Original Research

https://doi.org/10.36377/ET-0153

Features of pathological mechanisms of tooth damage in workers of chemical industries

Alexander V. Mitronin[1], Angelina M. Fulova[1]✉, Ilya A. Ivankov[2], Marina A. Dzhavakhyan[1], Alexey A. Prokopov[1,3]

[1] Russian University of Medicine, Moscow, Russian Federation

[2] Boarding School of the Russian Ministry of Foreign Affairs, Losino-Petrovsky, Moscow Region, Russian Federation

[3] Kurnakov Institute of General Inorganic Chemistry of the Russian Academy of Sciences, Moscow, Russian Federation

✉ angelina.fulova@mail.ru

Abstract

INTRODUCTION. Under conditions of increasing exposure to chemical factors that predispose individuals to the development of pathology, the processes of hard-tooth-tissue destruction undergo modification not only in terms of their kinetics but also through the direct incorporation of exogenous chemical agents. These circumstances inevitably affect the macro- and microelement composition of enamel, as well as dentin and cementum in cases of disease progression. Obtaining reliable information on elemental composition is crucial for choosing appropriate treatment strategies and substantiating preventive measures.

AIM. To perform X-ray fluorescence analysis of teeth from employees of chemical enterprises, assessing qualitative and quantitative changes in elemental composition associated with pathological processes.

MATERIALS AND METHODS. The dental status of 100 workers and engineering personnel involved in the production of biologically active substances, paint-and-coating materials, and metal products, all of whom had direct contact with inorganic and organic reagents, was assessed. The control group included teeth from 50 individuals working at the same enterprises but not exposed to occupational hazards. The chemical composition of tooth hard-tissue samples was determined using an M4 TORNADO (Bruker) X-ray fluorescence spectrometer. The MultiPoint mode was used. The software provides the content of each element relative to the total amount of detected elements, considering the entire spectrum as 100%. A relatively constant Ca/P ratio served as an additional reference point for discussing deviations from normal values.

RESULTS. The identified diseases in the affected zones were accompanied by atypical accumulations of trace elements detected via XRF spectra. In several employees of a metallurgical plant, high titanium content – up to 1.14 wt% of total elemental content – was found in areas of dental erosion. Titanium levels in adjacent intact enamel were significantly reduced, although trace amounts were still present. In patients with long-term employment at a paint, coating, and anti-corrosion materials enterprise, potassium content in deep carious lesions reached 12.64%, and most individuals also showed substantial levels of zinc, barium, iron, sulfur, chlorine, manganese, and copper. Among workers of an agrobiological enterprise without hot workshops or industrial dust – due to multistage air purification and sterilization – caries prevailed. In employees of a chemical-pharmaceutical production facility, no cases of caries were detected; only non-inflammatory conditions such as increased tooth wear and wedge-shaped defects were diagnosed.

CONCLUSIONS. XRF analysis demonstrated that enamel demineralization processes in workers of chemical industries are accompanied by qualitative and quantitative changes in trace-element profiles within pathological zones. Environmental exposure results in the isomorphic and isoinic incorporation of elements into apatite structures of hard tooth tissues and disrupts the natural kinetics of mineralization and demineralization. The intensity of trace-element accumulation in tooth tissues is directly related to the degree of industrial air purification. Treatment and prevention of dental disorders in these workers must account for industry-specific occupational factors.

Keywords: chemical industries, harmful occupational factors, X-ray fluorescence analysis, Ca/P ratio, occupational dental erosion, tooth mineral structure

Article info: received – 01.11.2025; revised – 24.12.2025; accepted – 15.01.2026

Conflict of interest: The authors report no conflict of interest.

Acknowledgements: There are no funding and individual acknowledgments to declare.

For citation: Mitronin A.V., Fulova A.M., Ivankov I.A., Dzhavakhyan M.A., Prokopov A.A. Features of pathological mechanisms of tooth damage in workers of chemical industries. *Endodontics Today.* 2026;24(1):6–16. https://doi.org/10.36377/ET-0153

Особенности механизмов патологии зубов у сотрудников химических предприятий

А.В. Митронин[1], А.М. Фулова[1]✉, И.А. Иваньков[2], М.А. Джавахян[1], А.А. Прокопов[1,3]

[1] Российский университет медицины, г. Москва, Российская Федерация

[2] Средняя школа-интернат Министерства иностранных дел Российской Федерации, Московская обл., Российская Федерация

[3] Институт общей и неорганической химии им. Н.С. Курнакова РАН, г. Москва, Российская Федерация

✉ angelina.fulova@mail.ru

Резюме

ВВЕДЕНИЕ. В условиях усиления влияния химического фактора, предрасполагающего к возникновению патологии, происходит модификация процессов деструкции твердых тканей зубов и в плане изменения их кинетики, и прямого включения в них экзогенных химических агентов. Эти обстоятельства не могут не влиять на макро- и микроэлементный состав не только эмали, но и дентина, и цемента в случае усугубления заболевания. Получение достоверной информации по составу элементов имеет существенное значение для выбора правильной тактики лечения и обоснования профилактических мер.

ЦЕЛЬ. Провести рентгенофлуоресцентный анализ твердых тканей зубов сотрудников химических предприятий, с оценкой качественных и количественных изменений элементного состава, сопровождающих развитие патологии.

МАТЕРИАЛЫ И МЕТОДЫ. Был определен стоматологический статус 100 рабочих и инженерно-технических работников, занятых в производстве биологически активных веществ, лакокрасочных материалов, металлопродукции, имевших непосредственный контакт с неорганическими и органическими реагентами. Контрольную группу составили зубы 50 человек, работавших на этих предприятиях в условиях отсутствия профессиональных вредностей. Химический состав образцов твердых тканей зуба определяли на рентгенофлуоресцентном спектрометре M4 TORNADO (Bruker). В ходе работы использовали режим MultiPoint. Программа показывает содержание данного элемента относительно суммы всех определяемых элементов, принимая весь полученный спектр за 100%. Ориентиром для обсуждения наблюдаемых отклонений содержания элементов от нормы служила, в том числе, относительно постоянная величина индекса Ca/P.

РЕЗУЛЬТАТЫ. Обнаруженные заболевания в зонах поражения зубов сопровождаются нетипичными накоплениями микроэлементов, которые зарегистрированы спектрами РФА. У ряда сотрудников металлургического завода, в области эрозии зубов отмечено высокое содержание титана, до 1,14 % по массе от общего содержания элементов. В составе интактной эмали, расположенной рядом с эрозией, содержание титана резко снижено, но все же он присутствует. У пациентов, длительное время проработавших на предприятии, производящем лакокрасочные и антикоррозионные материалы, содержание калия в зоне глубокого кариеса составило до 12,64 %, а также у большинства пациентов показано довольно существенное присутствие цинка, бария, железа, серы, хлора, марганца, меди. У обследованных работников агробиологического предприятия, на котором отсутствуют горячие цеха и в явном виде промышленная пыль, поскольку воздух в промзоне подвергается многоступенчатой очистке и стерилизации, в большей степени преобладает кариес. Среди обследованного персонала химико-фармацевтического производства практически не выявлено случаев кариеса, диагностированы заболевания невоспалительного характера, в основном повышенная стираемость и клиновидные дефекты зубов.

ВЫВОДЫ. Методом РФА установлено, что у сотрудников химических производств процессы деминерализации эмали зубов сопровождаются качественным и количественным изменением номенклатуры микроэлементов в зоне патологии. Воздействие элементов из окружающей среды состоит в их изоморфном и изоинном внедрении в апатитные структуры зубов и нарушении естественной кинетики процессов минерализации и деминерализации. Интенсивность накопления микроэлементов в твердых тканях зубов непосредственно связана со степенью очистки промышленного воздуха. Терапия и профилактика стоматологических проблем должна учитывать специфику производственной деятельности работников предприятий.

Ключевые слова: химические предприятия, вредный фактор, рентгенофлуоресцентный анализ, индекс Ca/P, профессиональная эрозия зубов, минеральная структура зуба

Информация о статье: поступила – 01.11.2025; исправлена – 24.12.2025; принята – 15.01.2026

Конфликт интересов: Авторы сообщают об отсутствии конфликта интересов.

