the Optima 2000 (Perkin Elmer, USA) and ICAP-9000 (Thermo Jarrell Ash Corporation, USA). The instruments were calibrated using Perkin Elmer mono-element standard solutions.

A certified standard human hair sample manufactured by the Shanghai Institute of Applied Physics, Chinese Academy of Sciences (Shanghai Institute of Nuclear Research, Academia Sinica, China, PO Box 8204, Shanghai 201849) was used as a standard sample.

The results of our own studies on the content of chemical elements in the hair were compared with the percentile intervals (25-75) obtained from population studies conducted in various regions of Russia (Skalny, 2003; Skalny *et al.,* 2014), which was taken as the norm. In some cases, P. Bertram reference values (1992) were also taken into account.

3. Results and Discussion

3.1 Study of the content of toxic elements in hair

In studying the elemental composition of hair, the upper limit of the permissible level of Ni was exceeded by 32.0-38.0% in all age groups (Table 1). In this case, Ni acts as a toxicant, leading to excess Ni in every second (third) subject, especially in the 1st age group (Table 2). On the other hand, a small number of subjects in the 18-29 age group was deficient in this element.

It was established that, from the age of 30, most subjects experienced an excess of toxic elements such as Cd and Pb. With age, the risk of developing an excess of these elements increases significantly. The established excess of Cd and Pb, primarily, is due to the impact of emissions from the enterprises of the metallurgical complex and heavy machinery located on the territory of the city that included OAO Mechel,

Table 1. Content of essential and toxic elements in the hair samples of volunteers by age group.

Element	Values of 25-75 percentile intervals	Age group (years)				
		18-29 (n=158)	30-39 (n=117)	40-49 (n=135)	50-59 (n=103)	≥60 (n=125)
Cr	0.32-0.96	0.65±0.02	0.82±0.03	0.84±0.01	0.85±0.02	0.85±0.02
Ni	0.14-0.53	0.71±0.03	0.70±0.03	0.72±0.05	0.72±0.05	0.73±0.03
As	0.00-0.56	0.05±0.002	0.08±0.004	0.08±0.002	0.08±0.002	0.08±0.002
Cd	0.02-0.12	0.07±0.002	0.13±0.004	0.17±0.002	0.22±0.003	0.25±0.002
Pb	0.38-1.40	0.75±0.05	1.85±0.10	2.23±0.2	2.36±0.2	2.39±0.2
Hg	0.05-2.00*	0.21±0.01	0.72±0.05	0.77±0.05	0.81±0.05	0.83±0.05

Data are presented as mg/kg.
Note: * - reference values

Table 2. Risk of developing trace element deficiency or excess among volunteers by age group.

Element	Age group (years)				
	18-29 (n=158)	30-39 (n=117)	40-49 (n=135)	50-59 (n=103)	≥60 (n=125)
Percentage of individuals with a relatively reduced element content					
Cr	15.8	6.8	6.7	5.8	5.6
Ni	1.9	3.4	5.9	8.7	9.6
As	-	-	-	-	-
Cd	33.5	15.4	13.3	11.7	9.6
Pb	41.8	17.1	15.6	14.6	12.0
Hg	4.4	-	0.7	1.9	1.6
Percentage of individuals with a relatively increased element content					
Cr	11.4	23.9	23.0	24.3	24.8
Ni	43.0	35.9	34.1	32.0	32.0
As	-	-	-	1.9	1.6
Cd	8.2	16.2	22.2	29.1	33.6
Pb	9.5	35.9	37.0	38.8	42.4
Hg	-	6.8	7.4	7.8	8.0

OAO Chelyabinsk Metallurgical Plant, OAO Chelyabinsk Electrode Plant, OAO Stankomash, OAO Electromashina, and others.

Cd levels exceeded the upper permissible level in a wide range from 8.0 to 108.0% which depended on age. The risk of developing Cd excess increased with age with every sixth subject in the 2nd age group and every third subject in the 5th age group. The metabolism of Cd is characterized by a long-term presence in the body and a long half-life period of 13-30 years in humans. Cd affects carbohydrate metabolism causing hyperglycemia due to inhibited synthesis of glycogen in the liver (Bazhenova *et al.*, 1990; Järup, 2003), and blocks the synthesis of vitamin D (Agarwal, 2009). Cadmium chloride has embryotoxic, mutagenic, and specific gonadotoxic effects (Ermishkin, 2004). The risk of developing Cd deficiency was found to be characteristic of adolescence. It was detected in the first age group (every third subject) with the risk decreasing 2-3 times with age.

Pb levels exceeded the upper permissible limit by 32.0-70.0% which depended on age. The risk of developing Pb excess was higher and occurred in every third volunteer in the early years of the second age group. Pb compounds are easily absorbed. Absorption of soluble Pb compounds occurs through the digestive tract. Other forms of this element can penetrate through the skin and wounds. In elevated concentrations, Pb affects the hemopoietic organs, nervous system, and kidneys. Pb also disrupts protein synthesis and causes changes in the endocrine, cardiovascular, and reproductive systems (Nezhdanova, 1998; Shepotko *et al.*, 1993). The risk of developing Pb deficiency is highest in the 1st age group at 41.8% and decreases by 2.5-3.5 times as the subjects grow older.

