四川大学学报（医学版） 2024，55（6）：1573－1580
J Sichuan Univ（Med Sci） doi: 10.12182/20241160509
在线全文

# 重庆市膳食砷暴露水平及健康风险评估*

代兴慧[1,2]，李旻涛[1,2]，陈佳辉[1,2]，冯　萍[2]，陈京蓉[2]，赵　舰[2]，周倩如[2]，罗书全[2]，
张华东[2]，严晓峰[3]，霍　娇[2,3△]，练雪梅[1△]

1. 重庆医科大学公共卫生学院（重庆 400016）；2. 重庆市疾病预防控制中心（重庆 400042）；
3. 重庆市公共卫生医疗救治中心（重庆 400016）

【摘要】 **目的** 了解重庆市食品中砷含量，评估重庆市居民膳食砷暴露水平及其潜在健康风险。**方法** 利用2018–2023年重庆市食品砷含量监测数据，结合2018年中国营养与健康调查项目重庆市膳食调查数据，采用二维蒙特卡洛模拟法估计重庆市居民膳食砷暴露水平，并应用暴露限值法（margin of exposure, MOE）对经膳食摄入砷产生的非致癌风险（皮肤损伤）和致癌风险（肺癌、泌尿系统癌症）进行评估。**结果** 在4 900份食物样品中，总砷检出率为36.40%，平均含量中限值为0.020 7 mg/kg，上限值为0.023 4 mg/kg，大米及其制品的砷平均含量最高，中限值为0.098 1 mg/kg，上限值为0.098 5 mg/kg。不同年龄、性别和居住地居民的无机砷日均暴露量中3～6岁组最高，中限值为1.046 μg/(kg·d)，上限值为1.116 μg/(kg·d)，60岁以上组最低，男性高于女性，农村高于城市。在非致癌风险方面，各人群无机砷的MOE值均大于1；致癌风险方面，各人群无机砷的MOE值均小于100。大米及其制品是重庆市膳食砷暴露的主要来源，占总暴露量的69.97%～74.37%。**结论** 重庆市居民膳食砷暴露引起非致癌风险的威胁相对较低，但可能存在一定的致癌风险，低龄儿童砷暴露水平需要持续关注。

【关键词】 砷　膳食暴露　风险评估　蒙特卡洛模拟

**Assessment of Dietary Arsenic Exposure Levels and the Associated Health Risks in Chongqing City, China**

*DAI Xinghui*[1,2], *LI Mintao*[1,2], *CHEN Jiahui*[1,2], *FENG Ping*[2], *CHEN Jingrong*[2], *ZHAO Jian*[2], *ZHOU Qianru*[2], *LUO Shuquan*[2], *ZHANG Huadong*[2], *YAN Xiaofeng*[3], *HUO Jiao*[2,3△], *LIAN Xuemei*[1△]. 1. *School of Public Health*, *Chongqing Medical University*, Chongqing 400016, China; 2. *Chongqing Center for Disease Control and Prevention*, Chongqing 400042, China; 3. *Chongqing Public Health Medical Center*, Chongqing 400016, China

△ Corresponding author, HUO Jiao, E-mail: lamarhj@126.com; LIAN Xuemei, E-mail: xuemeilian@cqmu.edu.cn

【**Abstract**】 **Objective** To determine the levels of arsenic in food in Chongqing city, and to assess the levels of dietary arsenic exposure and the associated potential health risks in residents of Chongqing city. **Methods** By using the monitoring data on arsenic levels in food in Chongqing between 2018 and 2023 in combination with the local dietary survey data for Chongqing from the 2018 China Nutrition and Health Survey Program, and adopting the 2-dimensional Monte Carlo simulation, we made an estimate of the dietary arsenic exposure levels of Chongqing residents. The margin of exposure (MOE) method was applied to assess both non-carcinogenic risks (skin damage) and carcinogenic risks (lung cancer and urinary system cancers) associated with dietary intake of arsenic. **Results** Out of 4 900 food samples, the detection rate of arsenic was 36.40%, with the average levels ranging from the median bound (MB) of 0.020 7 to the upper bound (UB) of 0.023 4 mg/kg. The highest average levels were found in rice and its products, with an MB of 0.098 1 and a UB of 0.098 5 mg/kg. The daily average exposure to inorganic arsenic for residents of different ages, sexes, and places of residence was highest in individuals aged 3 to 6, with an MB of 1.046 μg/(kg·d) and a UB of 1.116 μg/(kg·d), and lowest among individuals aged 60 and older. Arsenic exposure was higher in males than that in females and higher in people living in rural areas compared to those in urban areas. In terms of non-carcinogenic risks, the MOE values for inorganic arsenic were always higher than 1 in various populations. As for carcinogenic risks, the MOE values were all less than 100 in various populations. Rice and its products were the main source of dietary arsenic exposure in Chongqing, accounting for 69.97% to 74.37% of the total exposure. **Conclusion** The non-carcinogenic risk caused by dietary arsenic exposure in Chongqing is relatively low, but there may be a certain level of carcinogenic risk. Continued attentions should be given to dietary arsenic exposure levels in young children.

【**Key words**】 Arsenic　Dietary exposure　Risk assessment　Monte carlo simulation

---

* 中国博士后科学基金面上项目（No. 2022M710549）、重庆市博士后特别资助项目（No. 2022CQBSHTB2065）和重庆市疾病预防控制与公共卫生研究中心资助

△ 通信作者，霍娇，E-mail: lamarhj@126.com；练雪梅，E-mail: xuemeilian@cqmu.edu.cn

出版日期：2024-11-20

砷(arsenic, As)是一种常见的类金属，以不同化学形式广泛存在于空气、岩石、土壤、水中[1-2]。砷在自然界中的存在形式分为无机砷和有机砷，在陆地来源食品中，主要为无机砷($As^{3+}$和$As^{5+}$)和甲基砷化物(甲基砷酸、二甲基砷酸)；在海产品中，主要为有机砷，如砷甜菜碱和砷糖[2]。

