Research and Development on the Impact 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 attention. This article systematically reviews the current research status of the sources, health hazard mechanisms, detection techniques and risk assessment methods of heavy metals in cosmetics. Studies have shown that heavy metals can enter cosmetics through raw material introduction or production pollution. After being absorbed through the skin, they can cause multi-system damage to the human body, including neurotoxicity, nephrotoxicity, and carcinogenicity. At present, highly sensitive analytical techniques such as ICP-MS have achieved precise detection of trace heavy metals, and health risk assessment models based on exposure dose are replacing the traditional total comparison method and becoming more scientific evaluation tools. However, problems such as inconsistent regulatory standards among countries, insufficient localization of exposure assessment parameters, and lagging safety evaluation of nanomaterials remain prominent. Future research should focus on establishing a globally unified regulatory framework, developing precise risk assessment methods based on physiological pharmacokinetic models, and strengthening systematic reviews of the long-term health effects of new nanomaterials.

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1. Introduction

Cosmetics have become indispensable consumer goods in modern life, covering multiple categories such as skin care products, makeup, and hair care products. However, while pursuing effects such as whitening, covering up and makeup retention, consumers may accidentally come into contact with heavy metals like lead, cadmium, mercury, arsenic, chromium and nickel. These substances may be absorbed through the skin and enter the human body, posing potential health risks.

There are two situations where heavy metals exist in cosmetics: one is as intentionally added components in raw materials, such as certain inorganic dyes and ultraviolet filters.The second is impurities or pollutants introduced during the production process. In recent years, numerous investigations and studies have shown that heavy metals have been detected in cosmetics in many markets around the world, and some products have even exceeded regulatory limits. A study analyzed 113 types of cosmetics and found that 50.4% of the products violated at least one international impurity standard, among which the metal concentration was the highest in cosmetics rich in pigments and black Henna products.

In the face of this "hidden concern behind beauty", the academic community and regulatory agencies have conducted extensive research on the detection methods of heavy metals, their health impacts and risk management. This article aims to systematically review the research progress on the impact of heavy metals in cosmetics on human health from four dimensions: source and health hazards, detection and analysis methods, risk assessment framework, and regulatory status. It also looks forward to future research directions, with the expectation of providing references for the safety evaluation and risk control of cosmetics.

2. The sources and health hazards of heavy metals in cosmetics:

2.1. Sources and Distribution Characteristics of Heavy Metals

The sources of heavy metals in cosmetics can be classified into two categories: intentional addition and unintentional introduction. Intentional addition mainly refers to the use of certain metal compounds as functional ingredients, for instance, zinc and titanium nanoparticles are used as physical sunscreens, and certain metal oxides are used as pigments and dyes.