Although the average concentrations of mercury (Hg) and chromium (Cr) were established to be within the acceptable levels for all age groups, volunteers older than 30 were found to be at increased risk of developing toxic effects from these elements. In the second age group and subsequent groups, the risk of developing Hg excess appeared at 6.8-8.0% and remained at this level. The risk of developing Cr excess (11.4-23.9%), which also remained relatively stable over subsequent periods of life, increased almost 2-fold. The risk of developing Hg and Cr deficiency was also relatively high in the 1st age group at 4.4% and 15.8%, respectively.

However, throughout the length of the study, As content was consistently low. The risks of developing As excess was only found in single cases in individuals of pre-retirement and retirement ages. The risk of developing As deficiency was not identified in any of the studied age groups.

3.2 Study of trace element composition of hair

Experimental and clinical studies have confirmed that deficiency or excess of certain trace elements can contribute to increased frequency of malignant neoplasms, lymphoproliferative diseases, infectious pathology, autoimmune and degenerative diseases, and congenital anomalies (Chappius, Aral, & Celeballos-Picot, 1998; Dorman, Struve, & Vitarella, 2000; Gerber, Leonard, & Hantson, 2002; Gulson, Yui, & Howarth, 1998; Kanojia, Junaid, & Murthy, 1996; Negretti de Bratter, 1999; Prasad, 1995; Vincetti, Rovesti, & Bergomi, 2001).

Levels of trace elements iron (Fe) and manganese (Mn) that exceeded the permissible levels were found in all age groups (Table 3). However, at different periods of human life, the concentrations of these elements underwent fluctuations. Fe content was higher than the "norm" by 20.8% in the 1st age group and 67.1% in the 5th age group. The change in Mn content also differed. It was 50.4% above the norm in the 1st age group but within the norm in the 5th age group. An excess level of Mn is one of the factors leading to the appearance of respiratory, circulatory, ocular, and musculoskeletal disease due to reduced calcium absorption. The leading cause of excess Mn is consumption of dust and vapors that contain Mn compounds used in steelmaking and electrical engineering. With a moderate, regular excess of Fe in the diet, Fe accumulates in the liver cells, followed by deposition in the form of a colloidal form of iron oxide, i.e. hemosiderin, which is harmful to the body. It also accumulates in the cells of the heart and pancreas which leads to tissue damage and impaired physiological function of the affected

Table 3. Content of trace elements in the hair samples of volunteers by age group.

Element	Values of 25-75 percentile intervals	Age group (years)				
		18-29 (n=158)	30-39 (n=117)	40-49 (n=135)	50-59 (n=103)	≥60 (n=125)
Fe	11.0-24.0	29.0±0.5	36.2±0.2	38.1±0.3	39.8±0.1	40.1±0.2
Zn	155.0-206.0	175.3±3.2	170.3±3.1	166.2±2.2	160.7±2.5	158.5±2.3
Cu	9.0-14.0	12.3±0.5	11.2±0.5	10.9±0.4	10.7±0.4	10.6±0.3
I	0.27-4.20*	1.8±0.2	1.0±0.2	1.4±0.3	1.7±0.2	1.9±0.2
Se	0.69-2.20	0.20±0.01	0.17±0.02	0.21±0.02	0.25±0.01	0.22±0.02
Mn	0.32-1.13	1.7±0.2	1.5±0.1	1.3±0.2	1.2±0.1	1.1±0.1
Co	0.040-0.160	0.041±0.003	0.038±0.003	0.067±0.002	0.075±0.001	0.077±0.002

Data are presented as mg/kg.
Note: * reference values

organs. Excess Fe greatly impairs the absorption of phosphorus and copper (Oberlis, Harland, & Skalny, 2008). As a consequence, we established the insignificant risk of developing a deficiency in Fe (10.1-12.8%, depending on age) and Mn (5.7-12.0%, depending on age) (Table 4) and the high probability of developing excess levels of Fe (51.3-54.4% in age groups 2 and older) and Mn (41.1-28.0% in all age groups).

The levels of Co in the biological samples of the 1st and 2nd age groups were within the lower limit of the permissible level, but an increased level of this trace element was visible beginning from the 3rd age group. However, the levels did not exceed the upper limit of the permissible level. The risk of developing Co deficiency rose from 10.8% to 16.0% with age, while the risk of Co excess, on the contrary, decreased from 13.3% to 6.4%.

Although the average values of zinc (Zn) and copper (Cu) levels were within the permissible levels, the risk of developing Zn and Cu deficiency increased with age (16.5-28.0% and 10.8-15.2%, respectively). The risk of developing excess levels of Zn and Cu decreased slightly throughout the study period from 12.7% to 8.0% and from 15.2% to 12.0%, respectively.