砷的毒性主要与其形态和溶解度有关，体现为无机砷毒性强于有机砷，三价砷毒性强于五价砷[3]。对于成人，$As_2O_3$经口致死剂量为100～300 mg，急性、亚急性砷中毒可影响身体的几乎所有生理系统，包括胃肠道、心血管、肾脏和神经系统[4]。人类长期接触无机砷主要会引起皮肤损伤[5]、癌症[6]、神经毒性[7]、心血管疾病[8]、糖代谢异常和糖尿病[9]。此外，砷易通过哺乳动物的胎盘屏障，引起胎儿发育畸形、流产或死胎等[3]。2012年，国际癌症研究机构(International Agency for Research on Cancer, IARC)确定无机砷化合物对实验动物具有明显的致癌作用，并提出会直接引起人类患肺癌、皮肤癌、膀胱癌，此外，肾癌、肝癌和前列腺癌也与其有关，无机砷及其化合物被列为Ⅰ类致癌物(对人具有致癌性)[10]。

近期，一项针对重庆市主要农产品区土壤重金属的研究发现，重庆市土壤中砷的平均含量为5.93 mg/kg[11]。另一项对重庆某农业集中区的研究表明，区内土壤砷污染为中度污染[12]。土壤重金属不仅会影响农作物的生长过程，还会通过生物富集作用进入人体，从而威胁人体健康。对于一般人群来说，食物和饮用水是接触砷的主要途径[4]。目前尚无针对重庆市膳食砷暴露的风险评估研究，因此，做好食品中砷污染情况的监测以及相应的膳食暴露风险评估至关重要。本文根据近年来重庆市各类食物砷含量监测数据和重庆市居民食物量消费数据，运用概率评估法对本市人群通过膳食暴露砷的非致癌风险与致癌风险进行评估。

## 1 资料与方法

### 1.1 材料

#### 1.1.1 砷含量数据

食品中总砷含量数据来自于重庆市食品安全监测系统2018–2023年的化学污染物监测数据。采取随机抽样原则，在重庆市39个城区及周边县区采样，样品来源涵盖屠宰/种植、流通(农贸市场、超市、便利店、专营店、网店)和餐饮环节。样本采集种类包括蛋及蛋制品、豆及豆制品、谷物及其制品、坚果及籽类、肉及肉制品、乳及乳制品、蔬菜及其制品、水产动物及其制品、水果及其制品和特殊膳食用食品共10大类4 900份样品。

#### 1.1.2 膳食消费量数据

膳食消费量数据来自于2018年中国健康与营养调查项目重庆市膳食调查数据。采用多阶段分层随机抽样，对重庆市6个区县(沙坪坝区、南岸区、大足区、奉节县、江津区、綦江区)969名居民进行膳食问卷调查，被调查者需回忆24 h内所有的进食情况，包括在家和外出进食，调查人员连续3 d入户调查。该膳食调查收集了居民的个人基本信息(年龄、性别、体质量、居住地等)和饮食消费信息(各类食物消费频率、消费量等)。对于7岁以下或75岁以上的人由成年家庭成员协助其回忆进食情况。

### 1.2 方法

#### 1.2.1 食品中砷含量检测方法及数据转化

食品中砷含量的检测参照GB 5009.11-2014《食品安全国家标准食品中总砷及无机砷的测定》氢化物发生原子荧光光谱法[13]和GB 5009.268-2016《食品安全国家标准食品中多元素的测定》电感耦合等离子质谱法[14]进行。各类食品的检出限(limit of detection, LOD)范围为0.000 6～0.040 0 mg/kg，所得检测值均为总砷浓度。

鉴于砷毒性作用主要在于无机砷，且目前对于有机砷的毒性研究数据较少，故本次研究中主要按无机砷可能造成的健康损害进行风险评估。因本研究所获取数值均为总砷，需将各类食品中总砷含量转化为无机砷，参考EFSA和WHO报告中无机砷与总砷的比例进行转化，详见表1。

表1 食物中的无机砷与总砷之比

Table 1 Averate ratios of inorganic arsenic to total arsenic in food

| Reference | Category | (Inorganic arsenic/ total arsenic)/% |
|---|---|---|
| EFSA 2014[2] | Beans and bean products | 70 |
| | Eggs and egg products | 70 |
| | Fruits and fruit products | 70 |
| WHO 2011[15] | Grains and grain products | 84 |
| | Meat and meat products | 100 |
| | Poultry | 41 |
| | Milk and dairy products | 26 |
| | Vegetables and vegetable products | 84 |
| | Aquatic animals and their products | 2 |

#### 1.2.2 砷暴露量计算

为了更好地估计重庆市居民经膳食摄入砷的暴露水平，量化可变性和不确定性，本文运用联合国粮农组织/世界卫生组织(Food and Agriculture Organization of the United Nations/World Health Organization, FAO/WHO)推荐的概率评估法进行估计[16]。利用蒙特卡洛(monte carlo)模拟, 以砷含量数据为暴露变量, 不同类型人群体重和消费量为暴露参数变量计算无机砷的暴露量概率分布。并采用拉丁超立方抽样从砷含量数据和消费量数据中随机抽样100 000次, 最适函数曲线以赤池信息量准则(akaike information criterion, AIC)作为判断依据。个体每人每公斤体重无机砷暴露量计算公式为:

$$\mathrm{EDI}=\sum_{i=1}^{n}\frac{(\mathrm{F}_i\times \mathrm{C}_i)}{\mathrm{BW}} \tag{1}$$

公式(1)中, 估计日摄入量(estimated daily intake, EDI)为某个体每天每公斤体质量砷的暴露水平, 单位为μg/(kg·d); $F_i$为某个体第$i$种食物的消费量, 单位为g/d; $C_i$为第$i$种食物中砷含量, 单位为mg/kg; BW为某个体的体质量, 单位为kg。

