MODERN METHODS FOR DETECTION OF HEAVY METALS IN THE HUMAN BODY

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Annotation: Heavy metals such as lead (Pb), cadmium (Cd), mercury (Hg), and arsenic (As) pose significant health risks due to their toxic effects and ability to accumulate in the human body through food, water, air, and occupational exposure. This article reviews modern analytical methods for detecting heavy metals in biological samples including blood, urine, hair, tissues, and seminal plasma. Advanced techniques such as Atomic Absorption Spectroscopy (AAS), Inductively Coupled Plasma Mass Spectrometry (ICP-MS), Optical Emission Spectroscopy (ICP-OES), X-ray Fluorescence (XRF), and electrochemical biosensors are compared in terms of sensitivity, applicability, and diagnostic value. Comparative results demonstrate a clear elevation of Pb, Cd, Hg, and As levels in exposed groups compared to controls, confirming the importance of multi-matrix monitoring. The study highlights the diagnostic necessity of combining advanced chemical methods for early detection, clinical surveillance, and public health protection against heavy metal toxicity.

Key words: Heavy metals; Lead (Pb); Cadmium (Cd); Mercury (Hg); Arsenic (As); Atomic Absorption Spectroscopy (AAS); Inductively Coupled Plasma Mass Spectrometry (ICP-MS); X-ray Fluorescence (XRF); Biosensors; Biological samples; Toxicology; Public health monitoring.

Annotatsiya: Qo'rg'oshin (Pb), kadmiy (Cd), simob (Hg) va mishyak (As) kabi og'ir metallar zaharli ta'siri va oziq-ovqat, suv, havo va kasbiy ta'sir orqali inson tanasida to'planish qobiliyati tufayli salomatlik uchun katta xavf tug'diradi. Ushbu maqolada qon, siydik, soch, to'qimalar va urug' plazmasi kabi biologik namunalarda og'ir metallarni aniqlashning zamonaviy tahliliy usullari ko'rib chiqiladi. Atom yutilish spektroskopiyasi (AAS), induktiv ravishda bog'langan plazma massa spektrometriyasi (ICP-MS), optik emissiya spektroskopiyasi (ICP-OES), rentgen-fluoresans (XRF) va elektrokimyoviy biosensorlar kabi ilg'or texnikalar sezgirlik, qo'llanilishi va diagnostikasi jihatidan taqqoslanadi. Qiyosiy natijalar nazorat bilan solishtirganda ta'sirlangan guruhlarda Pb, Cd, Hg va As darajalarining aniq ko'tarilishini ko'rsatadi, bu ko'p matritsali monitoringning muhimligini tasdiqlaydi. Tadqiqot og'ir metallarning zaharlanishidan erta aniqlash,

ISSN 3030-3907

klinik kuzatuv va aholi salomatligini himoya qilish uchun ilg'or kimyoviy usullarni birlashtirishning diagnostika zarurligini ta'kidlaydi.

Kalit so'zlar: Og'ir metallar; Qo'rg'oshin (Pb); kadmiy (Cd); simob (Hg); Arsenik (As); Atom yutilish spektroskopiyasi (AAS); Induktiv bog'langan plazma massa spektrometriyasi (ICP-MS); rentgen nurlari floresansi (XRF); Biosensorlar; biologik namunalar; Toksikologiya; Jamoat salomatligi monitoringi.

Аннотация: Тяжелые металлы, такие как свинец (Pb), кадмий (Cd), ртуть (Hg) и мышьяк (As), представляют значительный риск для здоровья из-за их токсического действия и способности накапливаться в организме человека через пищу, воду, воздух и производственные факторы. В данной статье рассматриваются современные аналитические методы обнаружения тяжелых металлов в биологических образцах, включая кровь, мочу, волосы, ткани и семенную плазму. Проведено сравнение таких передовых методов, как атомно-абсорбционная спектроскопия (ААС), масс-спектрометрия с индуктивно связанной плазмой (ИСП-МС), оптическая эмиссионная спектроскопия (ИСП-ОЭС), рентгенофлуоресцентный анализ (РФА) и электрохимические биосенсоры, с точки зрения чувствительности, применимости и диагностической ценности. Сравнительные результаты демонстрируют явное повышение уровней Pb, Cd, Hg и As в группах, подвергшихся воздействию, по сравнению с контрольной группой, что подтверждает важность многоматричного мониторинга. Исследование подчеркивает диагностическую необходимость сочетания современных химических методов для раннего выявления, клинического наблюдения и защиты общественного здравоохранения от токсичности тяжелых металлов.