An absolute majority of the volunteers were found to have a deficiency in selenium (Se). Depending on the age, the content of this trace element was below the lower limit of the acceptable level by 29.0-32.0%. The possibility of developing Se deficiency during the study period was quite high at 93.2-96.2% (depending on age). Excess levels of Se were not found in the hair samples in any group.

The situation is similar for trace element iodine (I) in many respects. Although the mean values of I levels in the hair samples were within the normal levels in all age groups, the risk of developing a deficiency was quite high, especially in the youngest age group (58.9%), but decreased somewhat as the age of the individuals increased (41.6% in the 5th age group). The possibility of developing excess levels of I was found in a few individual cases.

Adverse changes in metabolism can lead to a decrease in immunity and antioxidant protection and disruption of hematopoiesis and anabolic processes (Bashkin, Galiulin, Galiulina, & Kalinin, 2009). Clinical issues from Se deficiency include increased morbidity and death of young men from cardiac muscle disease (Keshan's disease), as well as the risk of developing neoplasms and musculoskeletal system disease. Endemic goiter and cretinism are almost impossible to prevent by adding iodine to the diet when selenium deficiency is present (Hu, Mcintosh, & Young, 2012; Reilly, 2006). Se has a protective effect on the human body in acute and chronic poisoning from Hg, Cd, and As. It protects the heart from the destructive action of heavy metals, has a pronounced antioxidant effect, stimulates the formation of antibodies, participates in the production of red blood cells, has a carcinostatic effect, and slows the aging process (Roman *et al.,* 2014; Williams & Harrison, 2010).

Reduced content of Zn in the hair is an indicator of unfavorable tendencies in liver function, regulation of lipid metabolism, reproductive function issues, inflammation of the mucous membranes of the mouth and nose, and the appearance of hemorrhages, which was confirmed by numerous studies (Bashkin *et al.,* 2009; Skalny, Maymulov, & Chernyakina, 2004).

Zn and Se deficiency reflects a tendency to have decreased immunity and a tendency to skin and prostate disease, including prostate cancer (Bashkin *et al.,* 2009; Skalny & Rudakov, 2003; Zhavoronkov, 1999).

As the "building block" of thyroid hormones, a lack of I is often the cause of many abnormalities, such as memory and attention impairment, loss of intelligence, atherosclerosis, resistance to medication, weakened immune system, and arrhythmia in which the use of special drugs does not give a tangible and lasting effect. For example, a decrease in the level of hemoglobin in the blood in which treatment with iron preparations gives only a modest result.

The observations we made on trace element levels can be explained by the fact that by the age of 30 most volunteers were working in enterprises in the metallurgical and heavy industry in Chelyabinsk. They were faced with harmful production factors and subjected to an increased load from the above-listed toxic elements. In addition, with aging, not only does the work experience increase, but the period of residence in the area, initially unfavorable in an ecological sense, aggravates the intoxication with chemical elements.

The extent of the spread of the Se and I deficiency among the volunteers and the relatively deficient state of Zn is likely to indicate a deficiency in the intake of these trace elements from food sources and is often the result of toxic levels of heavy metals, primarily Pb, Hg, and Cd, as well as Fe and Mn.

Table 4. Risk of trace element deficiencies and excess in volunteers by age group.

Element	Age group (years)				
	18-29 (n=158)	30-39 (n=117)	40-49 (n=135)	50-59 (n=103)	≥60 (n=125)
Percentage of individuals with a relatively reduced level of trace elements					
Fe	10.1	11.1	11.9	12.6	12.8
Zn	16.5	22.2	23.7	25.2	28.0
Cu	10.8	6.0	10.4	13.6	15.2
I	58.9	53.9	49.6	43.7	41.6
Se	96.2	95.7	94.2	93.2	93.6
Mn	5.7	7.7	9.6	11.6	12.0
Co	10.8	12.8	13.3	14.6	16.0
Percentage of individuals with a relatively increased level of trace elements					
Fe	27.8	51.3	51.8	53.4	54.4
Zn	12.7	13.7	9.6	7.8	8.0
Cu	15.2	9.4	10.4	11.7	12.0
I	2.5	3.4	5.9	6.8	7.2
Se	-	-	-	-	-
Mn	41.1	31.6	30.4	29.1	28.0
Co	13.3	12.8	8.2	6.8	6.4

4. Conclusions

It is important to enrich the diet of the residents of the Chelyabinsk region with Se to regulate the metabolism of the most common xenobiotics, i.e. As, Pb, and Cd. Therefore, a scientific basis exists for the inclusion of biologically active additives containing Se, or foods enriched with this trace element, in the diets of volunteers. In this connection, the Department of Food and Biotechnology of the Higher Medical and Biological School of the South Ural State University is carrying out a complex of research work on the development of formulas and technologies for the production of therapeutic food products enriched with Se involving both the monocomponent administration of Se and a complex one with I and Zn. One of the goals of these studies is to make these enriched products economically accessible for all segments of the population.

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