#### 1.2.3　砷风险评估

2010年, 食品添加剂联合专家委员会(Joint Expert Committee on Food Additives, JECFA)撤销了无机砷15 μg/(kg·w)的暂定每周耐受摄入量(provisional tolerated weekly intake, PTWI), 目前无明确的无机砷健康指导值[17], 且由于砷为非遗传毒性致癌物, 故本研究采用暴露限值法(margin of exposure, MOE)来评估膳食砷暴露对人群健康风险的影响[4]。MOE数值越大, 表明潜在风险越小。计算公式(2)如下:

$$\mathrm{MOE}=\frac{\mathrm{PoD}}{\mathrm{EDI}} \tag{2}$$

本次研究将对无机砷的主要非致癌性和致癌性损伤进行风险评估, 前者主要为皮肤损伤, 后者主要为泌尿系统癌症和肺癌。相应终点起始点(point of departure, PoD)的推导和选择基于JECFA 2011年的报告, 在该报告中基于流行病学研究结果, 确定了皮肤损伤、泌尿系统癌症和肺癌发病率增加0.5%的基准剂量下限(benchmark dose lower confidence limit, BMDL)分别为5.4、5.2和3 μg/(kg·d)[17]。本文据此来计算重庆市居民膳食砷暴露的一般风险(皮肤损伤)和致癌风险(肺癌、泌尿系统癌症)。因上述BMDL均根据人类流行病学研究结果制定, 可以认为不存在种间和种内差异, 因此在本篇研究中对于非致癌性风险, MOE≤1, 认为需关注其引起的健康风险, 反之则健康风险较低; 对于致癌性风险, 该数值为100。

#### 1.2.4　统计学方法

对样品砷含量小于检出限(LOD)的数据, 参照WHO和EFSA对于左删失数据的推荐处理方法——替代法, 分别用1/2 LOD、LOD代替中限(median bound, MB)、上限(upper bound, UB)[18-19]。使用SPSS 25.0软件进行数据统计分析, @RISK 8.2软件进行蒙特卡洛模拟及绘图。

## 2　结果

### 2.1　砷含量水平

由表2可知, 在2018–2023年监测的4 900份样品中, 总砷平均检出率为36.40%。19组食物中, 大米及其制品、特殊膳食用食品、其他谷物及其制品、坚果及籽类、叶菜类蔬菜检出率较高, 分别为89.87%、75.78%、52.73%、52.17%、50.13%, 禽肉、猪肉、豆类蔬菜检出率较低, 分别为16.42%、14.89%、10.26%。所有食物组的总砷平均含量为0.020 7(MB)～0.023 4(UB) mg/kg, 其中平均含量最高的是大米及其制品, 为0.098 1(MB)～0.098 5(UB) mg/kg, 其次是特殊膳食用食品和其他谷物及其制品, 分别为0.060 3(MB)～0.061 4(UB) mg/kg、0.050 7(MB)～0.052 1(UB) mg/kg, 平均含量最低的是乳及乳制品, 为0.004 2(MB)～0.007 3(UB) mg/kg, 其余食品总砷含量介于0.004 3(MB)～0.028 3(UB) mg/kg之间。

### 2.2　重庆市居民膳食砷暴露水平

图1~图3为不同人群一般消费和高消费(P95)的膳食无机砷暴露水平。在不同年龄组中, 3～6岁组砷膳食暴露量最高, 其平均暴露量和P95暴露量分别为1.046 μg/(kg·d)(MB)～1.116 μg/(kg·d)(UB)和2.789 μg/(kg·d)(MB)～2.875 μg/(kg·d)(UB), 各年龄组的无机砷日均暴露量随年龄增加而有所降低; 在性别组中, 男性的平均暴露量和P95暴露量略高于女性, 男性暴露水平均值为0.412 μg/(kg·d)(MB)～0.467 μg/(kg·d)(UB), P95为1.115 μg/(kg·d)(MB)～1.153 μg/(kg·d)(UB), 女性暴露水平均值为0.410 μg/(kg·d)(MB)～0.441 μg/(kg·d)(UB), P95为0.999 μg/(kg·d)(MB)～1.040 μg/(kg·d)(UB); 在居住地分组中, 农村人群的砷每日平均暴露量和P95暴露高于城市, 农村人群暴露水平均值为0.525 μg/(kg·d)(MB)～0.560 μg/(kg·d)(UB), P95为1.283 μg/(kg·d)(MB)～1.320 μg/(kg·d)(UB), 城市人群暴露水平均值为0.388 μg/(kg·d)(MB)～0.422 μg/(kg·d)(UB), P95为0.956 μg/(kg·d)(MB)～0.981 μg/(kg·d)(UB)。

### 2.3　重庆市居民膳食砷暴露风险特征描述

表3为重庆市不同人群膳食无机砷暴露风险水平。整体来看, 各人群砷暴露的非致癌风险处于正常范围内(MOE>1), 但致癌风险超出了可接受范围, MOE值均<100, 表明所有人群存在可能的致癌风险。值得注意的是, MOE值随年龄增长有一定的下降趋势, 3～6岁组患皮肤损伤、肺癌、泌尿系统癌症的MOE值为各组最低值, 说明儿童因膳食砷暴露引起致癌风险和非致癌风险比其他人群高, 需要持续关注。