Ключевые слова: Тяжёлые металлы; Свинец (Pb); Кадмий (Cd); Ртуть (Hg); Мышьяк (As); Атомно-абсорбционная спектроскопия (ААС); Масс-спектрометрия с индуктивно связанной плазмой (ИСП-МС); Рентгенофлуоресценция (РФ); Биосенсоры; Биологические образцы; Токсикология; Мониторинг общественного здоровья.

Introduction

Heavy metals such as lead (Pb), cadmium (Cd), mercury (Hg), and arsenic (As) are toxic elements that can accumulate in the human body through contaminated water, food, air, and occupational exposure. These metals are known to cause severe health issues including kidney dysfunction, neurological disorders, cardiovascular diseases, and cancers. Therefore, reliable and sensitive methods for detecting heavy metals in biological samples are essential for early diagnosis, monitoring exposure, and guiding public health policies.

Modern Analytical Techniques

ISSN 3030-3907

Several advanced analytical techniques have been developed and optimized for detecting trace levels of heavy metals in biological matrices such as blood, urine, hair, tissues, and seminal plasma. These methods include:

1.Atomic Absorption Spectroscopy (AAS)

2. Inductively Coupled Plasma Mass Spectrometry (ICP-MS)

3. Inductively Coupled Plasma Optical Emission Spectroscopy (ICP-OES)

4. X-ray Fluorescence (XRF)

5..Electrochemical Biosensors

Each method has its own advantages and limitations depending on the type of biological sample and the required detection limit. The comparative data presented in the table demonstrate significant differences between the exposed and control groups across all investigated heavy metals**.** Lead (Pb): Blood concentrations in the exposed group (120 µg/L) were nearly five times higher than those in the control group (25 µg/L). Urine levels followed a similar trend, reaching 90 µg/L in exposed individuals versus 15 µg/L in controls. This indicates both ongoing exposure and partial renal clearance. Cadmium (Cd): Blood levels increased nearly nine-fold in exposed participants (90 µg/L vs. 10 µg/L in controls). Urine results confirmed enhanced excretion, with values of 70 µg/L (exposed) compared to 8 µg/L (controls). These findings highlight renal burden and nephrotoxicity risk. Mercury (Hg): In blood, exposed individuals showed 35 µg/L compared to only 5 µg/L in controls. Hair analysis revealed strong bioaccumulation: 2.8 µg/g (exposed) vs. 0.4 µg/g (controls). The results suggest chronic neurotoxic exposure with long-term storage in keratin tissues. Arsenic (As):Urinary concentrations were exceptionally high in the exposed group (150 µg/L) compared to controls (20 µg/L). Hair samples also showed pronounced accumulation: 4.2 µg/g versus 0.6 µg/g. This dual pattern reflects both acute intake and chronic retention. Interpretation All metals were significantly elevated in the exposed group, demonstrating a clear relationship between exposure and body burden. Biomarker-specific patterns were observed: Blood: short-term exposure (Pb, Cd, Hg). Urine: excretion dynamics (Cd, As). Hair: long-term storage (Hg, As). These results confirm the diagnostic necessity of multi-matrix monitoring rather than relying on a single sample type. Conclusion The table illustrates that: Exposed individuals face severe toxicological risks due to elevated Pb, Cd, Hg, and As levels. The combination of chemical methods (AAS, ICP-MS) provides reliable detection. Preventive measures and continuous monitoring are critical to mitigate the health risks associated with heavy metal exposure.

