Exploration and Research on the Principle of Damaging Effects of Heavy Metals in Cosmetics on Human Health

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Abstract: Cosmetics, as daily consumer goods, their safety is closely related to the health rights and interests of the majority of consumers. In recent years, the issue of heavy metal pollution in cosmetics has continuously drawn social attention. This article systematically reviews the sources of heavy metals in cosmetics, the mechanisms of health hazards, and prevention and control strategies. Research shows that heavy metals in cosmetics mainly come from three sources: natural coexistence of raw materials, introduction during the production process, and illegal and intentional addition. Heavy metals such as lead, mercury, arsenic and cadmium can be absorbed into the human body through the skin, causing multi-target damage to the nervous system, kidneys, immune system, etc. Their toxic mechanisms involve pathways such as oxidative stress, enzyme activity inhibition and mitochondrial dysfunction. At present, China has established a relatively complete standard system for heavy metal limits in cosmetics. The implementation of the new comprehensive mercury ban regulations in 2026 marks a new stage in supervision. The prevention and control strategy should adhere to the integrated approach of "source control, process supervision, and end-of-pipe monitoring", and make concerted efforts in improving regulations and standards, strengthening detection technologies, and enhancing consumer literacy.

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1. Introduction

Cosmetics have become indispensable consumer goods in modern life, ranging from daily skin care to makeup and decoration. Their usage frequency and variety are constantly expanding. However, with the advancement of detection technology and the transparency of regulatory information, the issue of heavy metal pollution in cosmetics has gradually come into the public eye. Heavy metal elements such as lead, mercury, arsenic and cadmium have been frequently detected in some products, with even extreme cases of exceeding the standard by tens of thousands of times, which has triggered safety anxiety behind "beautiful consumption".

Cosmetics have become indispensable consumer goods in modern life, ranging from daily skin care to makeup decoration. The frequency of use and the types of heavy metals have the characteristics of accumulation, concealment and multi-system harm to health. Compared with acute poisoning, long-term low-dose exposure is more alarming - it may quietly damage the nervous system, kidney function and immune barrier without causing immediate symptoms. The significance of this issue is also reflected in the particularity of the exposed population: most cosmetic users are women of childbearing age, and heavy metals can pass through the placental barrier and the blood-brain barrier, posing a potential threat to fetal development and the health of the offspring.

It is worth noting that the issue of heavy metals in cosmetics has a dual nature: on the one hand, as heavy metals are widely present in nature, it is technically unfeasible to achieve complete "zero residue". On the other hand, some unscrupulous merchants deliberately add prohibited substances such as mercury in pursuit of quick whitening effects, posing a serious public health risk. This mixture of "technical residue" and "addition of illegality" makes the understanding and governance of the problem more complicated. This article aims to systematically analyze the sources and fate of heavy metals in cosmetics, as well as the toxicological mechanisms of health hazards. Based on a review of domestic and international regulatory frameworks, it proposes integrated prevention and control strategies, with the expectation of providing references for consumers' scientific understanding and for regulatory authorities to implement precise policies.

2. Sources and exposure routes of heavy metals in cosmetics:

2.1. Source Analysis:

The sources of heavy metals in cosmetics, ranging from naturally occurring to artificially added ones, can be classified into three categories, with significant differences in their properties and risk levels. The specific classification is as follows.

The first category involves the presence of heavy metals in natural raw materials. They are widely present in the earth's crust, water bodies and soil. During the collection and extraction of cosmetic raw materials, trace amounts of heavy metals are inevitably introduced. Mineral pigments (such as iron oxide and titanium dioxide) often contain elements like lead, chromium and cobalt. Plant extracts may enrich elements such as arsenic and nickel in their growth environment. This type of source is "passively brought in", and its content is usually at trace levels.

The second category: Mixing in during the production process; During the raw material transportation, production and manufacturing, and packaging processes, the wear of metal pipes and the migration of packaging materials may all lead to the entry of elements such as nickel and chromium into the products. Even enterprises that strictly follow good manufacturing practices find it difficult to completely eliminate the introduction of such technical technologies.

The third category, illegal and intentional addition: This is the most alarming source. Mercury compounds can irreversibly inhibit tyrosinase activity, block melanin production, and produce significant whitening effects in a short period of time. Mercuric aminochloride and other substances have extremely low procurement costs and are packaged by unscrupulous merchants as products such as "Special effect spot-removing Cream" and "seven-day skin rejuvenation essence", and are sold through weak-regulated channels such as wechat business, live streaming, and beauty salons.

A market survey in Beijing in 2005 showed that 40.7% of the products in beauty salons were "three-no" products, with a mercury non-compliance rate as high as 43.8%, and the mercury content in some samples exceeded the national standard by tens of thousands of times. A test on cosmetics purchased online in seven Asian countries found that over 58% of the samples had excessive mercury content, with the highest reaching 144,893.9 mg/kg, which was 140,000 times higher than the limit standard.