表 2 2018–2023年重庆市售食品总砷含量

**Table 2 Total arsenic levels in food products sold in Chongqing in 2018-2023**

| Category | *n* | Detection rate/% | P5/(mg/kg) | | P50/(mg/kg) | | Mean/(mg/kg) | | P95/(mg/kg) | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | MB | UB | MB | UB | MB | UB | MB | UB |
| Eggs and egg products | 530 | 24.91 | 0.0020 | 0.0030 | 0.0050 | 0.0100 | 0.0164 | 0.0186 | 0.0677 | 0.0677 |
| Beans and bean products | 91 | 47.78 | 0.0010 | 0.0020 | 0.0050 | 0.0100 | 0.0113 | 0.0139 | 0.0593 | 0.0593 |
| Grains and grain products | 869 | 64.79 | 0.0010 | 0.0020 | 0.0320 | 0.0320 | 0.0624 | 0.0637 | 0.1725 | 0.1725 |
| Rice and rice products | 464 | 89.87 | 0.0050 | 0.0090 | 0.1070 | 0.1070 | 0.0981 | 0.0985 | 0.1833 | 0.1833 |
| Wheat and wheat products | 314 | 33.12 | 0.0010 | 0.0020 | 0.0050 | 0.0100 | 0.0131 | 0.0156 | 0.0711 | 0.0711 |
| Other grains and their products | 91 | 71.43 | 0.0016 | 0.0021 | 0.0050 | 0.0100 | 0.0507 | 0.0521 | 0.2100 | 0.2100 |
| Nuts and seeds | 46 | 52.17 | 0.0034 | 0.0050 | 0.0063 | 0.0100 | 0.0261 | 0.0283 | 0.1176 | 0.1176 |
| Alcoholic beverages | 48 | 27.08 | 0.0050 | 0.0010 | 0.0050 | 0.0100 | 0.0140 | 0.0177 | 0.0671 | 0.0671 |
| Meat and meat products | 807 | 18.22 | 0.0010 | 0.0020 | 0.0050 | 0.0100 | 0.0079 | 0.0108 | 0.0152 | 0.0152 |
| Pork | 262 | 14.89 | 0.0005 | 0.0010 | 0.0050 | 0.0100 | 0.0030 | 0.0112 | 0.0130 | 0.0130 |
| Beef, lamb, and rabbit meat | 60 | 26.67 | 0.0010 | 0.0020 | 0.0050 | 0.0100 | 0.0108 | 0.0138 | 0.0208 | 0.0208 |
| Poultry | 201 | 16.42 | 0.0005 | 0.0011 | 0.0050 | 0.0100 | 0.0067 | 0.0099 | 0.0169 | 0.0169 |
| Livestock and poultry offal | 284 | 20.77 | 0.0010 | 0.0020 | 0.0040 | 0.0047 | 0.0080 | 0.0105 | 0.0161 | 0.0161 |
| Milk and dairy products | 115 | 18.26 | 0.0011 | 0.0021 | 0.0040 | 0.0080 | 0.0042 | 0.0073 | 0.0080 | 0.0100 |
| Vegetables and vegetable products | 1383 | 35.36 | 0.0010 | 0.0020 | 0.0050 | 0.0080 | 0.0119 | 0.0139 | 0.0420 | 0.0420 |
| Leafy vegetables | 393 | 50.13 | 0.0014 | 0.0027 | 0.0050 | 0.0100 | 0.0159 | 0.0177 | 0.0650 | 0.0650 |
| Leguminous vegetables | 39 | 10.26 | 0.0010 | 0.0020 | 0.0040 | 0.0080 | 0.0043 | 0.0074 | 0.0100 | 0.0100 |
| Root and tuber vegetables | 319 | 26.33 | 0.0010 | 0.0019 | 0.0020 | 0.0040 | 0.0101 | 0.0120 | 0.0514 | 0.0514 |
| Other fresh vegetables | 632 | 32.28 | 0.0010 | 0.0020 | 0.0050 | 0.0080 | 0.0108 | 0.0129 | 0.0265 | 0.0272 |
| Aquatic animals and their products | 72 | 34.72 | 0.0005 | 0.0010 | 0.0050 | 0.0100 | 0.0223 | 0.0251 | 0.0947 | 0.0947 |
| Fruits and fruit products | 489 | 18.81 | 0.0010 | 0.0020 | 0.0050 | 0.0100 | 0.0080 | 0.0109 | 0.0295 | 0.0295 |
| Special dietary foods | 450 | 75.78 | 0.0023 | 0.0045 | 0.0500 | 0.0500 | 0.0603 | 0.0614 | 0.1500 | 0.1500 |
| Total | 4900 | 36.40 | 0.0016 | 0.0025 | 0.0125 | 0.0163 | 0.0207 | 0.0234 | 0.0673 | 0.0674 |

MB: median bound; UB: upper bound.