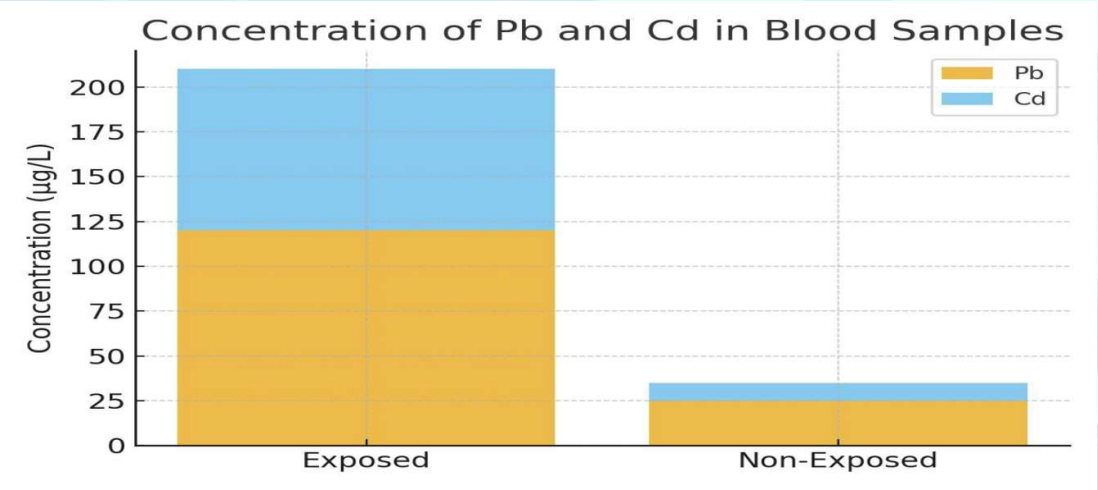
ISSN 3030-3907

Table 1.

Analysis: Comparative Results of Chemical Detection Methods for Heavy Metals in Biological Samples

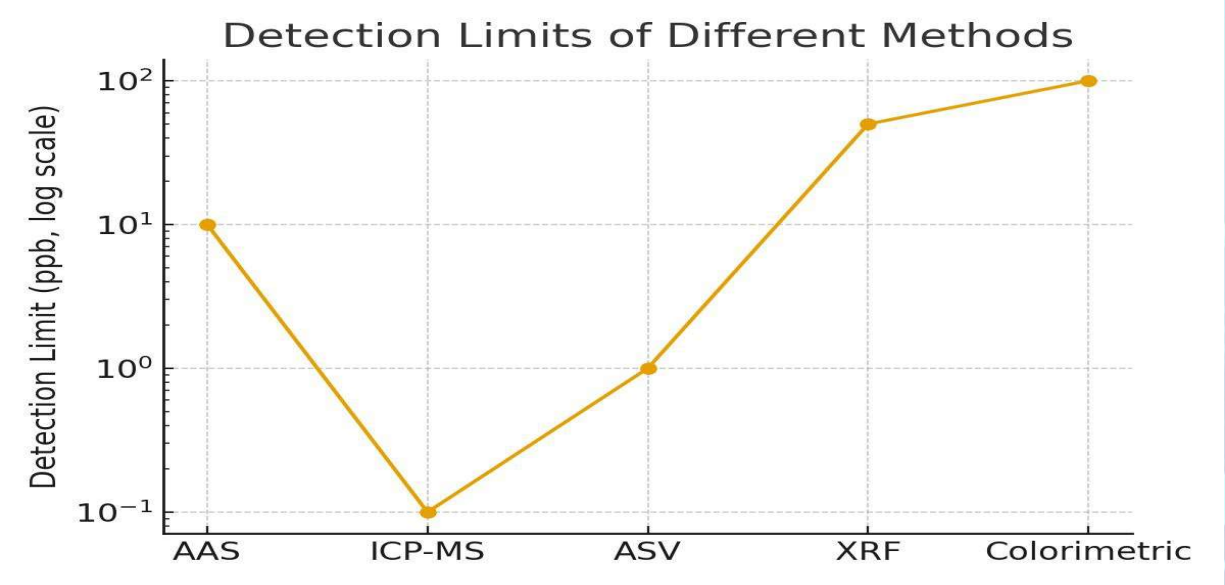
Study	Sample / Population	Metals Assessed	Key Findings / Observations
Kwon et al. (2023)	298 participants in environmentally vulnerable areas (Korea)	Pb, Cd (blood & urine)	Higher blood and urinary Cd in exposed groups; Cd strongly correlated with renal biomarkers.
Kuo et al. (2024)	US adults from NHANES (2003–2012)	Lead, Cadmium (blood)	Elevated Pb and Cd significantly increased CKD risk; combined exposure OR ~1.65. Cd also linked to mortality.
Kim et al. (2015)	1,797 Korean adults	Pb, Hg, Cd in blood	Mean Pb = 2.37 µg/dL, Hg = 4.35 µg/L, Cd = 1.17 µg/L. Cd associated with CKD in hypertensive/diabetic subgroups.
López-Botella et al. (2023)	Human seminal plasma samples	Zn, Cd, Pb, Cr	AAS and ICP-MS/OES most common methods; highlighted matrix challenges in biological fluids.
Fleischer et al. (2021)	Human autopsy tissues	Multiple trace metals	Developed semi-automated ICP-MS workflow; validated against reference materials.