Благодарности: Финансирование и индивидуальные благодарности для декларирования отсутствуют.

Для цитирования: Митронин А.В., Фулова А.М., Иваньков И.А., Джавахян М.А., Прокопов А.А. Особенности механизмов патологии зубов у сотрудников химических предприятий. *Эндодонтия Today.* 2026;24(1):6–16. https://doi.org/10.36377/ET-0153

INTRODUCTION

In numerous publications of recent years, the chemical, biochemical, and physical aspects of various dental diseases have been comprehensively addressed under both *in vitro* and *in vivo* conditions. These studies describe fundamentally different mechanisms of hard dental tissue destruction occurring as a result of microbial activity (dental caries) as well as widely prevalent non-carious dental disorders that are non-inflammatory in nature, primarily including dental erosion, wedge-shaped defects, and increased tooth wear [1–5].

An increased research focus has been placed on the clinical manifestations of dental diseases among workers exposed to hazardous occupational conditions, particularly those employed in chemical industries [6; 7], as they are subject to a significantly higher risk. It is evident that under conditions of enhanced chemical exposure predisposing to the development of pathology, the processes of hard dental tissue destruction are modified not only in terms of their kinetics but also through the direct involvement of exogenous chemical agents. These factors inevitably affect the macro- and microelemental composition not only of enamel but also of dentin and cementum in cases of disease progression.

Obtaining reliable information on elemental composition is of critical importance for the selection of appropriate therapeutic strategies and for substantiating preventive measures aimed at reducing the risk of dental damage among personnel involved in chemical raw material processing, organic or inorganic synthesis, or related analytical activities.

As has been repeatedly demonstrated [2; 4], the acquisition of accurate and statistically significant data on elemental content in hard dental tissues is optimally achieved using modern X-ray fluorescence spectrometers designed for direct analysis of solid surfaces. One of the key advantages of X-ray fluorescence analysis (XRF) is that the analyzed samples do not require complex sample preparation.

AIM

To perform X-ray fluorescence analysis of the hard dental tissues of employees of chemical enterprises, with an assessment of qualitative and quantitative changes in elemental composition accompanying the development of pathology.

MATERIALS AND METHODS

The study was conducted at the Departments of Therapeutic Dentistry and Endodontics, as well as General and Bioorganic Chemistry of the Russian University of Medicine (Ministry of Health of the Russian Federation), and in the laboratories of the N.S. Kurnakov Institute of General and Inorganic Chemistry of the Russian Academy of Sciences.

The dental status of 100 workers and engineering-technical personnel involved in the production of biologically active substances, paints and coatings, and metal products, who had direct contact with inorganic and organic reagents, was assessed. The control group consisted of teeth obtained from 50 individuals employed at the same enterprises under conditions without occupational hazards.

Teeth subjected to X-ray fluorescence analysis were, in all cases, extracted for periodontal or orthodontic indications. Only intact teeth without signs of prior dental treatment were used. The samples were cleaned of soft tissues, disinfected, and stored in distilled water at 4°C.

The chemical composition of hard dental tissue samples was determined using an M4 TORNADO X-ray fluorescence spectrometer (Bruker), a micro-XRF analyzer designed for non-destructive qualitative and quantitative material analysis. The method is based on the interaction of elements present in the sample with high-energy X-ray radiation, resulting in the emission of detectable secondary X-ray radiation (X-ray fluorescence) characteristic of each atomic species. The operating unit of the instrument is a rhodium fine-focus X-ray tube (maximum excitation voltage 50 kV, power 30 W, current 600 μA). Measurements were performed in the Multi-Point mode, allowing analysis at several points within a selected area of the enamel surface.

During the analysis, the X-ray beam was directed at a predetermined point on the sample surface, and elemental composition was determined for a spot with a diameter of 20 μm. The computer integrated into the instrument processed the data using specialized software and provided measurement results for the selected point as an average value over 100 pulses, presented as a spectrum of detected elements. The resulting spectrum was subsequently converted into a table of mass percentage ratios of the constituent elements in the analyzed area. The software reports the content of each element relative to the total sum of all detected elements, considering the entire spectrum as 100%. As is well known, X-ray fluorescence analysis does not allow sufficiently accurate determination of elements from the first two periods of the Periodic Table or sodium; however, this limitation did not impede the achievement of the study objectives.

The instrument was calibrated using a standard sample of calcium dihydrogen phosphate, $Ca(H_2PO_4)_2$, with respect to calcium and phosphorus content. The measurement accuracy was 0.01%. Statistical analysis of the obtained data was performed using a personal computer and the software package *Statistica 9.0*.

In discussing deviations of elemental content from normal values, reference was made, among other parameters, to the relatively constant Ca/P ratio. According to the literature, this ratio for enamel resistant to acid exposure ranges from 1.6 to 2.1 by mass. In the present study, the Ca/P ratio for enamel samples of healthy teeth from the control group ranged from 1.9 to 2.2.

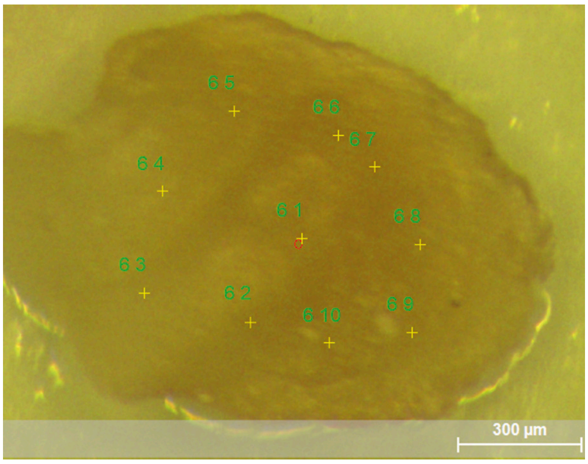
RESULTS

The detected diseases in the affected areas were accompanied by atypical accumulations of trace elements, as evidenced by X-ray fluorescence (XRF) spectra. Without addressing the pathways by which these elements enter the hard dental tissues (potentially via industrial air), which constitutes the subject of a separate investigation, it can be stated that an association was observed between elevated concentrations of specific elements or groups of elements and the type of dental pathology.

For example, in a number of employees of a metallurgical plant that utilizes zinc-, aluminum-, and other non-ferrous metal-containing alloys in its core operations, a high titanium content was detected in areas of dental erosion, reaching up to 1.14 wt% of the total elemental content registered in the spectrum. These observations were made in patients whose oral cavities contained no metallic restorations or prosthetic structures. As an illustration, Fig. 1 presents a fragment of one such tooth (Patient No. 1), together with the corresponding X-ray fluorescence spectrum and the numerical values of the relative elemental contents at the analyzed points.

Similarly elevated titanium concentrations were identified in erosion zones of teeth in a number of other patients from this enterprise. In Patient No. 2, multiple cervical non-carious lesions were diagnosed, including concurrent erosions and wedge-shaped defects, with a titanium mass fraction of 1.06%.

Of particular interest is the observation that in the intact enamel adjacent to the erosion (Patient No. 1), the titanium content was markedly reduced, yet still detectable, as evidenced by the data presented in Fig. 2.



