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研究报告

应用定量微生物风险评估海水浴场人体健康风险

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Liu Yikai, Ming Hongxia, Shi Tingting, Huang Huiling, Ren Kaijia, Li Dongwei, Su Jie, Jin Yuan, Fan Jingfeng. Assessment of human health risks from marine bathing beach: based on quantitative microbial risk assessment[J]. Microbiology China, 2022, 49(8): 3008-3020

摘　要：【背景】定量微生物风险评估作为定量评估游泳人群暴露于病原微生物后健康风险的方法，在国外已得到广泛应用，但目前国内的应用处于起步阶段且缺乏所需的游泳人群暴露数据。【目的】收集游泳人群暴露数据，并在海水浴场中进行应用，评估粪大肠菌群作为风险评估指标的可行性。【方法】通过对 6 个典型海水浴场的水质状况、粪大肠菌群浓度与环境因子的相关性进行分析，并发放调查问卷收集国内游泳人群的暴露数据，进而应用定量微生物风险评估方法，得出各个海水浴场的胃肠道疾病患病风险。【结果】6 个海水浴场中粪大肠菌群浓度均与水温、气温及总云量具有显著相关性(P<0.01)。位于南方的海水浴场粪便污染情况较北方严重，粪大肠菌群浓度第 95 百分位数远高于国内“差”类水质标准的阈值。儿童、成年男性、成年女性单次沐浴事件吞下海水的体积分别为 35.1 mL (95%置信区间为 32.4−37.8，α=0.578，β=0.016)，45.0 mL (95%置信区间为 31.1−59.3，α=0.532，β=0.012)，35.7 mL (95%置信区间为 29.7−41.8，α=0.753，β=0.032)。6 个海水浴场患胃肠道疾病的风险均远低于美国环保署规定的安全阈值。【结论】粪大肠菌群虽然对粪便污染具有良好的指示作用，但不适用作为评估海水浴场人体健康风险的指标，建议选取肠球菌与人源拟杆菌作为指示微生物。

关键词：海水浴场；定量微生物风险评估；模型参数；国内游泳人群；问卷调查；粪大肠菌群

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Assessment of human health risks from marine bathing beach: based on quantitative microbial risk assessment

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Abstract: [Background] Quantitative microbial risk assessment (QMRA), a valuable tool for estimating the burden of disease due to the exposure to pathogenic microorganisms, has been widely used abroad. However, the application in China is in its infancy and there is a lack of data on human exposure in marine bathing beaches. **[Objective]** To collect exposure data of swimming populations and apply them in marine bathing beaches to assess the feasibility of fecal coliform as a risk assessment indicator. **[Methods]** The correlation of water quality and fecal coliform concentration in six marine bathing beaches with environmental factors was analyzed, and the exposure data of domestic swimming populations were collected based on questionnaire survey. Then QMRA was employed to evaluate the risk of gastrointestinal diseases from each marine bathing area. **[Results]** Fecal coliform concentration in the six bathing areas was significantly correlated (P<0.01) with water temperature, air temperature, and total cloud cover. The fecal contamination in the southern bathing areas was more serious than that in the northern bathing areas, and the 95th percentile of fecal coliform concentration was much higher than the threshold of the domestic "poor" water quality standard. The volume of seawater swallowed by children, male adults, and female adults in a single bathing event was 35.1 mL (95% confidence interval=32.4–37.8, α=0.578, β=0.016), 45 mL (95% confidence interval=31.1–59.3, α=0.532, β=0.012), and 35.7 mL (95% confidence interval=29.7–41.8, α=0.753, β=0.032), respectively. The risk of gastrointestinal diseases from all six marine bathing sites was well below the safety threshold set by the US Environmental Protection Agency. **[Conclusion]** It is recommended *Enterococcus* and human *Bacteroides*, rather than fecal coliform which can reflects fecal contamination, be used as indicators of human health risk from marine bathing sites.

Keywords: marine bathing beach; quantitative microbial risk assessment; model parameters; domestic swimmers; questionnaire survey; fecal coliforms

接触娱乐水体通常会导致人体感染胃肠道疾病及急性发热呼吸道疾病。据报道，全世界每年因在娱乐水体中活动而感染胃肠道疾病的人数达 1.2 亿，感染急性呼吸道疾病的人数达 5 000 万例，感染肝炎等疾病的人数达 500 万−1 000 万人[1]。娱乐海域因病原微生物感染而造成的人体健康风险已成为公众及研究学者普遍关注的焦点问题。监测研究表明，娱乐水体可以作为多种病原体的载体，包括病毒(如腺病毒、诺如病毒、甲型肝炎病毒等)、细菌(如粪大肠菌群、肠球菌、创伤弧菌等)及寄生原生动物(如贾第鞭毛虫、隐孢子虫等)，并且在海水