2.2. Exposure pathways and absorption kinetics:

Heavy metals mainly enter the human body through three pathways: transdermal absorption, oral intake and respiratory inhalation. The specific description is as follows.

Transdermal absorption is the main route of exposure for cosmetics. Inorganic mercury can be absorbed through the transepidermal or via skin appendages (sweat glands, sebaceous glands, hair follicles), and the transdermal absorption rate can reach 6% of the local practical dose under specific conditions. The absorption rate is affected by the anatomical site, dosage form matrix and the integrity of the skin barrier. It is worth noting that application around the mouth or hand-mouth contact may lead to accidental ingestion of cosmetics. Inorganic mercury absorbed through the digestive tract has a higher bioavailability.

Once entering the body, the distribution of heavy metals is selective towards target organs. About 80% of inorganic mercury accumulates in the kidneys, making them the most common target organ for mercury poisoning. Lead can be stored in bones for a long time and serves as a biomarker reflecting chronic exposure. Mercury can penetrate the blood-brain barrier and the placental barrier, and its residue in brain tissue can last up to 20 years.

3. The Impact of Heavy Metals on Human Health and Their Toxicological mechanisms

3.1. Target organ toxicity:

Kidney damage; The kidneys are the main target organs for mercury accumulation. Mercury ions that enter the renal tubular epithelial cells combine with enzymes containing sulfhydryl groups, interfering with the energy metabolism and transport function of the cells, causing proteinuria and nephrotic syndrome. In severe cases, it can lead to renal failure. In a clinical case, a 45-year-old woman used whitening cosmetics with excessive mercury for six months. Edema in both lower extremities and massive proteinuria occurred, with the ratio of urinary mercury to urinary creatinine reaching 31.7 μg/g (normal value: 0-4 μg/g), and the diagnosis was secondary nephrotic syndrome.

Neurological damage Both lead and mercury are highly neurotoxic substances. Lead ions can block voltage-gated and receptor-manipulated calcium channels, interfere with synaptic development and neurotransmitter release, and lead to a decline in learning and memory abilities. Early manifestations of mercury poisoning include neurasthenia syndrome (insomnia, memory loss, and unstable emotions), and in the progressive stage, intentional tremors and ataxia may occur.

Other systemic effects: Cadmium can activate the caspase protease cascade reaction, induce apoptosis of nerve cells, and simultaneously inhibit Ca-ATPase activity, interfering with calcium homeostasis. Lead can also cause mitochondrial dysfunction, leading to DNA damage and apoptosis through the accumulation of reactive oxygen species. In addition, mercury can accumulate in testicular tissue, affecting sperm quality. Penetrating the placental barrier directly damages the development of the fetal nervous system.

3.2. Toxicological Mechanism:

The molecular mechanisms of heavy metal toxicity mainly include the following pathways:

In the oxidative stress pathway, heavy metal ions catalyze the generation of reactive oxygen species through Fenton-like reactions, leading to lipid peroxidation, protein carbonylation and DNA strand breaks. Lead-induced opening of mitochondrial permeability transition pores is a key link in apoptosis.

Enzyme activity inhibition. Mercury ions have a high affinity for enzymes containing thiol groups and can bind to the cysteine residues of various enzymes such as superoxide dismutase and arginase I, interfering with their catalytic functions. The irreversible inhibition of tyrosinase by mercury is the molecular basis of its whitening effect, but it is precisely the interruption of this mechanism that leads to the disorder of melanin metabolism and damage to the skin barrier.

Ion steady-state interference. Lead and cadmium can simulate calcium ions, interfere with calcium channels and calcium-binding proteins, and affect neurotransmitter release, muscle contraction and cell signal transduction.

3.3. Spatial Differences in Health Risks:

It is worth noting that the health risks of heavy metals in cosmetics vary significantly among different groups of people. A study in remote areas of Pakistan suggests that people with poorer socioeconomic conditions are more likely to use cheap and unregulated cosmetics, thus bearing a higher risk of exposure. The weak supervision of online sales channels has further magnified this problem - the rate of heavy metal over-standard cosmetics purchased online is significantly higher than that of regular products in physical stores.

4. Measurement Technology and Regulatory framework:

4.1. Advances in Detection Technology:

Accurate heavy metal detection is the foundation of risk assessment and regulatory enforcement. The current main detection methods include: Atomic spectroscopy is the most widely used technical platform. Atomic fluorescence spectrometry has high sensitivity and low detection limits for arsenic and mercury. The optimized method can reduce the detection limits to 0.012 μg/L and 0.008 μg/L respectively.Inductively coupled plasma atomic emission spectrometry can achieve simultaneous detection of multiple elements, with detection limits for Hg, Pb, Cr, Ni, Cd, As, Bi, and Ti being 0.50-2.03 μg/L. Fluorescence photoelectrochemical method, as an emerging technology, can simultaneously determine six heavy metals with a correlation coefficient of 0.999968 and a spiked recovery rate ranging from 99.38% to 104.86%.