Spectrum	Mass percent (%) P	S	Cl	K	Ca	Ti	Fe	Zn
6 10	5.50	0.26	0.40	0.96	91.67	0.62	0.22	0.37
6 9	5.61	0.13	0.27	0.85	91.09	1.59	0.15	0.32
6 8	5.84	0.15	0.47	0.65	90.54	1.93	0.05	0.36
6 7	6.54	0.17	0.46	0.69	89.89	1.84	0.20	0.22
6 6	6.11	0.21	0.38	1.07	89.52	2.06	0.22	0.44
6 5	6.86	0.28	0.50	0.72	89.56	1.63	0.13	0.31
6 4	6.74	0.11	0.24	0.51	90.91	0.98	0.13	0.38
6 3	6.09	0.16	0.33	0.52	92.17	0.12	0.31	0.29
6 2	6.26	0.15	0.30	0.73	91.96	0.04	0.23	0.33
6 1	6.49	0.29	0.48	0.58	91.19	0.57	0.12	0.28
Mean value:	6.21	0.19	0.38	0.73	90.85	1.14	0.18	0.33
Sigma:	0.46	0.06	0.09	0.18	0.96	0.76	0.07	0.06
Sigma mean:	0.15	0.02	0.03	0.06	0.30	0.24	0.02	0.02

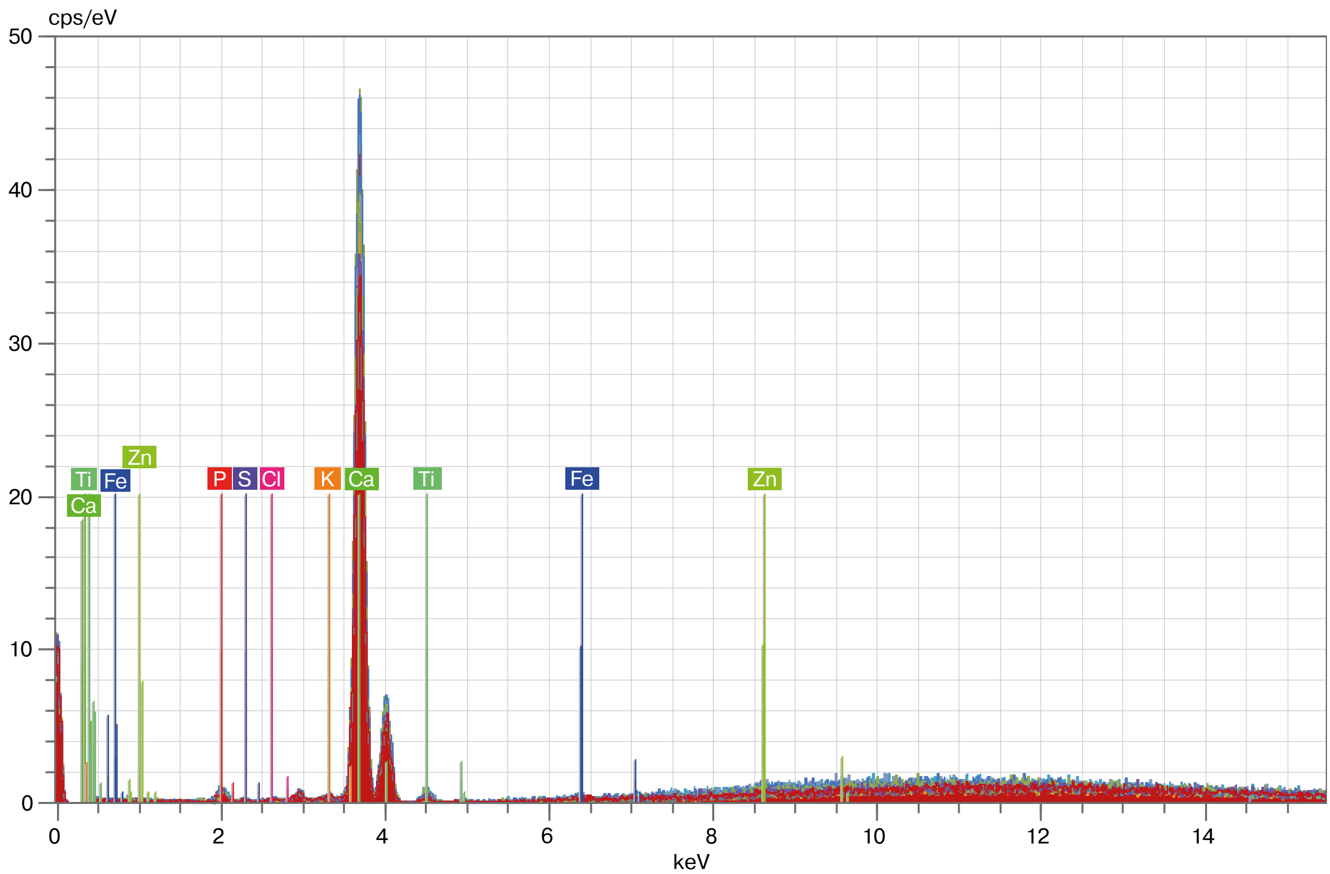
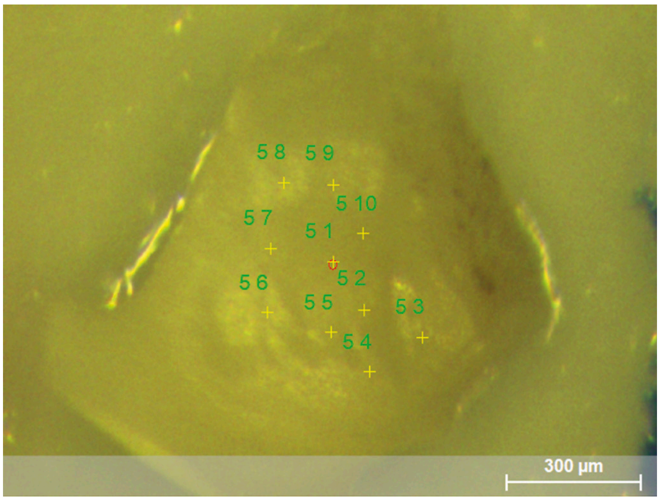


Fig. 1. Data on the analysis of the tooth erosion site of patient No. 1 (XRF, MultiPoint mode)

Рис. 1. Данные по анализу участка эрозии зуба пациентки № 1, (РФА, режим MultiPoint)

Notably, a high potassium content, reaching up to 1.86% in the affected areas, was observed; in some cases, though not consistently, this was associated with elevated titanium levels. Data reported by researchers from different laboratories regarding potassium content in healthy enamel are contradictory, although potassium is consistently regarded as a trace element. Our previous results obtained using laser mass spectrometry [8] demonstrated that the potassium mass fraction in intact enamel does not exceed 0.1% and is usually considerably lower.

In Patient No. 3, who had been employed for an extended period at an enterprise producing paints, coatings, and anticorrosive materials, the potassium content in the area of deep caries reached 12.64%, as shown in Fig. 3. In the same region, a substantial presence of zinc, barium, iron, sulfur, chlorine, manganese, and copper was also detected. Manganese accompanied by a similar spectrum of associated trace elements was identified in another employee of the same enterprise, who presented not with caries but with dental erosion.



Spectrum	Mass percent (%) P	Ca	Ti	Zn	Sr
5 10	8.30	90.86	0.26	0.13	0.46
5 9	7.73	91.73	0.16	0.13	0.25
5 8	8.19	91.14	0.26	0.10	0.31
5 7	7.81	91.42	0.31	0.14	0.32
5 6	8.08	91.44	0.06	0.10	0.31
5 5	8.39	90.91	0.25	0.10	0.35
5 4	8.36	90.94	0.20	0.11	0.39
5 3	8.30	90.67	0.52	0.13	0.38
5 2	8.79	90.45	0.30	0.15	0.32
5 1	8.03	91.29	0.27	0.12	0.29
Mean value:	8.20	91.09	0.26	0.12	0.34
Sigma:	0.31	0.39	0.12	0.02	0.06
Sigma mean:	0.10	0.12	0.04	0.01	0.02

