



## Results of Mathematical Modeling of the Microelement Composition of the Body and Women's Reproductive Health

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(Received: 25 November 2025    Revised: 27 December 2025    Accepted: 01 January 2026)

### KEYWORDS

petal diagrams of statistical indicators, reliability of differences in indicators, Student's criterion, cluster statistical analysis, reproductive potential, biogeochemical provinces, factors of reproductive health, trace element analysis.

### ABSTRACT:

**Introduction** Biogeochemical zoning of the Chuvash Republic's territory has established the negative influence of trace element composition on the population's health status. Mathematical modeling has not previously been used to investigate the impact of trace element status on health development and obstetric outcomes.

**Objectives:** To develop a methodological approach for software-integrated representation of mathematical modeling results regarding trace element composition in women of reproductive age within the region, and to evaluate the statistical significance of differences in their indicators.

**Methods:** The trace element composition of hair samples was examined in women of reproductive age residing in the Chuvash Republic using atomic emission spectroscopy and mass spectrometry methods: Group I (n=58) comprised women with diagnosed iron deficiency anemia and a history of pregnancy; Group II (n=61) included women with trace element deficiency in the body without obstetric history; Group III (n=64) consisted of healthy women as controls. A methodology for software-integrated representation of mathematical modeling results regarding health status was developed. The Student's t-test was calculated and visualized in spiral space determined by binary code parameters. The following binary code parameters were computed: n (code digit length), t (error multiplicity of code vectors), d-min (Hamming distance between code vectors), k (number of vectors), coefficients C1 and C2, and C-total (cumulative coefficient).

**Results:** In parturient women residing in the Alatyrdistrict, iron deficiency leads to chronic fetal hypoxia and intrauterine growth restriction, placental insufficiency, and dental lesions. In the Poretsk district, particularly in Poretsk-3 (with a deficiency of 10 trace elements) and Poretsk-2 (with a deficiency of 7 trace elements and an excess of selenium), parturient women were found to have a high risk of developing chronic fetal hypoxia, chorioamnionitis, preeclampsia, and dental enamel disorders.

**Conclusions:** In women from the five examined biogeochemical provinces (Alatyrdistrict-1:  $t=-5.102$ ; Poretsk-1:  $t=3.19$ ; Poretsk-2:  $t=6.099$ ; Poretsk-3:  $t=3.15$ ; Cheboksary-1:  $t=3.308$ ; Cheboksary-2:  $t=-4.019$ ), the Student's t-test values were high, indicating an elevated risk of developing diseases and complications during obstetric. Mathematical modeling of the transformation, represented as binary code vectors with parameters n, t, k, d min, C1, C2, and C-total, enables the construction of a stability zone for these adverse processes.

### 1. Introduction

The trace element status of the human body depends on the biogeochemical composition of the region [1-2].

Mathematical methods and models from various fields of natural and engineering sciences are applied in biomedical research. The methodology employs a suite of mathematical tools, including neural network



algorithms, elements of discrete mathematics and Boolean algebra, as well as methods from probability theory and mathematical statistics [3-11].

The utilization of new mathematical modeling methods enables the development of novel analytical standards for research groups, facilitates their comparison based on new qualitative characteristics, and reveals the differences and dynamics of their change.

This is particularly relevant given the continuous transformation of epidemiological indicators and pandemic trajectory. Dynamic models are required, incorporating updated temporal snapshots of indicators and registration of disease stabilization dynamics.

The rise in mortality rates for various disease entities is driven by a set of distinct patterns and is supported by statistical and experimental research data [4, 5, 7], including findings from neural network models [6].

Researchers studying hereditary diseases often apply functional analysis and differential equations to model cyclical biological processes [11].

Mathematical modeling is used in molecular biology to study organismal and system development, as well as to analyze life cycles [8, 12].

Specific applications include research on circadian rhythm disruptions [10] and wound regeneration [9].

Furthermore, studies have been conducted to analyze dynamic models of trace element interactions in the human body. These studies also explored managing the competition between these trace elements using decision support information systems [3].

No studies were found that used mathematical modeling to assess the levels of chemical elements and their impact on the development of reproductive health complications.

## 2. Objectives

To develop a methodological approach to comprehensive software visualization of mathematical modeling results regarding trace-element composition in the bodies of women of reproductive age within the region, and to conduct an assessment of the statistical significance of differences in indicators.