The non-destructive nature of X-ray fluorescence spectrometry makes it suitable for rapid screening. A large-scale survey on cosmetics purchased online was completed using this method. The applicability of different methods depends on the purpose of the detection - law enforcement screening requires high throughput, while confirmatory detection demands high precision.

4.2. Comparison of Domestic and International Regulatory Standards.

According to the "Cosmetics Safety Technical Specifications" (2015 Edition) of our country, mercury ≤1 mg/kg, lead ≤10 mg/kg, arsenic ≤2 mg/kg, and cadmium ≤5 mg/kg. Starting from July 1, 2026, the newly revised standards for mercury and its compounds have been officially implemented, completely banning the use of organic mercury preservatives (phenylmercury borate, thimerosal) that were previously allowed in trace amounts in eye products. This marks a "complete ban on mercury" in cosmetics.

At the international level, the Minamata Convention on Mercury requires contracting parties to phase out mercury-containing cosmetics. The FDA of the United States stipulates that mercury must not be contained except for trace impurities. The EU allows eye products to contain 70 ppm organic mercury preservatives, but the SCCS continues to tighten its assessment standards. The differences in standards lead to regulatory arbitrage space - some substandard products may flow from regions with loose regulation to those with strict regulation, especially through online shopping channels.

4.3. Current Situation and Challenges of Industry Compliance.

The regular brands have basically completed the formula upgrade, and mercury-containing preservatives are hard to find in legal channels. However, the problem of illegal addition remains severe in the gray channels. Annual random inspections by the National Medical Products Administration have shown that whitening and freckle-removing products have long been among the top substandard categories. The main challenges faced by supervision include: difficulty in tracing the source of online sales, high cost of identifying illegal products, and insufficient penalties to form an effective deterrent.

5. Prevention Strategies and Consumer Protection:

5.1 Regulatory level: Equal Emphasis on systems and technologies.

Improve regulations and standards. The new comprehensive mercury ban regulations have set a higher benchmark for the industry. In the future, the risk assessment of heavy metals should be strengthened in the approval of new cosmetic raw materials and the review of efficacy claims. For elements for which limit standards have not yet been set (such as chromium and nickel), scientific limits should be established based on exposure assessment.

Strengthen the supervision of online sales; The over-standard rate of cosmetics purchased online is significantly higher than that of physical channels. It is suggested to establish an online supervision closed loop of "platform review - regular spot checks - problem traceability" to solidify the main responsibility of e-commerce platforms. Promote technological innovation in detection. Develop rapid screening equipment suitable for grassroots law enforcement and high-precision methods applicable to confirmatory testing to enhance the coverage and timeliness of supervision.

5.2. At the consumer level, scientific cognition and rational choice.

Dispel the myth of "zero residue". Since heavy metals are widely present in nature, it is neither scientific nor reliable to claim that "it contains no heavy metals at all". Consumers should focus on whether the products meet the national standard limits rather than pursuing absolute "purity".

Identify risk signals. Be vigilant about claims such as "three-day whitening" and "immediate spot removal" that violate the skin's metabolic patterns. These products are highly likely to contain prohibited ingredients. Before purchasing, you can check the registration and filing information of the product through the official website of the National Medical Products Administration or the "Cosmetics Supervision" APP.

Choose a regular channel; Stay away from "three-no" products sold through non-formal channels such as door-to-door sales and wechat business agents, and give priority to shopping malls. Purchase from brand counters or official e-commerce flagship stores.

5.3. Industry Level: Raw Material Innovation and Quality Upgrade.

The "complete mercury ban" has forced the industry to seek safer alternative ingredients for whitening. After the implementation of the "Regulations on the Supervision and Administration of Cosmetics" in 2020, the approval process for new raw materials has been accelerated, and raw materials from plant extracts, peptides, and synthetic biology sources have flourished. This is not only a compliance requirement, but also a strategic opportunity for China's cosmetics industry to achieve differentiated competition. Enterprises should incorporate heavy metal control into the entire chain of quality management, forming a closed loop from raw material procurement, production monitoring to finished product inspection

6. Conclusion:

The issue of heavy metals in cosmetics is a topic that combines both scientific depth and social breadth. From a scientific perspective, it involves the intersection of multiple disciplines such as trace analytical chemistry, toxicology, and epidemiology. From a governance perspective, it tests the collaborative capabilities of regulatory design, supervision enforcement and industry self-discipline. The implementation of the new comprehensive mercury ban regulations in 2026 marks a new stage in China's cosmetics heavy metal governance, moving from "limited control" to "zero at the source". However, technical residues cannot be completely eliminated, and there is still room for illegal additives to breed. The prevention and control work is bound to be a protracted battle. Only by adhering to scientific cognition, improving institutional design and enhancing public literacy can beauty no longer come at the cost of health.

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