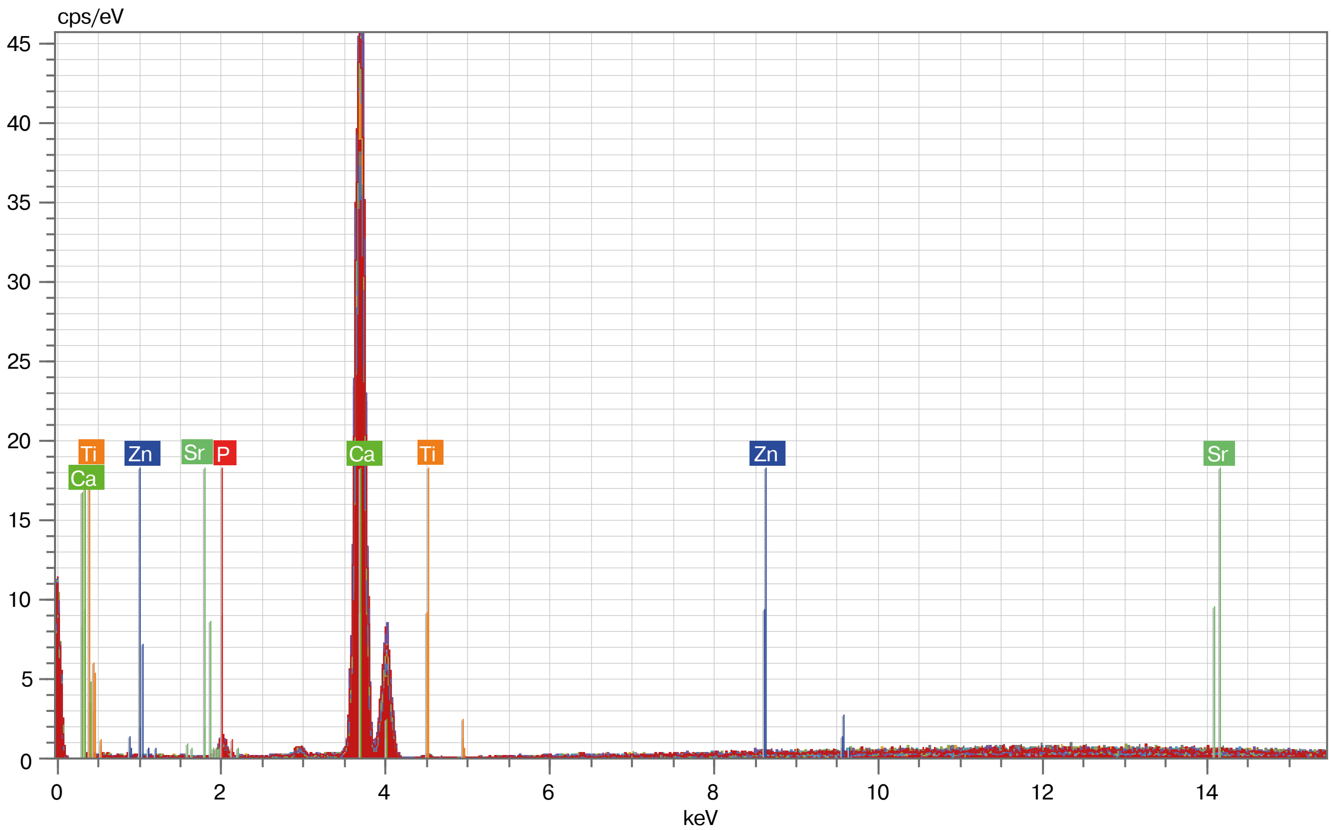
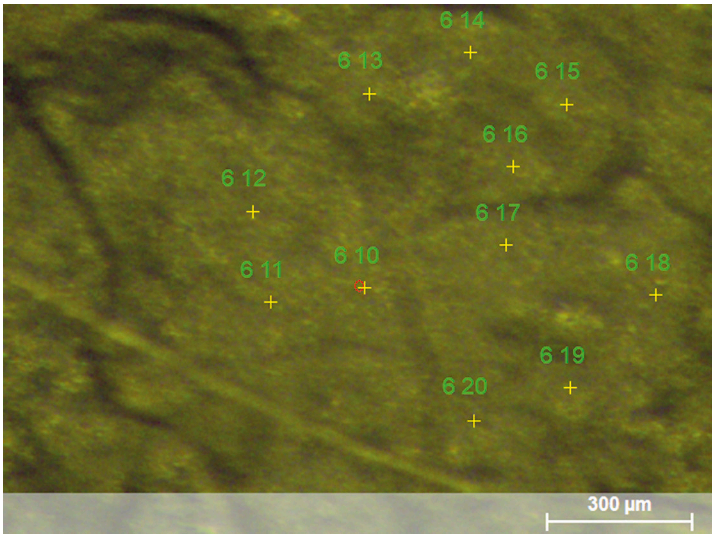


Fig. 2. Data on the analysis of an intact enamel area near the erosion of tooth in patient No. 1, (XRF, MultiPoint mode)

Рис. 2. Данные по анализу участка интактной эмали рядом с эрозией зуба пациентки № 1, (РФА, режим MultiPoint)



Mass percent (%)

Spectrum	P	S	Cl	K	Ca	Ti	Mn	Fe	Cu	Zn	Sr	Ba
6 20	4.07	1.36	1.89	11.86	75.61	0.01	0.25	0.85	0.43	2.22	0.56	0.88
6 19	3.91	1.16	1.93	12.06	76.61	0.00	0.25	0.77	0.45	1.68	0.37	0.80
6 18	3.99	1.42	1.95	9.96	78.92	0.00	0.25	0.74	0.39	1.55	0.37	0.45
6 17	4.21	1.57	2.19	11.52	74.23	0.00	0.23	0.72	0.35	1.75	0.75	2.49
6 16	4.57	1.57	2.18	12.55	74.50	0.00	0.31	0.71	0.50	1.70	0.53	0.88
6 15	5.05	1.73	2.65	14.27	71.71	0.00	0.33	0.93	0.47	1.75	0.44	0.67
6 14	5.69	1.97	3.80	18.52	65.10	0.00	0.36	1.03	0.57	2.19	0.49	0.28
6 13	4.97	1.77	2.52	12.61	73.61	0.00	0.34	0.82	0.48	2.09	0.49	0.28
6 12	4.46	1.53	2.12	13.58	74.33	0.00	0.21	0.75	0.41	1.85	0.43	0.33
6 11	4.43	1.41	2.02	11.28	76.78	0.00	0.28	0.83	0.43	1.87	0.37	0.30
6 10	4.40	1.24	1.81	10.83	77.82	0.00	0.26	0.70	0.41	1.73	0.28	0.54
Mean value:	4.52	1.52	2.28	12.64	74.47	0.00	0.28	0.80	0.44	1.85	0.46	0.72
Sigma:	0.53	0.24	0.57	2.29	3.72	0.00	0.05	0.10	0.06	0.22	0.12	0.63
Sigma mean:	0.16	0.07	0.17	0.69	1.12	0.00	0.01	0.03	0.02	0.07	0.04	0.19