## 3. Methods

An analysis was conducted on the influence of trace-element composition in the organism of the population, specifically iron-deficiency anemia, on the course of pregnancy and childbirth in conditions of stable established biogeochemical provinces in the Chuvash Republic.

A multifactorial comparison of groups of women with trace-element deficiency was performed: Group I comprised women with a history of pregnancy, and Group II comprised women without a history of pregnancy.

The first investigated group included 58 women of reproductive age with diagnosed iron-deficiency anemia, observed in inpatient conditions in perinatal centers and maternity hospitals. Based on specific types of pregnancy resolution, the territories of Alatyr and Poretskoye districts and the city of Cheboksary were identified. Simultaneously, trace-element composition in the organism was determined, specifically iron deficiency.

The second group consisted of women with trace-element deficiency in the organism who had no history of pregnancy (n=61). The third research group on trace-element composition of hair comprised 64 healthy women residing in the territories of Alatyr and Poretskoye districts and in the city of Cheboksary.

Analysis of 15 chemical elements (see Table 1) was performed in the laboratory of the Autonomous Non-Profit Organization "Center for Biotic Medicine" (Moscow), accredited with the Federal Center of State Sanitary and Epidemiological Surveillance of the Ministry of Health of the Russian Federation (MH RF), using Optima 2000 DV spectrometers (Perkin-Elmer, USA) and ELAN9000 (Perkin-Elmer, USA) according to standard methodology of atomic emission and mass spectrometry with inductively coupled plasma in accordance with methodological guidelines MUK 4.1.1482-03, 4.1.1483-03.

A model was developed for representing the distribution of the t-criterion and its visualization in the space of spirals defined by binary code. Binary code parameters were utilized: n—code digit length, t—error multiplicity of code vectors, d min—distance between code vectors, k—number of vectors. Since spirals are represented



geometrically by linear equations with coefficients  $C_1$  and  $C_2$ , the product of these coefficients, designated as C-total, corresponds to the stability zone of the spiral. Values of C-total obtained for each pair of compared groups were plotted on a radar chart. The distribution of Student's t-test is described by an expression containing a gamma function, which was calculated using the numerical Runge-Kutta method.

#### 4. Results

Trace element composition in scalp hair was quantified via inductively coupled plasma mass spectrometry (ICP-MS) in 64 healthy women of reproductive age from Alatyrsky and Poretskiy districts and Cheboksary city, Chuvash Republic. Fifteen elements were analyzed (Table 1); measurement errors were accounted for per column 1 specifications.

**Table 1: Hair Trace Element Reference Intervals and Precision, Chuvash Republic (mg/kg, Mean  $\pm$  SEM)**

№	Element	M $\pm$ m	Normal range (25th–75th percentiles)
1	Ca	771 $\pm$ 44,5	254 – 611
2	Cd	0,01 $\pm$ 0,003	0,03 – 0,18
3	Co	0,04 $\pm$ 0,002	0,02 – 0,11
4	Cr	0,17 $\pm$ 0,007	0,26 – 0,7
5	Cu	9,62 $\pm$ 4,36	8 – 12
6	Fe	25,18 $\pm$ 4,36	13 – 27
7	I	1,03 $\pm$ 0,43	0,42 – 2,7*
8	K	93,02 $\pm$ 72,6	53 – 663
9	Mg	97,2 $\pm$ 8,5	18 – 56
10	Mn	1,7 $\pm$ 0,13	0,32 – 0,93
11	Na	560,23 $\pm$ 17,4	75 – 562
12	Se	0,26 $\pm$ 0,021	0,65 – 2,43
13	Si	27,37 $\pm$ 1,26	10 – 27
14	V	0,03 $\pm$ 0,009	0,005 – 0,5*
15	Zn	152 $\pm$ 4,3	94 – 183

Note: M - arithmetic mean; m - standard error of the mean (SEM);

\*conditionally permissible biological level.