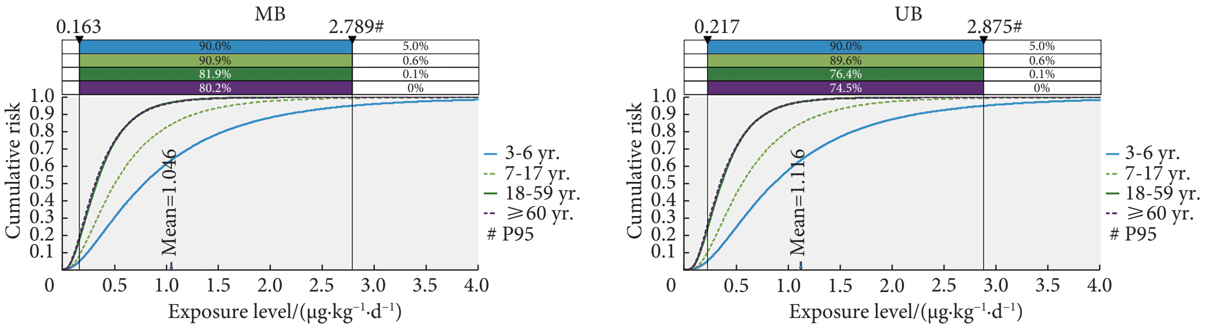


图 1 不同年龄组膳食砷暴露量

**Fig 1 Dietary arsenic exposure by different age groups**

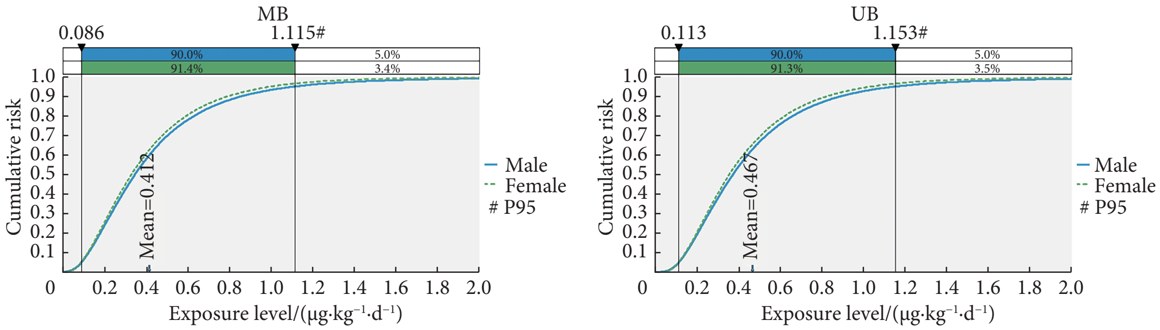


图 2 不同性别组膳食砷暴露量

**Fig 2 Dietary arsenic exposure for different sex groups**

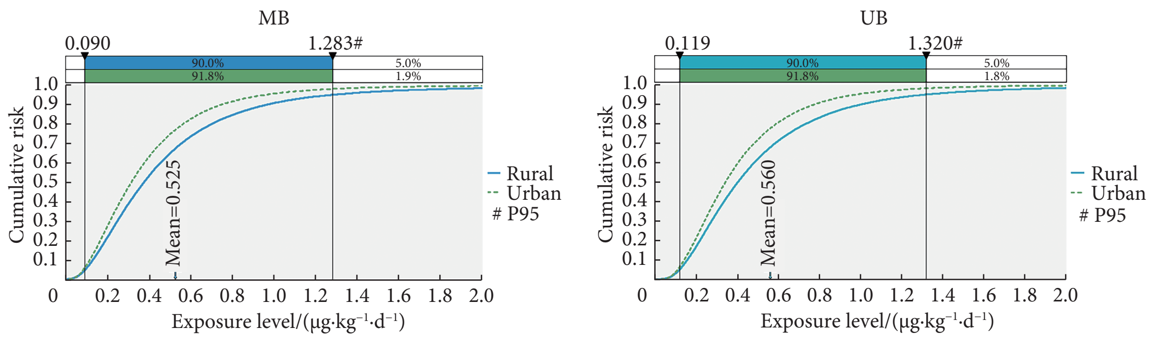


**图 3 不同居住地膳食砷暴露量**

**Fig 3 Dietary arsenic exposure by place of residence**

**表 3　重庆市不同人群膳食无机砷暴露风险水平**

**Table 3　Risk levels for exposure to dietary inorganic arsenic in different populations in Chongqing city**

| Population groups | | *n* | MOE (Skin damage) | | | | MOE (Urinary System Cancer) | | | | MOE (Lung cancer) | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | Mean (MB) | Mean (UB) | P95 (MB) | P95 (UB) | Mean (MB) | Mean (UB) | P95 (MB) | P95 (UB) | Mean (MB) | Mean (UB) | P95 (MB) | P95 (UB) |
| Age | 3-6 yr. | 31 | 5.163 | 4.858 | 1.936 | 1.878 | 4.971 | 4.678 | 1.864 | 1.809 | 2.868 | 2.699 | 1.076 | 1.043 |
| | 7-17 yr. | 113 | 8.438 | 7.837 | 3.364 | 3.261 | 8.125 | 7.547 | 3.240 | 3.140 | 4.688 | 4.354 | 1.869 | 1.812 |
| | 18-59 yr. | 399 | 13.740 | 12.796 | 5.902 | 5.690 | 13.232 | 12.322 | 5.683 | 5.479 | 7.634 | 7.109 | 3.279 | 3.161 |
| | ≥60 yr. | 426 | 13.953 | 13.012 | 5.794 | 5.666 | 13.437 | 12.530 | 5.579 | 5.456 | 7.752 | 7.229 | 3.219 | 3.148 |
| Sex | Male | 432 | 13.107 | 11.563 | 4.865 | 4.696 | 12.621 | 11.135 | 4.685 | 4.522 | 7.282 | 6.424 | 2.703 | 2.609 |
| | Female | 537 | 13.171 | 12.245 | 5.405 | 5.192 | 12.683 | 11.791 | 5.205 | 5.000 | 7.317 | 6.803 | 3.003 | 2.885 |
| Residence | Urban | 501 | 13.918 | 12.796 | 5.649 | 5.505 | 13.402 | 12.322 | 5.439 | 5.301 | 7.732 | 7.109 | 3.138 | 3.058 |
| | Rural | 468 | 10.286 | 9.643 | 4.219 | 4.060 | 9.905 | 9.286 | 4.063 | 3.910 | 5.714 | 5.357 | 2.344 | 2.256 |

### 2.4　重庆市居民膳食中砷暴露的各类食品贡献率

各类食物对不同人群的砷膳食暴露的贡献率见图4。由图可知，大米及其制品的贡献率远高于其他食物，是居民膳食砷暴露的主要来源，占总膳食暴露量的69.97% ~ 74.37%。其次是叶菜类蔬菜和其他谷物及其制品，分别占总膳食暴露量的4.89% ~ 8.85%、3.25% ~ 5.04%，其余食物的贡献率均小于5%。

## 3　讨论

本研究对2018–2023年重庆市4 900份食物样本的砷含量结果进行统计分析，结果表明，食品中砷含量的均值范围为0.020 7 ~ 0.023 4 mg/kg，检出率为36.40 %，低于吉林省(0.030 8 mg/kg)[20]和广西壮族自治区(0.061 mg/kg)[21]，这与我国土壤中砷含量分布情况基本一致[22]，说明膳食砷含量存在一定的不均衡性和地域性差异。在所有食物类别中，大米及其制品中砷的检出率和平均含量最高，分别为89.87%和0.098 1 ~ 0.098 5 mg/kg。