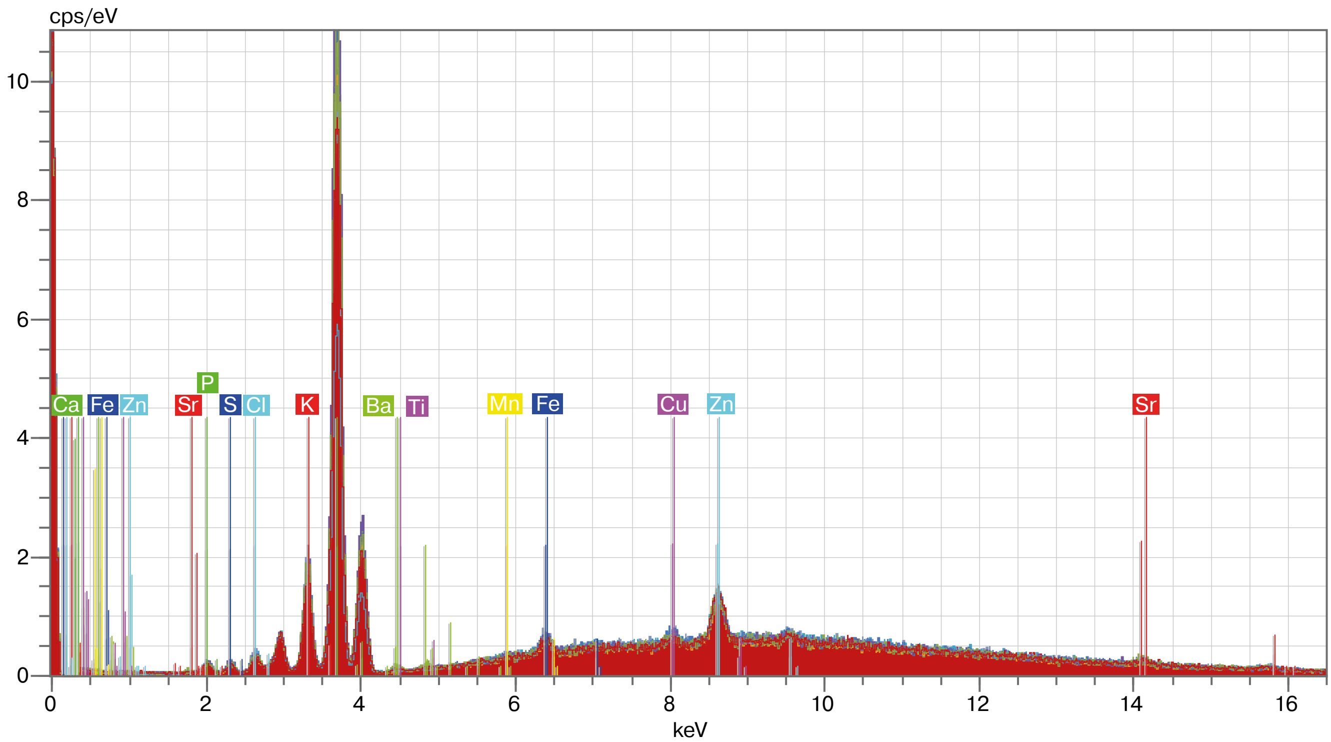
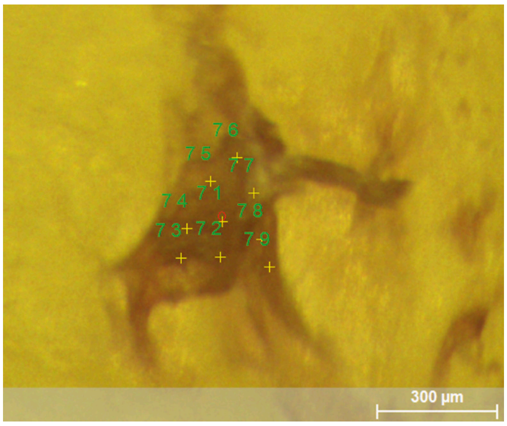


Fig. 3. Data on the analysis of the deep caries area of tooth No. 3, (XRF, MultiPoint mode)

Рис. 3. Данные по анализу участка глубокого кариеса зуба пациента № 3, (РФА, режим MultiPoint)

The nature of predominant negative changes in the oral cavity among the patient sample appears to be, to some extent, specific to each enterprise engaged in chemical production. Among the workers examined at an agrobiological facility – where there are no hot workshops and industrial dust is not present due to multistage air purification and sterilization in the production area – dental caries was the most prevalent condition. For example, Patient No. 4 exhibited pronounced light-brown pigmentation, with the corresponding spectral data presented in Fig. 4. The production processes at this enterprise involve various biological objects, nutrient media, and pharmacologically active compounds, which may explain the presence of a wide range of elements in the inflammatory focus, including chlorine, zinc, strontium, potassium, titanium, barium, iron, and sulfur.

By contrast, a more technologically advanced facility is the chemical-pharmaceutical plant operating under GMP requirements, which has implemented technical and technological solutions to purify workshop air and create clean zones where the accumulation of production dust, solvent vapors, and other volatile substances is minimized. Among the personnel examined at this facility, no cases of dental caries were detected; only non-inflammatory conditions were diagnosed, primarily increased tooth wear and wedge-shaped defects. Moreover, as shown in Fig. 5, Patient No. 5, employed at this enterprise, exhibited a relatively limited spectrum of detectable trace elements at low concentrations (iron, nickel, zinc), while the content of other elements was, apparently, below the instrument's detection threshold.



Spectrum	P	S	Cl	K	Ca	Ti	Fe	Zn	Sr	Ba
					Mass percent (%)					
7 9	3.13	0.90	0.84	1.75	91.99	0.01	0.48	0.51	0.19	0.20
7 8	3.20	0.73	0.80	1.70	92.12	0.10	0.51	0.49	0.15	0.20
7 7	3.75	0.65	0.68	1.51	91.95	0.17	0.44	0.43	0.16	0.27
7 6	3.64	0.47	0.59	1.38	92.76	0.15	0.35	0.42	0.13	0.11
7 5	3.47	0.59	0.65	1.35	92.71	0.15	0.26	0.49	0.14	0.17
7 4	1.31	1.01	1.10	2.23	92.36	0.11	0.50	0.74	0.29	0.36
7 3	1.06	1.37	1.46	2.82	90.59	0.31	0.79	0.78	0.28	0.53
7 2	1.36	1.28	1.57	2.91	89.57	0.98	0.81	0.80	0.27	0.46
7 1	1.74	1.28	1.42	2.74	89.33	0.90	0.65	0.76	0.33	0.85
Mean value:	2.52	0.92	1.01	2.04	91.49	0.32	0.53	0.60	0.21	0.35
Sigma:	1.12	0.33	0.38	0.64	1.32	0.36	0.19	0.16	0.08	0.23
Sigma mean:	0.37	0.11	0.13	0.21	0.44	0.12	0.06	0.05	0.03	0.08

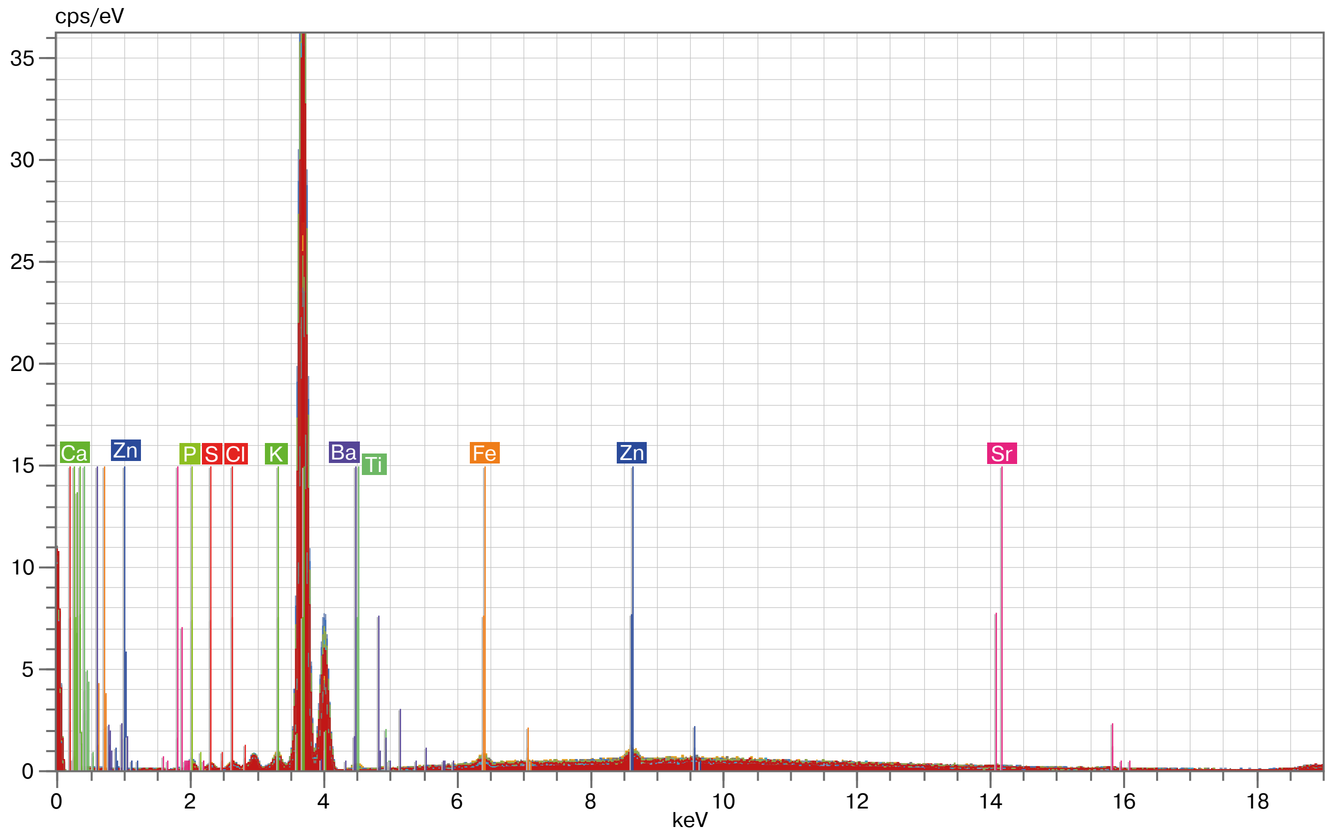
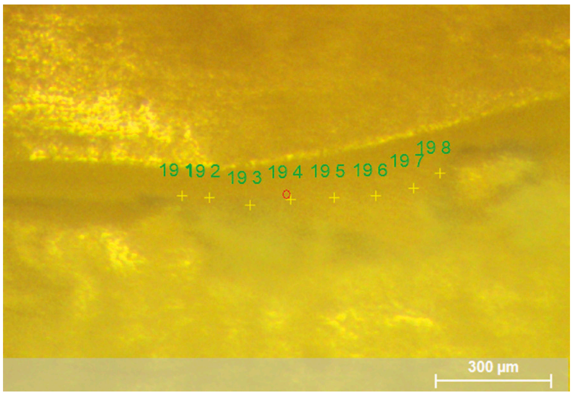