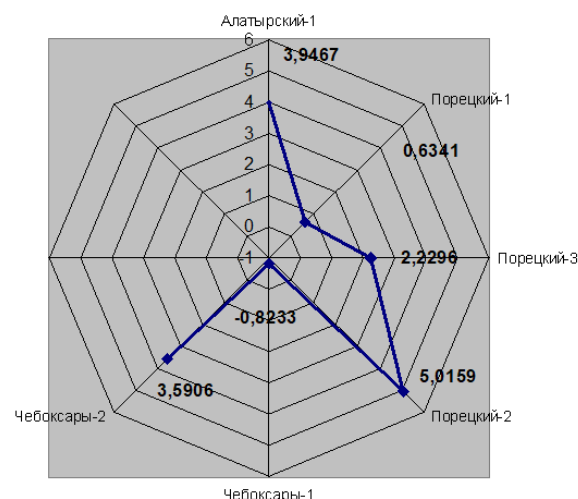
Mathematical modeling of trace element status in Cheboksary and Alatyrsky/Poretskiy districts identified six cohorts (Table 2) of parturient women from three biogeochemical provinces, differentiated by trace element deficiency profiles and risk weights impacting reproductive outcomes. These cohorts demonstrated universal iron deficiency, iodine/sodium deficiency (5/6 groups each), cobalt deficiency (4/6), potassium/copper deficiency (3/6), chromium/silicon/manganese deficiency (2/6), plus isolated

calcium/vanadium/magnesium (Poretskiy-3) and zinc (Poretskiy-2) deficiencies.

**Table 2: Iron deficiency was quantified in hair samples from parturients (Study Group 1) versus age-matched controls (Group 2) across six cohorts from three biogeochemical provinces, assessing active trace element imbalance risk factor**

№	Region Name, reg	Indicator 1st, Iron Deficiency in Group 1, studied pok1, mg/kg	Weight, com1	Indicator Weight Error, $\pm$ eps1	Indicator 2nd, Iron Deficiency in Group 2, studied pok2, mg/kg	Weight, com2	Indicator Weight Error, $\pm$ eps2
1	Alatyrsky-1	7,1	4,1207	0,21415	7,67	5,9866	0,29641
2	Poretskiy-1	7,1	4,1207	0,21415	4,03	3,1455	0,21808
3	Poretskiy-3	7,9	4,585	0,22535	4,57	3,567	0,23172
4	Poretskiy-2	7,5	4,3529	0,21984	3,27	2,5523	0,19704
5	Cheboksary-1	8,1	4,7011	0,22804	4,64	3,6216	0,23342
6	Cheboksary-2	8,3	4,8172	0,2307	8,14	6,3534	0,30476

Mathematical modeling (Table 2) of trace element status impact, particularly iron deficiency anemia, on labor progression and reproductive outcomes across established biogeochemical provinces of the Chuvash Republic yielded a radar plot (Figure 1) visualizing effect size patterns.



**Figure 1: A map of metrically measured interactions (based on the t criterion) in characteristic**



**biogeochemical provinces of the Chuvash Republic, where a deficiency of trace elements is observed among women of reproductive age — namely, in three selected biogeochemical provinces of Chuvashia with an active influence of risk factors associated with the deficiency of trace elements in the body**

In Cheboksary, among cohorts with deficiencies in iron, iodine, sodium, cobalt, copper, and silicon, post-term pregnancy, altered labor stereometry (particularly flat fetal membranes), enamel pathology, and caries were more frequently observed. In iodine-excess cohorts with concurrent deficiencies in iron, sodium, cobalt, and chromium, TORCH infection rates increased, elevating fetal malformation risks. Parturients exhibited varicose veins, low body weight, and placental insufficiency signs (FPI).

Data visualization was performed using specialized software, with certain computational procedures implemented in the FoxPro programming language. Mathematical modeling results (Table 5), including representation and statistical significance assessment of intergroup differences, were obtained via MS Visual FoxPro environment.

Modeling outcomes encompassed t-statistic (Student's t-distribution) correlation significance testing and spiral coefficients (C<sub>1</sub>, C<sub>2</sub>, C-total) computed within a polar coordinate system.

**Table 3: Results obtained from the modeling program and from the calculation of the reliability of detecting correlation based on the Student's t distribution statistics and the spiral coefficients C<sub>1</sub>, C<sub>2</sub>, and the total coefficient C-total in a polar coordinate system**

No	Region Name, reg	Indicator 1	In %	Error of indicator 1	Indicator 2	In %	Error of indicator 3	t-criterion	P
1	Alatyrsky-1	7,1	4,1207	0,21415	7,67	5,9866	0,29641	-5,1	1,29
2	Poretsky-1	7,1	4,1207	0,21415	4,03	3,1455	0,21808	3,2	0,99
3	Poretsky-3	7,9	4,585	0,22535	4,57	3,567	0,23172	3,1	0,99
4	Poretsky-2	7,5	4,3529	0,21984	3,27	2,5523	0,19704	6,1	0,99
5	Cheboksary-1	8,1	4,7011	0,22804	4,64	3,6216	0,23342	3,3	0,99
6	Cheboksary-2	8,3	4,8172	0,2307	8,14	6,3534	0,30476	-4,0	0,00