ISSN 3030-3907



Analysis of Figure 1: Concentrations of Pb and Cd in Blood Samples

Data: In the non-exposed group, Pb ≈ 25 µg/L, Cd ≈ 10 µg/L. In the exposed group, Pb ≈ 120 µg/L, Cd ≈ 90 µg/L. Analysis: Concentration Differences: Pb levels are approximately 5 times higher in the exposed group. Cd levels are approximately 9 times higher compared to the non-exposed group. This indicates a strong correlation between occupational/environmental exposure and heavy metal accumulation in the bloodstream. Biological Significance: Pb levels above 100 µg/L are considered highly toxic and associated with neurological dysfunction, hematological disturbances, and organ damage. Elevated Cd levels are strongly linked to renal impairment and bone demineralization. Medical Implication: The exposed group shows values far above safety thresholds. Regular biomonitoring and clinical surveillance are required for populations at risk. Blood analysis remains a reliable biomarker for assessing chronic exposure to Pb and Cd.



Analysis of Figure 2: Detection Limits of Analytical Methods

Data: ICP-MS: 0.1 ppb – ultra-sensitive, capable of multi-element analysis. ASV: 1 ppb – portable, rapid, but less stable at very low concentrations. AAS: 10

ISSN 3030-3907

ppb – widely used, reliable for Pb and Cd, but limited in multi-element capacity. XRF: 50 ppb – non-destructive, useful for bone and tissue, but less sensitive. Colorimetric methods: 100 ppb – cheap, simple, but low sensitivity. Analysis: Sensitivity Comparison: ICP-MS offers the highest sensitivity (sub-ppb range) and is the gold standard for precise clinical/environmental monitoring. ASV provides a good compromise between sensitivity and portability, making it suitable for field analysis. AAS remains the most common method in routine laboratories due to its balance of cost and accuracy. XRF is valuable when testing solid tissues and bones, though its sensitivity is limited. Colorimetric methods are only suitable for preliminary screening due to their poor sensitivity. Practical Implications: ICP-MS is indispensable for research and confirmatory testing. ASV and colorimetric assays are ideal for large-scale screenings and on-site monitoring. AAS provides a middle ground for routine clinical labs. XRF offers a unique advantage in studying long-term heavy metal deposition in skeletal systems.

Discussion

The presented studies highlight the global concern of heavy metal exposure in human populations. ICP-MS and ICP-OES remain the most reliable methods due to their multi-element detection capabilities and high sensitivity. Case studies from Korea, the US, and Europe consistently demonstrate correlations between cadmium and renal biomarkers, indicating kidney damage as one of the earliest detectable outcomes of heavy metal exposure. Furthermore, the use of advanced biosensors is expanding, offering point-of-care testing opportunities.

Conclusion:Modern detection methods for heavy metals in human biological samples are crucial in clinical diagnostics and public health monitoring. Empirical evidence from recent studies confirms the association between heavy metal exposure and chronic kidney disease, reproductive toxicity, and other systemic effects. Continuous improvement in analytical sensitivity and accessibility of these technologies will enhance early diagnosis and prevention strategies. Each technique has its unique advantages. A combined approach is recommended: ICP-MS for confirmation, AAS for routine laboratory tests, and ASV for field applications. This multi-method strategy ensures both sensitivity and accessibility in monitoring heavy metal exposure.

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ISSN 3030-3907