Fig. 4. Data on the analysis of the caries site of the pigmented tooth of patient No. 4, (XRF, MultiPoint mode)

Рис. 4. Данные по анализу участка кариеса пигментированного зуба пациента № 4, (РФА, режим MultiPoint)



	Mass percent (%)				
Spectrum	P	Ca	Fe	Ni	Zn
19 8	7.44	91.85	0.13	0.18	0.39
19 7	7.06	92.47	0.09	0.12	0.27
19 6	8.01	91.72	0.04	0.08	0.15
19 5	9.15	90.45	0.08	0.11	0.21
19 4	7.91	91.61	0.07	0.11	0.31
19 3	7.83	91.65	0.10	0.10	0.33
19 2	9.00	90.52	0.12	0.09	0.27
19 1	7.99	91.54	0.12	0.06	0.29
Mean value:	8.05	91.48	0.09	0.10	0.28
Sigma:	0.71	0.68	0.03	0.03	0.07
Sigma mean:	0.25	0.24	0.01	0.01	0.03

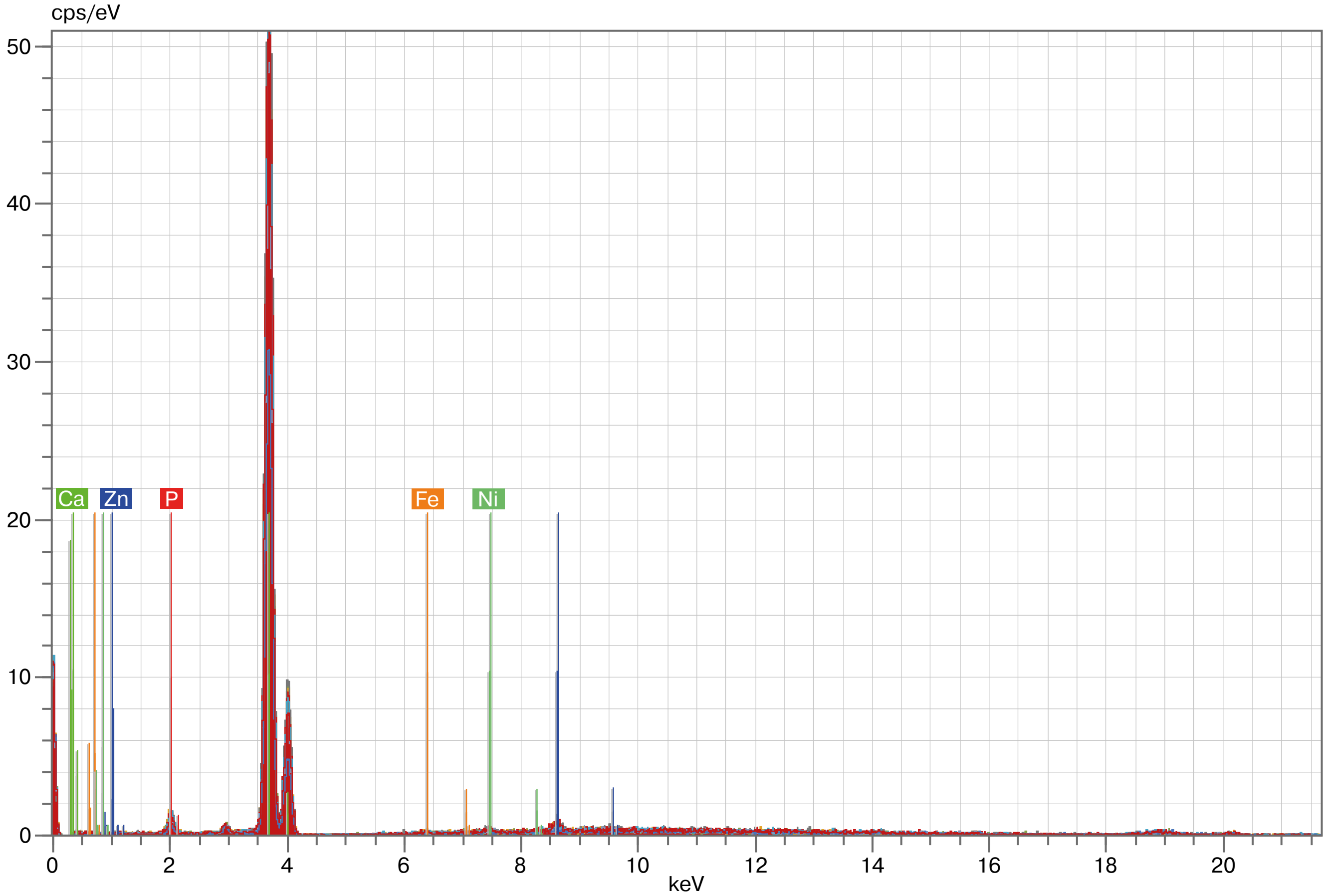


Fig. 5. Data on the analysis of the wedge-shaped tooth defect in patient No. 5 (XRF, MultiPoint mode)

Рис. 5. Данные по анализу участка клиновидного дефекта зуба пациента № 5, (РФА, режим MultiPoint)

DISCUSSION

The findings obtained in this study logically integrate into the broader body of knowledge generated by numerous investigations aimed at identifying the characteristics of dental disease progression in workers involved in chemical production [9–12]. Harmful occupational factors shift the dental status of individuals toward pathology, with exogenous intoxication clearly affecting the macro- and microelement composition not only in the lesion area but also in adjacent regions where clinical signs of disease are absent, yet the elemental composition of the tooth surface already differs from normal both qualitatively and quantitatively.

The elevated titanium content observed in erosion zones of teeth among several employees of a metallurgical enterprise is of particular concern for occupational health services, which would likely identify the source of this trace element exposure. Titanium itself is known to be one of the most biocompatible metals, widely used in medicine, including orthopedic and dental implants. However, first, the examined patients had no metallic restorations in the oral cavity, and second, titanium in the hard dental tissues was present in oxidized forms rather than as the pure metal. Whereas titanium was once considered biologically inert, recent studies increasingly highlight its potential toxicity: titanium particles and ions can accumulate in tissues and induce inflammatory responses [13].

Regarding the concurrent elevation of potassium and titanium in the pathological zones, such an association requires further investigation, as these elements perform distinct biological functions and are not directly linked in biochemical pathways. It should be noted that among employees of the metallurgical plant, noncarious lesions predominated, and the Ca/P ratio, exceeding the normal range and reaching 3.27, indicates a canonical pattern of enamel demineralization characterized by more rapid dephosphorylation relative to decalcification. Notably, XRF spectra from intact enamel adjacent to erosion returned the Ca/P ratio to 2.19, effectively restoring it too normal.