**Table 4: Continuation of Table 5 Calculation of the parameters of spacing and point density for construction — n, k, d-min.**

No	Region Name, reg	n	t	k	dmin	C1	C2
1	Alatyrsky-1	41	5	11	6	0,25	15,49
2	Poretsky-1	41	3	23	6	0,06	10,55
3	Poretsky-3	46	3	28	6	0,17	13,35
4	Poretsky-2	44	3	35	3	0,72	7
5	Cheboksary-1	47	3	29	6	-0,08	10,72
6	Cheboksary-2	48	4	24	6	0,27	13,53

In the Cheboksary-1 cohort—one of three biogeochemical regions—absent iodine (even excess) and potassium deficiency, unlike Poretskiy districts and Cheboksary-2, but with iron, sodium, cobalt, and chromium deficits, yielded a low negative effect size (-0.8233; Fig. 1) characterizing trace element deficiency impact on birth rates, labor progression, dental status, and caries. Progressive deficiency failed to enhance infection resistance or reproductive stabilization capacity.

Cheboksary-1 women exhibited pre-pregnancy iron depletion, further exacerbated during gestation due to physiological hemodilution and impaired erythropoiesis under iron-deficient conditions. In Cheboksary-1 cohort, pre-pregnancy iron depletion persisted dynamically from 4.64 to 8.1 µg/kg during gestation—remaining below normal range (13-27 µg/kg).

Other biogeochemical provinces exhibited positive effect sizes (Fig. 1), where worsening trace element deficiencies paradoxically enhanced infection resistance and reproductive stabilization capacity in parturients..

## 5. Discussion

During the course of the study, a model was developed to represent the dispersion of the t-statistic and to project it onto a space of spirals defined by a binary code. The following binary code parameters were used: n, the length of the code digit; t, the error multiplicity of the code vectors; d-min, the minimum distance between code vectors; and k, the number of vectors.



Since the spirals are described by geometric linear equations with coefficients  $C_1$  and  $C_2$ , the product of these coefficients, denoted as  $C$  total, is interpreted as the stability region of the corresponding spiral. The  $C$  total values obtained for each pair of groups under comparison are displayed on a radar chart (spider plot) in Figure 1, which enables a compact visualization of the multidimensional stability profiles.

This model was developed and implemented for the first time by the authors. Software was created for the automated calculation and visualization of radar charts, as well as for the computation and output of all tables associated with this method.

The advantages of this method, compared to other approaches, include digital data processing and the application of binary coding to model pathological processes in women of reproductive age residing in the Chuvash Republic across various eco-biogeochemical zones. Conventional static methods fail to reveal the structural characteristics of groups exhibiting micronutrient deficiencies in the selected female population.

The software component presented in this article forms a structural element of a comprehensive system designed for the automated analysis of any patient groups entered into the database, with registration of their micronutrient profiles, place of residence, and age. Within this program, databases of indicators are generated to enable comparison of their values using the Student's  $t$ -test. The Student's  $t$ -distribution is described by an expression involving the gamma function, which is computed numerically using the Runge-Kutta method.

The Runge-Kutta method is widely encountered in most medico-biological studies and is regarded as a classical approach in numerical analysis theory.

The software module described in this paper is an integral component of an automated system for the analysis of patient cohorts. The system registers individuals' trace element profiles, geographic location, and age, subsequently building databases for the statistical comparison of these parameters via Student's  $t$ -test. The  $t$ -distribution is implemented using an expression that incorporates the gamma function, the value of which is computed numerically via the classical

fourth-order Runge-Kutta method — a standard and reliable technique in computational biomedicine.

When comparing two groups of women from Cheboksary—with and without a history of childbirth — the  $C$ -total value was calculated and plotted on a radar chart. Spirals were fitted only to those  $t$ -statistics with absolute values exceeding 3, as such cases are conventionally considered statistically significant in comparative analyses of two indicators. Accordingly, the  $p$ -value for significance was computed for each pair of groups; in the Cheboksary-1 and Cheboksary-2 groups, high  $t$ -values indicated substantial differences between the compared indicators ( $t=3.3$ ;  $t=4.2$ ).