Unintentional introduction is even more common. Mineral raw materials themselves contain trace
Amounts of metals and wear and tear of production equipment and migration of packaging materials may cause pollution.
From the perspective of product types, the characteristics of heavy metal pollution in different categories of cosmetics vary significantly. Studies show that products with higher pigment content (such as loose powder, blush, and eyeshadow) and traditional formula products (such as Henna dye and eyeliner powder) have the highest metal concentration. An investigation based on ICP-MS analysis revealed that the systemic exposure dose of facial powder was as high as 35.29 mg/kg bw/day, with a safety margin (MoS) of less than one and a cumulative hazard index of approximately 140,000. In contrast, the exposure contribution of lipsticks and skin care creams is relatively small. This difference is closely related to the application site, frequency and duration of the product - products that are widely used on the face and stay for a long time have a significantly higher exposure risk than those used locally and for a short period.
2.2. Heavy metals in cosmetics are any harmful to human health:
The harm of heavy metals to human health has the characteristics of multiple organs and multiple targets. Lead mainly damages the nervous system and hematopoietic system. Children are particularly sensitive to the neurodevelopmental toxicity of lead. Cadmium is nephrotoxic and ototoxic and can accumulate in the body for decades. Mercury causes serious damage to the kidneys and the nervous system. Arsenic is classified as a human carcinogen, and long-term exposure is closely related to skin cancer, bladder cancer and other diseases.
Absorption through the skin is the main way for heavy metals in cosmetics to enter the human body, but the absorption efficiency is affected by multiple factors, including the age of the skin, anatomical location, molecular volume, protein reactivity and formula matrix. It is worth noting that the skin barrier is not absolutely safe. Metal compounds or nanoparticles with strong lip solubility may be absorbed through the hair follicle and sweat gland pathways. A review indicates that when chronic exposure exceeds the safety threshold, metals/metalloids in cosmetics may increase the risk of cancer, neurological disorders, organ failure and abnormal fetal development.
Mercury poisoning has special warning significance in the field of cosmetics. In recent years, non-occupational mercury exposure has been on the rise, with cosmetics (especially whitening and freckle-removing products) being a significant source. Mercury poisoning can damage major organs such as the heart, liver and kidneys. Its mechanisms involve oxidative stress induction, mitochondrial dysfunction and inhibition of enzyme activity.
3. Research and Progress on Detection and Analysis Methods of Heavy Metals in Cosmetics.
3.1. Mainstream Detection technologies:
The accurate determination of heavy metals in cosmetics is the basis of risk assessment. The commonly used analytical methods at present include atomic absorption spectrometry (AAS), graphite furnace atomic absorption spectrometry (GFAAS), atomic fluorescence spectrometry (AFS), inductively coupled plasma optical emission spectrometry (ICP-OES), and inductively coupled plasma mass spectrometry (ICP-MS). The performance differences among various methods are mainly reflected in sensitivity, detection throughput and anti-interference ability.
The AAS method is relatively low in cost and easy to operate, but it can usually only perform single-element analysis, and its sensitivity is difficult to meet the requirements of trace detection. The GFAAS method significantly improves the detection limit through high-temperature atomization of graphite tubes and is particularly suitable for the analysis of trace amounts of lead and cadmium, but the analysis speed is relatively slow. ICP-OES can simultaneously determine multiple elements with a wide dynamic range, but its sensitivity to some trace elements is still inferior to that of ICP-MS. The ICP-MS method, with its high sensitivity, simultaneous determination of multiple elements and isotope analysis capabilities, has become the "gold standard" for heavy metal analysis in cosmetics.
3.2. Technical Advantages and Challenges of ICP-MS:
The core advantages of the ICP-MS method lie in: low detection limit (up to the ng/L level), wide linear dynamic range (up to nine orders of magnitude), the ability to simultaneously determine dozens of elements, and the provision of isotope abundance information. These features make it particularly suitable for multi-element screening and the confirmation analysis of trace excessive elements in cosmetics.
However, ICP-MS still faces several challenges in practical applications. Mass spectrometry interference is the main problem, including polyatomic ion interference, oxide interference, double-charged ion interference and isosterin interference. Non-mass spectrometry interference mainly stems from matrix effects and physical effects, such as signal drift and blockage caused by high-salt samples. In response to

these interferences, researchers have developed strategies such as collision/reaction cell technology, Years, the combination of new sample pretreatment techniques (such as microwave digestion and solid-

4. Assessment Framework and key Parameters for Health risks of Cosmetic.

mathematical correction (such as interference equations), and matrix matching standards. In recent phase extraction) with ICP-MS has further enhanced the efficiency and accuracy of analysis.

4.1. From concentration comparison to exposure assessment

For a long time, the safety assessment of cosmetics has mainly adopted the "concentration-limit comparison method" to detect whether the content of heavy metals in the products exceeds the maximum allowable concentration stipulated by regulations. However, this method has obvious limitations: it fails to reflect the exposure level of the product under actual usage conditions and neglects key factors such as usage frequency, dosage, and location.