In workers at the enterprise producing paints and anticorrosive materials, the elemental composition within carious lesions – including essential elements – exhibited considerable diversity and significant quantitative deviations from normal, particularly for iron, sulfur, chlorine, zinc, and barium. The presence of these elements, incorporated as cations and anions into the lesion, suggests their direct or indirect involvement in mineralization processes, whereby their isomorphic or isoelectronic integration into apatite-like structures alters the usual kinetics of the opposing demineralization process. While classical caries progression typically reduces the Ca/P ratio from the normal range of 1.9–2.1 [14], in this patient group it increased up to 3.24, indicating intensified dephosphorylation relative to decalcification. This effect may be linked to the simultaneous presence in the lesion and saliva of salts comprising cations of strong bases (strontium, potassium, barium) and anions of weak acids (sulfides, sulfites), whose hydrolysis produces an alkaline environment that reduces the concentration of hydronium ions responsible for calcium substitution in hydroxyapatite [15–17].

At the agrobiological enterprise, the number of caries cases among examined workers was more than twice that of recorded increased tooth wear, potentially reflecting variations in work across different production areas. XRF spectra from carious lesions demonstrated not only a wide range of trace elements, as in previous examples, but also similar deviations of the Ca/P ratio above normal, reaching 5.92 in one patient. In contrast, spectra from intact enamel adjacent to the lesion reduced this ratio to 2.98.

For the subset of patients at the same enterprise exhibiting increased tooth wear, XRF spectra revealed no deviations from normal. The Ca/P ratio ranged from 2.07 to 2.46, a slight elevation consistent with observations for non-inflammatory hard tissue lesions [18].

Among employees of the chemical-pharmaceutical enterprise, all deviations from normal dental status were non-inflammatory. Erosive lesions and wedge-shaped defects occurred with roughly equal frequency. Detected trace elements showed only sporadic and minor quantitative deviations and were typical in type. In nearly all cases, the macroelement Ca/P ratio was slightly elevated, reflecting standard enamel demineralization processes in the absence of microbial involvement.

CONCLUSION

1. X-ray fluorescence analysis (XRF) demonstrated that, in employees of chemical production facilities, enamel demineralization is accompanied by both qualitative and quantitative changes in the microelement composition within pathological zones. In nearly all cases, the Ca/P ratio was increased, in some instances reaching 3.27, indicating a canonical pattern of enamel demineralization characterized by more rapid dephosphorylation relative to decalcification.
2. Environmental elements exert their effect through isomorphic and isoelectronic incorporation into the apatite structures of hard dental tissues, disrupting the natural kinetics of mineralization and demineralization. The detection of iron, sulfur, chlorine, zinc, and barium, incorporated as cations and anions into inflammatory foci, indicates their direct or indirect involvement in the mineralization process.
3. The intensity of microelement accumulation in hard dental tissues is directly related to the degree of industrial air purification from toxic chemical agents. For example, in erosion zones of teeth from metallurgical plant employees, titanium content reached as high as 1.14%.
4. Therapy and preventive strategies for dental disorders should take into account the specific occupational exposures of employees working in chemical production facilities.

REFERENCES / СПИСОК ЛИТЕРАТУРЫ

1. Patano A., Malcangi G., De Santis M., Morolla R., Settanni V., Piras F. et al. Conservative Treatment of Dental Non-Carious Cervical Lesions: A Scoping Review. *Biomedicines*. 2023;11(6):1530. https://doi.org/10.3390/biomedicines11061530
2. Mitronin A.V., Fulova A.M., Osipova A.V., Ivankova Yu.A., Prokopov A.A. XRF analysis of tooth enamel under conditions of experimental erosion in vitro. *Endodontics Today*. 2025;23(3):480–486. https://doi.org/10.36377/ET-0121
Митронин А.В., Фулова А.М., Осипова А.В., Иванькова Ю.А., Прокопов А.А. Рентгенофлуоресцентный анализ (РФА) эмали зуба в условиях экспериментальной эрозии in vitro. *Эндодонтия Today*. 2025;23(3):480–486. https://doi.org/10.36377/ET-0121
3. Muslov S.A., Arutyunov S.D. *Physical properties of tooth tissues*. Moscow: Prakticheskaya meditsina; 2021. 176 p. (In Russ.)
Муслов С.А., Арутюнов С.Д. *Физические свойства тканей зуба*. М.: Практическая медицина; 2021. 176 с.
4. Mitronin A.V., Prokopov A.A., Darsigova Z.T., Alikhanian A.S., Gokzhaev M.B., Dashkova O.P. X-ray fluorescence analysis of dental hard tissues in the early stages of erosive lesions. *Cathedra. Dental Education*. 2020;71:22–27. (In Russ.)
Митронин А.В., Прокопов А.А., Дарсигова З.Т., Алиханян А.С., Гокжаев М.Б., Дашкова О.П. Рентгенофлуоресцентный анализ твердых тканей зубов на ранней

стадии эрозивного поражения. *Cathedra-Кафедра. Стоматологическое образование*. 2020;71:22–27.

5. Fulova A.M., Ostanina D.A., Mitronin A.V. Analysis of risk factors for the development of dental erosion (systematic review). *Cathedra. Dental Education*. 2024;(89):16–19. (In Russ.)
Фулова А.М., Останина Д.А., Митронин А.В. Анализ факторов риска развития эрозии зубов (систематический обзор). *Cathedra-Кафедра. Стоматологическое образование*. 2024;(89):16–19.
6. Zaidullin I.I., Karimova L.K., Larionova T.K., Gimranova G.G., Masyagutova L.M. Impact of production and non-production risk factors on the formation of dental pathology among chemical industry workers. *Yakut Medical Journal*. 2024;(4):68–71. (In Russ.) https://doi.org/10.25789/YMJ.2024.88.16
Зайдуллин И.И., Каримова Л.К., Ларионова Т.К., Гимранова Г.Г., Масягутова Л.М. Влияние производственных и непроизводственных факторов риска на формирование стоматологической патологии у работников химического производства. *Якутский медицинский журнал*. 2024;(4):68–71. https://doi.org/10.25789/YMJ.2024.88.16
7. Fulova A.M., Ryazantseva P.A., Ostanina D.A., Mitronin A.V., Baitokova A.D. Analysis of dental morbidity of employees of a chemical enterprise. *Endodontics Today*. 2024;22(4):436–441. (In Russ.) https://doi.org/10.36377/ET-0060
Фулова А.М., Рязанцева П.А., Останина Д.А., Митронин А.В., Байтокова А.Д. Анализ стоматологической заболеваемости сотрудников химического предприятия. *Эндодонтия Today*. 2024;22(4):436–441. https://doi.org/10.36377/ET-0060
8. Arutyunov S.D., Nagoeva A.A., Prokopov A.A. Elemental composition of dental tissue and its dynamics in buffer solutions. *Dentist*. 2009;(3):25–33. (In Russ.)
Арутюнов С.Д., Нагоева А.А., Прокопов А.А. Элементный состав зубной ткани и его динамика в буферных растворах. *Стоматолог*. 2009;(3):25–33.
9. Malara P., Fischer A., Malara B. Selected toxic and essential heavy metals in impacted teeth and the surrounding mandibular bones of people exposed to heavy metals in the environment. *J Occup Med Toxicol*. 2016;11:56. https://doi.org/10.1186/s12995-016-0146-1
10. Gulyaeva O.A., Bakirov A.B., Chemikosova T.S., Aver'janov S.V., Arsenina O.I., Karimova L.K. Dependence of dental status from the level of endogenous intoxication in chemical industry workers based on the oral fluid composition study. *Stomatology*. 2019;98(6):18–21. (In Russ.) https://doi.org/10.17116/stomat20199806118
Гуляева О.А., Бакиров А.Б., Чемикосова Т.С., Аверьянов С.В., Арсенина О.И., Каримова Л.К. Зависимость отклонений стоматологического статуса от уровня эндогенной интоксикации у работников химического производства: результаты изучения состава ротовой жидкости. *Стоматология*. 2019;98(6):18–21. https://doi.org/10.17116/stomat20199806118
11. Mukhsinova L.A. Clinical-Laboratory Examination of Dental Diseases in Chemical Industry Workers. *American Journal of Pediatric Medicine and Health Sciences*. 2024;2(4):33–38. Available at: https://grnjournal.us/index.php/AJPMHS/article/view/4169 (accessed: 27.10.2025).
12. Zaydullin I.I., Karimova L.K., Kaptsov V.A., Karimov D.O., Muldasheva N.A. Dental status as an indicator of the intensity of exposure to chemical pollution of the air in the working area. *Hygiene and Sanitation*. 2024;103(11):1292–1297. (In Russ.) https://doi.org/10.47470/0016-9900-2024-103-11-1292-1297
Зайдуллин И.И., Каримова Л.К., Капцов В.А., Каримов Д.О., Мулдашева Н.А. Стоматологический статус как показатель интенсивности воздействия химического загрязнения воздуха рабочей зоны. *Гигиена и санитария*. 2024;103(11):1292–1297. https://doi.org/10.47470/0016-9900-2024-103-11-1292-1297
13. Kim K.T., Eo M.Y., Nguyen T.T.H., Kim S.M. General review of titanium toxicity. *Int J Implant Dent*. 2019;5(1):10. https://doi.org/10.1186/s40729-019-0162-x
14. Mitronin A., Darsigova Z., Alikhanian A., Prokopov A., Dashkova O. X-ray fluorescence analysis of the normal teeth enamel and in case of erosion. *Endodontics Today*. 2017;15(3):7–13. (In Russ.) Available at: https://www.endodont.ru/jour/article/view/76 (accessed: 27.10.2025).
Митронин А., Дарсигова З., Алиханян А., Прокопов А., Дашкова О. Рентгенофлуоресцентный анализ эмали зубов в норме и при эрозии. *Эндодонтия Today*. 2017;15(3):7–13. Режим доступа: https://www.endodont.ru/jour/article/view/76 (дата обращения: 27.10.2025).
15. Widanarko B., Modjo R. Occupational risk factors for acute fatigue symptoms among Indonesian beverage industry workers. *Journal of International Dental and Medical Research*. 2017;10(3):1052–1054.
16. Alruthea M.S. Intrinsic dental erosion: Review of dental management. *Journal of International Dental and Medical Research*. 2020;13(2):738–744.
17. Adiba S.H., Effendy R., Zubaidah N. Fluoride varnish effect on dental erosion immersed with carbonated beverages. *Journal of International Dental and Medical Research*. 2018;11(1):299–302.
18. Leontiev V.K. *Tooth enamel as a biocybernetic system*. Moscow: GEOTAR-Media; 2016. 72 p. (In Russ.)
Леонтьев В.К. *Эмаль зубов как биокибернетическая система*. М.: ГЭОТАР-Медиа; 2016. 72 с.