膳食暴露评估结果显示，不同人群无机砷暴露量为男性高于女性，农村高于城市，未成年人高于成年人。在不同的年龄组中，3 ~ 6岁组平均暴露量、P95暴露量最高，是成年人的2 ~ 3倍，这一研究结果与EFSA在2009年、2014年对欧洲人群食品中砷含量暴露评估的研究结果基本一致[2, 4]。庞洁等[23]对南宁市居民膳食砷暴露的研究中也发现，未成年人砷的日均暴露量比成年人更高。出现这一结果是因为，在相同的单位体重下，幼儿的食物摄入量是成人的3倍，导致饮食中无机砷的暴露量更大[4]。此外，婴幼儿辅食大多以大米为原料，也会导致该年龄段的暴露量更高。ZHENG等[24]在我国北京、广州、杭州的膳食调查也发现男性无机砷暴露量更高，这可能与不同人群的摄入量、体质量等暴露系数不同有关。大米及其制品因其消费量大且易富集砷，在人群中的膳食暴露贡献率可达69.97% ~ 74.37%。这提示我们应加强对各类食品，尤其是大米中砷含量的监测，着重关注大米及其制品对婴幼儿人群产生的健康影响。

根据JECFA制定的$BMDL_{0.5}$来计算重庆市居民膳食砷暴露的非致癌风险和致癌风险，发现各人群的MOE值均大于1，非致癌健康风险低，与我国吉林省[20]、嘉兴市[25]的研究结果类似，低于江西省[26]、内蒙古河套平原地区[27]和

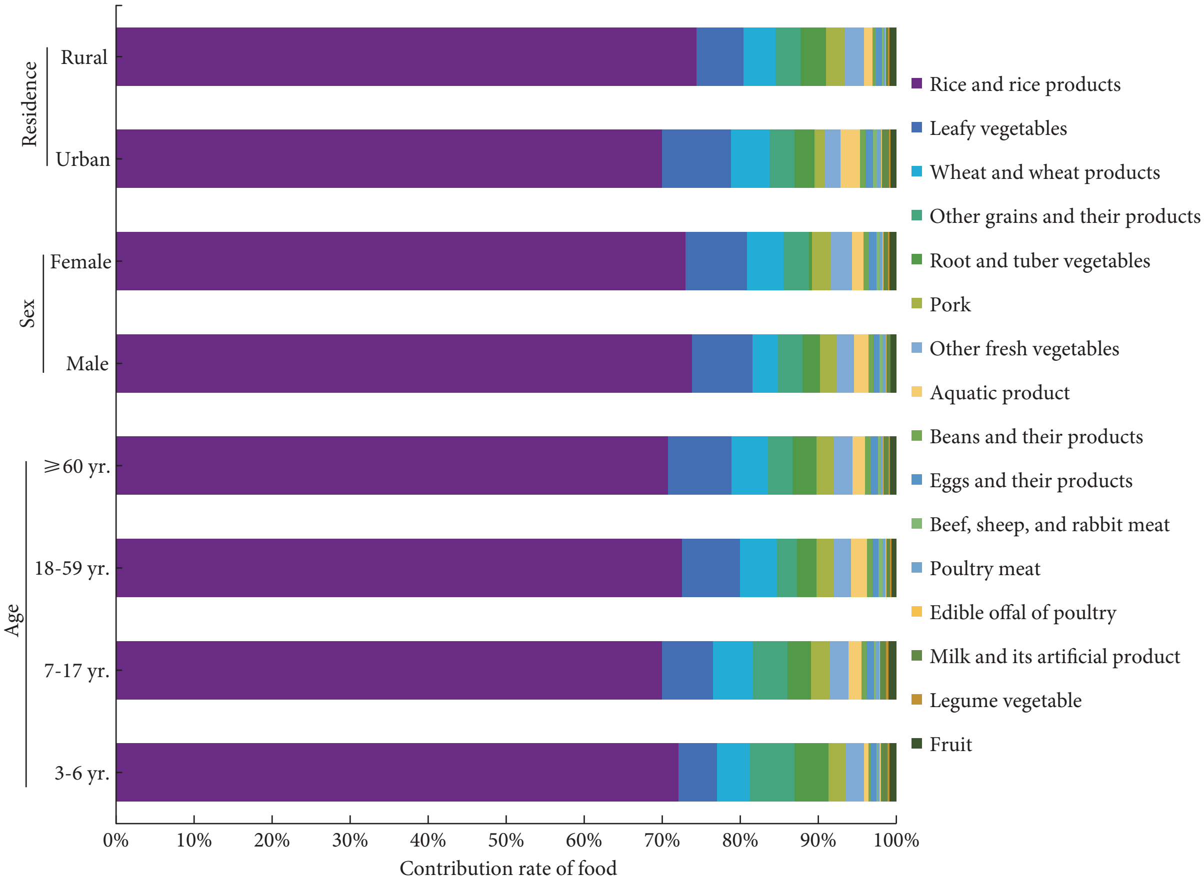


**图 4 各类食物对膳食砷暴露的贡献率**

**Fig 4 Contribution of food groups to dietary arsenic exposure (the contribution is calculated in MB)**

孟加拉国[28]的研究结果；可能存在一定的致癌风险，LIU等[29]对湖南省水稻砷暴露进行健康评价时也发现有潜在的致癌风险。不同研究结果出现差异的原因可能主要在于以下几点：① 本研究针对不同食物类别使用了不同的无机砷转换率，相比于其他使用同一转化率或直接计算总砷暴露量更为准确[27, 30]；② 本研究运用了概率评估法，使用二维蒙特卡洛模拟估计人群暴露水平，而其他研究[21]使用的是确定性评估方法(点评估或简单分布评估)，估计准确度不如概率评估方法；③ 部分研究在评估时纳入了饮水砷暴露量，而在本次研究中暂未纳入，可能会导致风险的低估[31]。

本研究也存在一定的不确定性，主要是以下几方面：一是本次研究中砷含量检测值均为总砷，虽然在暴露评估时已用转换系数转换为无机砷，但该方法可能会导致所得结果与实际情况存在一定偏差，可能会导致风险的低估或是高估；二是使用替代法处理左删失数据，可能会带来一定的不确定性，可能导致风险的低估或高估；三是数据获取过程可能会带来一定的不确定性，例如不同的检测机构、仪器设备以及操作人员对于食品样本检测的差异、居民膳食消费量使用的是3天24小时调查方式可能会损失一些食用频率较少的食品类型数据。