In recent years, health risk assessment models based on exposure dose have gradually become mainstream. This type of method calculates the systemic exposure dose (SED) to derive toxicological indicators such as the margin of safety (MoS), hazard quotient (HQ), hazard index (HI), and lifetime cancer risk (LCR). Among them, MoS reflects the safe distance between the actual exposure level and the level of unobserved adverse effects (NOAEL), and it is generally considered safe only when MoS is greater than 100. HI is used to evaluate the non-carcinogenic combined effects of multiple metals, and a HI value less than 1 is acceptable. LCR quantifies the risk of cancer, and the US Environmental Protection Agency usually takes 10^{-6} to 10^{-4} as the acceptable range.

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4.2. Computational Model of SED: The calculation formula for systemic exposure dose (SED) is:

$SED = (Cs \times AA \times SSA \times RF \times F \times BF) / BW \times 10^{-3}$;

Among them, Cs represents the metal concentration in the product (mg/kg), AA is the daily product usage (g/day), SSA is the application area (cm²), RF is the retention factor (1 for retention type products), F is the daily usage frequency, BF is the bio accessibility factor, and BW is the average body weight (kg). The key parameters of this model (such as AA, SSA, and F) directly affect the evaluation results. However, most current studies adopt internationally recognized default values and lack measured data based on local consumption behavior. This direction needs to be improved in the future. For instance, some studies have evaluated the risks of facial products using parameters such as a cream usage of 0.51g per day, an application area of 565 cm², and a daily application frequency of twice. Whether these values are applicable to different countries and populations still needs to be verified.

5. Current regulatory Status and Development Trends of Heavy metals in cosmetics:

At present, there are significant differences in the regulatory requirements for heavy metals in cosmetics among various countries, and this inconsistency has caused troubles for multinational enterprises and consumers. The EU prohibits the intentional addition of heavy metals and only allows trace residues that are technically unavoidable. The mercury limit for eye products in the United States is 65 mg/kg, while California's Proposition 65 requires lead for lip products to be ≤5 mg/kg and for other products to be ≤10 mg/kg. China's "Cosmetics Safety Technical Specifications" (2015 Edition) has set clear limits for many harmful elements, but the specific limits are not exactly the same as those in other countries and regions. A systematic review points out that "there are significant differences in regulations and allowable limits among countries, which is a major challenge for the cosmetics industry", and it is urgent to promote the international coordination of limit standards.

5.2. Future Development Direction;

Based on the analysis of the current research status, future research can be deepened in the following directions:

First, establish a localized exposure assessment parameter system. At present, parameters such as usage volume, frequency and area in SED calculations mostly refer to data from European and American populations. There is an urgent need to conduct large-scale surveys based on the usage habits of Chinese consumers to provide a data basis for precise risk assessment.

Second, develop alternative toxicological evaluation methods for non-animals. With the increasingly strict restrictions on animal experiments, toxicity prediction methods based on cell models, organ-on-a-chip and computer simulation (in silico) will become an important development direction.

Third, pay attention to the safety of nanomaterials. Nano zinc oxide, nano titanium dioxide and other materials are widely used in sunscreen products, but their transdermal absorption, distribution in the body and long-term health effects remain unclear. How to evaluate the safety of nano-form metals is a new issue that needs to be urgently addressed.

Fourth, explore a comprehensive risk assessment of multi-pathway joint exposure. Consumers may use multiple products simultaneously, and the risk assessment of a single product may underestimate the actual exposure load. The evaluation of cumulative exposure and combined toxic effects requires more complex models and more sufficient data support.

6. Conclusion：

The impact of heavy metals in cosmetics on human health is an issue that combines scientific complexity and public importance. Over the past decade or so, detection technology has evolved from single-element atomic absorption to ICP-MS for multi-element synchronous analysis, and risk assessment has progressed from simple concentration comparison to comprehensive evaluation based on exposure dose and toxicological indicators. The advancement of research paradigms has provided stronger scientific support for consumer protection. However, the fragmentation of regulatory standards, the localization and absence of exposure parameters, as well as the insufficiency of safety data on new materials, remain the bottlenecks restricting precise risk assessment. In the future, interdisciplinary collaboration and global regulatory coordination will help build a safer and more scientific cosmetic safety management system - making beauty no longer come at the cost of health.

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