INFORMATION ABOUT THE AUTHORS

Alexander V. Mitronin – Dr. Sci. (Med.), Professor, Deputy Director of the A.I. Evdokimov Institute of Dentistry, Head of the Department of Therapeutic Dentistry and Endodontics, Honored Doctor of the Russian Federation, Russian University of Medicine, 4 Dolgorukovskaya St., Moscow 127006, Russian Federation; https://orcid.org/0000-0002-3561-6222

Angelina M. Fulova – Postgraduate Student, Assistant of the Department of Therapeutic Dentistry and Endodontics, Russian University of Medicine, 4 Dolgorukovskaya St., Moscow 127006, Russian Federation; https://orcid.org/0009-0006-2396-9625

Ilya A. Ivankov – Student, Secondary Boarding School of the Ministry of Foreign Affairs of the Russian Federation, 15 Yunost Village, Losino-Petrovsky District, Moscow Region 141142, Russian Federation; https://orcid.org/0009-0007-5731-2063

Marina A. Dzhavakhyan – Dr. Sci. (Pharm.), Associate Professor, Deputy Director of NOI Pharmacy named after K.M. Lakin, Russian University of Medicine, 4 Dolgorukovskaya St., Moscow 127006, Russian Federation; https://orcid.org/0000-0003-2673-6203

Alexey A. Prokopov – Dr. Sci. (Chem.), Professor, Head of the Department of General and Bioorganic Chemistry, Russian University of Medicine, 4 Dolgorukovskaya St., Moscow 127006, Russian Federation; Leading Researcher, Kurnakov Institute of General Inorganic Chemistry of the Russian Academy of Sciences, 31 Leninsky Avenue, Moscow 119071, Russian Federation; Honored Healthcare Worker of the Russian Federation, Full member of the Academy of Engineering Sciences A.M. Prokhorov; https://orcid.org/0000-0003-0099-3690

ИНФОРМАЦИЯ ОБ АВТОРАХ

Митронин Александр Валентинович – д.м.н., профессор, заместитель директора НОИ стоматологии им. А.И. Евдокимова, заведующий кафедрой терапевтической стоматологии и эндодонтии, Заслуженный врач РФ, ФГБОУ ВО «Российский университет медицины», 127006, Российская Федерация, г. Москва, ул. Долгоруковская, д. 4; https://orcid.org/0000-0002-3561-6222

Фулова Ангелина Манолисовна – аспирант, ассистент кафедры терапевтической стоматологии и эндодонтии, ФГБОУ ВО «Российский университет медицины», 127006, Российская Федерация, г. Москва, ул. Долгоруковская, д. 4; https://orcid.org/0009-0006-2396-9625

Иваньков Илья Александрович – учащийся, ФГБОУ «Средняя школа-интернат Министерства иностранных дел Российской Федерации», 141142, Российская Федерация, Московская обл., г. о. Лосино-Петровский, п. Юность, стр. 15; https://orcid.org/0009-0007-5731-2063

Джавахян Марина Аркадьевна – д.фарм.н., доцент, заместитель директора НОИ фармации им. К.М. Лакина, ФГБОУ ВО «Российский университет медицины», 127006, Российская Федерация, г. Москва, ул. Долгоруковская, д. 4; https://orcid.org/0000-0003-2673-6203

Прокопов Алексей Александрович – д.х.н., профессор, заведующий кафедрой общей и биоорганической химии, ФГБОУ ВО «Российский университет медицины», 127006, Российская Федерация, г. Москва, ул. Долгоруковская, д. 4; ведущий научный сотрудник, ФГБУН «Институт общей и неорганической химии им. Н.С. Курнакова» РАН, 119991, Российская Федерация, г. Москва, Ленинский проспект, д. 31; Заслуженный работник здравоохранения РФ, действительный член Академии инженерных наук им. А.М. Прохорова; https://orcid.org/0000-0003-0099-3690

AUTHOR'S CONTRIBUTION

Alexander V. Mitronin – has made a substantial contribution to the concept or design of the article; revised the article critically for important intellectual content; approved the version to be publish.

Angelina M. Fulova – the acquisition, analysis, or interpretation of data for the article; drafted the article.

Ilya A. Ivankov – the acquisition, analysis, or interpretation of data for the article; drafted the article.

Marina A. Dzhavakhyan – the acquisition, analysis, or interpretation of data for the article; drafted the article.

Alexey A. Prokopov – has made a substantial contribution to the concept or design of the article; the acquisition, analysis, or interpretation of data for the article; drafted the article; revised the article critically for important intellectual content.

ВКЛАД АВТОРОВ

А.В. Митронин – существенный вклад в замысел и дизайн исследования, критический пересмотр статьи в части значимого интеллектуального содержания, окончательное одобрение варианта статьи для опубликования.

А.М. Фулова – сбор данных, анализ и интерпретация данных, подготовка статьи.

И.А. Иваньков – сбор данных, анализ и интерпретация данных, подготовка статьи

М.А. Джавахян – сбор данных, анализ и интерпретация данных, подготовка статьи.

А.А. Прокопов – существенный вклад в замысел и дизайн исследования, сбор данных, анализ и интерпретация данных, подготовка статьи, критический пересмотр статьи в части значимого интеллектуального содержания.