综上所述，重庆市膳食无机砷暴露导致的非致癌风险在可接受的范围内，但无机砷所致泌尿系统癌症和肺癌的MOE值均小于100，表明当地居民存在潜在的致癌风险。对重庆市居民而言，目前膳食砷暴露的主要风险来源于大米及其制品。本次研究发现目前仍严重缺乏不同食物类别中的无机砷含量数据，需要更多的研究数据提供进一步的风险信息。此次研究结果提示，特殊人群(婴幼儿、青少年)通过大米及其制品暴露于砷的健康风险需要持续关注，建议针对可能风险人群开展基于生物标志物的专项风险评估，以进一步确定健康风险大小。

* * *

**作者贡献声明** 代兴慧负责论文构思、数据审编、正式分析、研究方法、可视化和初稿写作，李旻涛负责数据审编和可视化，陈佳辉负责数据审编和正式分析，冯萍、陈京蓉和赵舰负责调查研究和研究项目管理，周倩如负责调查研究和提供资源，罗书全、张华东和严晓峰负责提供资源和监督指导，霍娇负责论文构思和审读与编辑写作，练雪梅负责审读与编辑写作。所有作者已经同意将文章提交给本刊，且对将要发表的版本进行最终定稿，并同意对工作的所有方面负责。

**Author Contribution** DAI Xinghui is responsible for conceptualization, data curation, formal analysis, methodology, visualization, and writing--

original draft. LI Mintao is responsible for data curation and visualization. CHEN Jiahui is responsible for data curation and formal analysis. FENG Ping, CHEN Jingrong, and ZHAO Jian are responsible for investigation and project administration. ZHOU Qianru is responsible for investigation and resources. LUO Shuquan, ZHANG Huadong, and YAN Xiaofeng are responsible for resources and supervision. HUO Jiao is responsible for conceptualization and writing--review and editing. LIAN Xuemei is responsible for writing--review and editing. All authors consented to the submission of the article to the Journal. All authors approved the final version to be published and agreed to take responsibility for all aspects of the work.

**利益冲突**　所有作者均声明不存在利益冲突

**Declaration of Conflicting Interests**　All authors declare no competing interests.

## 参 考 文 献


[1] European Food Safety Authority, ARCELLA D, CASCIO C, *et al*. Chronic dietary exposure to inorganic arsenic. EFSA J, 2021, 19(1): e06380. doi: 10.2903/j.efsa.2021.6380.

[2] European Food Safety Authority. Dietary exposure to inorganic arsenic in the european population. EFSA J, 2014, 12(3): 2014.3597. doi: 10.2903/j.efsa.2014.3597.

[3] EFSA Panel on Contaminants in the Food Chain (CONTAM), SCHRENK D, BIGNAMI M, *et al*. Update of the risk assessment of inorganic arsenic in food. EFSA J, 2024, 22(1): e8488. doi: 10.2903/j.efsa.2024.8488.

[4] EFSA Panel on Contaminants in the Food Chain. Scientific opinion on arsenic in food. EFSA J, 2009, 10: 1351. doi: 10.2903/j.efsa.2009.1351.

[5] YANG L, CHAI Y, YU J, *et al*. Associations of arsenic metabolites, methylation capacity, and skin lesions caused by chronic exposure to high arsenic in tube well water. Environ Toxicol, 2017, 32(1): 28-36. doi: 10.1002/tox.22209.

[6] KUMAR A, ALI M, KUMAR R, *et al*. Arsenic exposure in indo gangetic plains of bihar causing increased cancer risk. Sci Rep, 2021, 11(1): 2376. doi: 10.1038/s41598-021-81579-9.

[7] MOORE C L, FLANIGAN T J, LAW C D, *et al*. Developmental neurotoxicity of inorganic arsenic exposure in sprague-dawley rats. Neurotoxicol Teratol, 2019, 72: 49-57. doi: 10.1016/j.ntt.2019.01.007.

[8] GRAU-PEREZ M, CABALLERO-MATEOS M J, DOMINGO-RELLOSO A, *et al*. Toxic metals and subclinical atherosclerosis in carotid, femoral, and coronary vascular territories: the aragon workers health study. Arterioscler Thromb Vasc Biol, 2022, 42(1): 87-99. doi: 10.1161/ATVBAHA.121.316358.

[9] LI W, LI Z, YAN Y, *et al*. Urinary arsenic metabolism, genetic susceptibility, and their interaction on type 2 diabetes. Chemosphere, 2023, 345: 140536. doi: 10.1016/j.chemosphere.2023.140536.

[10] IARC Working Group on the Evaluation of Carcinogenic Risks to Humans. Arsenic, metals, fibres, and dusts. IARC Monogr Eval Carcinog Risks Hum, 2012, 100(Pt C): 11-465.

[11] MA J, CHU L, SUN J, *et al*. Health risk assessment of trace metal(loid)s in agricultural soils based on monte carlo simulation coupled with positive matrix factorization model in chongqing, southwest China. Journal of Mountain Science, 2024, 21(1): 100-112. doi: 10.1007/s11629-023-8304-2.

[12] 张雨涵, 李瑜, 官开江, 等. 重庆某农业集中区土壤重金属污染评价与来源解析. 中国土壤与肥料, 2024(7): 10-18. doi: 10.11838/sfsc.1673-6257.23527.
ZHANG Y H, LI Y, GUAN K J, *et al*. Evaluation of soil heavy metal pollution and source analysis in a agricultural concentrated area in Chongqing. Soil Fert Sci China, 2024(7): 10-18. doi: 10.11838/sfsc.1673-6257.23527.

[13] 中国人民共和国国家卫生和计划生育委员会. GB 5009.11—2014 食品安全国家标准 食品中总砷及无机砷的测定: GB 5009.11—2014. 北京: 中国标准出版社, 2015.http://down.foodmate.net/standard/yulan.php?itemid=47736.
National Health and Family Planning Commission of the People's Republic of China. GB 5009.11-2014 National Food Safety Standard Determination of Total Arsenic and Inorganic Arsenic in Food: GB 5009.11-2014. Beijing: China Standards Press, 2015. http://down.foodmate.net/standard/yulan.php?itemid=47736.