Certain regions of Russia are recognized as high-risk areas for micronutrient deficiencies. Vorobiev D.V. (2011) examined the dependence of blood selenium concentration on administration timing, while Bolodurina I.P. et al. (2010) conducted mathematical modeling using differential equations to analyze interdependencies among antagonist micronutrients, establishing mechanisms of elemental antagonism disproportions. Makhalkina V.V. (2009) applied logical expressions from discrete mathematics to model micronutrient disruptions induced by environmental factors, an approach synchronized with Yakolev A.A. (2022), who investigated the intensity function of pathologically altered target organs lacking restorative processes.

The binary representation employed in our modeling serves as a prototype for simulating physiological and pathological processes in the human body using binary vectors. Binary structures prove universally applicable in describing real biological processes across various domains of biology and medicine. In this study, the content of all micro- and macroelements was assessed in women, revealing the impact of their deficiencies on pregnancy and childbirth outcomes. Negative loadings on the radar chart highlight distinct micronutrient profiles in patients' hair and demonstrate the influence of micronutrients on vital processes

In patients, organism reactivity is altered due to varying metric limits specific to the region. This approach aligns with the work of Yakolev A.A. (2022), which investigates the intensity function of pathologically altered target organs lacking restorative processes. A limitation of Yakolev's (2022) predictions regarding



immune response and target organ reactivity lies in the absence of a comprehensive description of the anticipated epidemiological situation; our development facilitates evaluation of resilience to external adverse effects based on patients' permanent residence zones.

Data processing from the study yielded direct results identifying the proportion of problematic cases in obstetric care across groups exhibiting varying micronutrient profiles. The analysis produced a profile for this dynamic cross-section: the incidence of problematic cases alongside differences in micronutrient deficiencies among women of reproductive age diagnosed with iron-deficiency anemia residing in various districts of the republic.

Thus, a radar chart of loading profiles was generated, representing a map of metric interactions within characteristic biogeochemical provinces of the Chuvash Republic, where micronutrient deficiencies occur in women of reproductive age—specifically across three selected biogeochemical provinces of Chuvashia actively influenced by risk factors such as micronutrient deficits.

## 6. Conclusion

The novel approach developed in this study—metric and factor-cartographic mapping of risk factors associated with micronutrient deficiencies in women of reproductive age to the quantity and quality of problematic obstetric situations—enables assessment of the statistical significance of differences in these factors across study groups and modeling of their impact on documented cases of complications and risks during delivery, as well as fetal development in intrauterine and neonatal periods.

The article presents a model for selecting critical states of population reproductive potential in biogeochemical provinces when indicators deviate from norms by amounts exceeding half or more of the total variance of significant differences observed between parturient groups and healthy populations. Overall, the study introduces and implements, via programming, an algorithm for graphical monitoring of Chuvashia's reproductive potential status and evaluation of indicator differences based on multifactor cluster modeling.

Thus, a new software-integrated form of displaying mathematical modeling results has been developed for

representing Chuvashia's reproductive potential status and assessing the statistical significance of its indicator differences

## 7. Summary.

1. High t-statistics and significant differences between parous and nulliparous women with micronutrient deficiencies reflect pathologies in pregnancy and childbirth progression, including dental conditions and caries, across various biogeochemical provinces. These differences remain undetected when analyzing only aggregated statistical indicators from a unified dataset for the Chuvash Republic.
2. In women across five studied provinces (Alatyr-1  $t=-5.102$ ; Porotsky-1  $t=3.19$ ; Porotsky-2  $t=6.099$ ; Porotsky-3  $t=3.15$ ; Cheboksary-1  $t=3.308$ ; Cheboksary-2  $t=-4.019$ ), elevated t-statistics indicate high risk for disease development, including caries, as well as complications during pregnancy and delivery.
3. Transformation of study results into a metric spiral space enables construction of a radar chart marking loadings from the metric space center along various directions. Modeling this transformation as binary code vectors with parameters  $n$ ,  $t$ ,  $k$ ,  $d$ -min,  $C1$ ,  $C2$ , and  $C$ -total delineates the stability zone of these adverse processes.
4. The radar chart displays both negative and positive loading values, thereby identifying distinct patterns in the development of reproductive and dental pathologies among women.
5. A universal methodological approach has been created as a software-integrated representation of mathematical modeling results for dynamic processes, specifically depicting the health status and group structures of Chuvashia women, along with significance testing of differences in their indicators due to varying micronutrient compositions in women of reproductive age observed in hospitals, perinatal centers, and maternity homes.



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