[14] 中国人民共和国国家卫生和计划生育委员会. GB 5009.268—2016 食品安全国家标准 食品中多元素的测定: GB 5009.268—2016. 北京: 中国标准出版社, 2016.
National Health and Family Planning Commission of the People's Republic of China. GB 5009.268-2016 National Food Safety Standard Determination of Multiple Elements in Food: GB 5009.268-2016. Beijing: China Standards Press, 2016. http://down.foodmate.net/standard/yulan.php?itemid=50423.

[15] World Health Organization. Evaluation of certain contaminants in food. World Health Organ Tech Rep Ser, 2011(959): 1-105.

[16] Food and Agriculture Organization of the United Nations/World Health Organization. Principles and methods for the risk assessment of chemicals in food. Ottawa: WHO Press, 2021.

[17] Food and Agriculture Organization/World Health Organization. Joint FAO/WHO Expert committee on food additives, Seventy-second meeting: summary and conclusions. FAO/WHO, 2010: 1-16. (2010-03-16)[2024-05-14]. https://www.who.int/publications/i/item/JECFA-72-SC.

[18] World Health Organization/international Programme Ve The Lo On Chemical Safety. Principles and methods for the risk assessment of chemicals in food, international programme on chemical safety, environmental health criteria 240. Chapter 6: Dietary exposure assessment of chemicals in food.

[19] European Food Safety Authority. Management of left-censored data in dietary exposure assessment of chemical substances. EFSA J, 2010, 8(3): 1557. doi: 10.2903/j.efsa.2010.1557.

[20] 刘思洁, 王慧, 王博, 等. 吉林省主要食品中砷污染状况及居民膳食暴露风险评估. 中国食品卫生杂志, 2018, 30(6): 645-649. doi: 10.13590/j.cjfh.2018.06.018.
LIU S J, WANG H, WANG B, *et al*. Arsenic contamination in main foods and the dietary exposure assessment for the population of Jilin Province. China Chin J Food Hyg, 2018, 30(6): 645-649. doi: 10.13590/j.cjfh.2018.

06.018.

[21] 蒋玉艳, 蒙浩洋, 陈晖, 等. 广西主要食品中砷污染及居民膳食暴露风险评估. 中国食品卫生杂志, 2017, 29(6): 745-749. doi: 10.13590/j.cjfh.2017.06.022.
JIANG Y Y, MENG H Y, CHEN H, *et al*. Risk assessment on the dietary exposure of arsenic in Guangxi residents. China Chin J Food Hyg, 2017, 29(6): 745-749. doi: 10.13590/j.cjfh.2017.06.022.

[22] ZHOU Y, NIU L, LIU K, *et al*. Arsenic in agricultural soils across China: Distribution pattern, accumulation trend, influencing factors, and risk assessment. Sci Total Environ, 2018, 616-617: 156-163. doi: 10.1016/j.scitotenv.2017.10.232.

[23] 庞洁, 梁善范, 唐琼, 等. 南宁市居民主要食品砷暴露健康风险评估. 实验室检测, 2023, 1(1): 44-49.
PANG J, LIANG S F, TANG Q, *et al*. Health risks assessment of arsenic exposure in main foods of residents in Nanning city. Lab Test, 2023, 1(1): 44-49.

[24] ZHENG X, ZHAO W, YAN X, *et al*. Pollution characteristics and health risk assessment of airborne heavy metals collected from beijing bus stations. Int J Environ Res Public Health, 2015, 12(8): 9658-9671. doi: 10.3390/ijerph120809658.

[25] 葛淼华, 周莹, 张翔, 等. 嘉兴市经营环节海产品中砷的形态分布与膳食暴露风险评估. 中国食品卫生杂志, 2023, 35(10): 1468-1474. doi: 10.13590/j.cjfh.2023.10.010.
GE M H, ZHOU Y, ZHANG X, *et al*. Speciation analysis and health risk assessment of arsenic in seafood from Jiaxing markets. Chin J Food Hyg, 2023, 35(10): 1468-1474. doi: 10.13590/j.cjfh.2023.10.010.

[26] 李娟, 谭洪涛, 周鸿, 等. 江西居民膳食中砷和硒暴露风险评估. 现代预防医学, 2021, 48(13): 2355-2357.
LI J, TAN H T, ZHOU H, *et al*. Risk assessment on dietary exposure of arsenic and selenium, Jiangxi. Mod Prev Med, 2021, 48(13): 2355-2357.

[27] ZHANG L, YANG Q, WANG H, *et al*. Genetic interpretation and health risk assessment of arsenic in hetao plain of inner mongolia, China. Environ Res, 2022, 208: 112680. doi: 10.1016/j.envres.2022.112680.

[28] AHMED Md K, SHAHEEN N, ISLAM Md S, *et al*. A comprehensive assessment of arsenic in commonly consumed foodstuffs to evaluate the potential health risk in bangladesh. Sci Total Environ, 2016, 544: 125-133. doi: 10.1016/j.scitotenv.2015.11.133.

[29] LIU Y, HUANG Y, LI L, *et al*. Arsenic source analysis of rice from different growing environments and health risk assessment in hunan province, China. J Food Composition Analysis, 2023, 123: 105637. doi: 10.1016/j.jfca.2023.105637.

[30] 袁文婷, 刘宇, 程国霞, 等. 陕西主要食品中砷污染及居民膳食暴露风险评估. 现代预防医学, 2021, 48(1): 55-58.
YUAN W T, LIU Y, CHENG G X, *et al*. Arsenic pollution in main foods in Shaanxi and risk assessment of residents' dietary exposure. Mod Prev Med, 2021, 48(1): 55-58.

[31] MANTHA M, YEARY E, TRENT J, *et al*. Estimating inorganic arsenic exposure from U.S rice and total water intakes. Environ Health Perspect, 2017, 125(5): 057005. doi: 10.1289/EHP418.

(2024－08－12收稿, 2024－10－22修回)

编辑 汤 洁