浴场中最常见的感染性疾病为肠道疾病[2-4]。因此，对海水浴场中的病原微生物浓度进行监测，从而评估人体接触海水后的健康风险是非常有必要的。然而，在海水浴场的水体中病原微生物种类繁多，并且它们所引起的疾病取决于流行病学情景和环境条件。但对水体中所有病原微生物的浓度进行监测是不现实的，目前世界卫生组织(World Health Organization，WHO)建议在微生物水质管理方面应用定量微生物风险评估(quantitative microbial risk assessment，QMRA)方法进行风险评估[1]。

QMRA 作为一种结构化、系统、基于科学的方法，可以定量评估暴露于病原微生物危害的水平和由此产生的对人类健康的风险，其步骤主要为危害识别、剂量-反应评价、暴露评价和风险表征[1]。在过去的十几年里，国外已将 QMRA 方法应用于多种情形的海水浴场水质安全评价，其中包括：(1) 通过年龄或性别因素评估健康风险的差异[5-16]；(2) 在流行病学数据不完整的情况下人体接触病原微生物造成的健康风险[17-20]；(3) 强降雨天气和污水管道溢流(combined sewer overflow，CSO)对人体健康的影响[18,21-29]；(4) 游泳、钓鱼等水上活动对人体健康造成的影响[11,13,21-22,24,27-36]；(5) 水中多种粪便污染源对人体健康的影响[36-41]；(6) 从健康角度对 microbial source tracking (MST)标志物浓度进行分析[18,29,31,34,36,38,40]；(7) 休闲娱乐水域流行病学的研究[30]；(8) 评估控制措施对健康风险的影响[9]。虽然我国已经将 QMRA 方法初步应用于海水浴场中，并且国内城市居民暴露于寄生虫污染的娱乐性水体中的年暴露频率及单次暴露时间等参数已有研究，但是还不够全面，缺乏单次暴露的吞咽体积以及对儿童暴露参数的研究[42-45]。

本研究通过对国内不同年龄游泳人群进行问卷调查，以得到适用于对国内海水浴场健康风险评估的各项参数，并采用全国典型海水浴场 2003−2018 年的粪大肠菌群浓度数据来评价病原微生物带来的潜在人体健康风险，为海水浴场管理提供依据。

1 材料与方法

1.1 数据收集

综合考虑全国各海水浴场的区位、水质状况及数据获取条件等因素，选取深圳大梅沙海水浴场、海口假日海滩海水浴场、葫芦岛绥中海水浴场、大连金石滩海水浴场、秦皇岛北戴河老虎石海水浴场和青岛第一海水浴场等 6 个海水浴场，收集其在 2003−2018 年间粪大肠菌群常规监测数据。监测时段为每年游泳高峰期(6 月–10 月)，监测频率为每周一次，监测方法为发酵法(GB 17378.7—2007)，每个海水浴场的数据量为 1 394−4 074 条[46]。

于 2017−2019 年对游泳人群做了流行病学调查，共发放调查问卷 2 000 份，经筛查有效问卷 1 493 份，男性 768 份、女性 725 份，调查内容包括游泳人群的游泳年平均次数、游泳时长、游泳者的年龄信息及游泳习惯。根据年龄将其分为 6 个年龄段，0−4 岁(0.54%)、4−10 岁 (53.32%) 、10−20 岁 (25.25%) 、20−40 岁 (16.00%) 、40−60 岁 (4.29%) 及 60 岁以上 (0.60%)，并将 0−4 岁、4−10 岁及 10−20 岁归为儿童组。

1.2 数据处理

使用 SPSS 统计分析软件(V23.0)分析调查问卷数据，并将被调查者与国内一般人群(国家统计局，http://data.stats.gov.cn)在性别分布方面通过卡方检验进行比较，以评估被调查者是否能够很好地代表国内的一般人群。

关于吞咽海水体积的问卷数据由 4 个体积

类别的频率组成，这些体积类别按如下方式转换为实际体积。共有 200 人参加调查，被调查者分别从装有相同体积水的杯中共饮用 10 次(考虑到游泳时不慎摄入海水时应为正常吞咽体积)，测量每次饮用前后水的体积差。根据 Schets 等的研究，将口腔的容积假定为伽马分布，并在男性、女性和儿童之间进行比较[47]。问卷中关于吞咽量的类别都被假定为离散均匀分布，这意味着吞咽每一口水的概率是相等的。然后通过将测试得出的单口吞咽体积与调查问卷中的下水次数及吞咽口数相乘，得到单次海水浴场沐浴中吞咽海水量。

1.3 感染风险

在人体健康风险评估过程中，海水浴场的病原微生物浓度、游泳者所吞咽的病原微生物数量及其剂量反应关系是关键的 3 个参数。

1.3.1 暴露评价

本研究中暴露情景是指在海水浴场沐浴的游泳者不慎摄入海水所造成的感染肠道疾病的风险。本研究将游泳人群分为 3 种类型，分别为男性、女性和儿童。三类游泳人群所摄入水的体积根据流行病学调查获得。摄入病原微生物的剂量根据公式(1)得出[48]。

$$D=I\times C \tag{1}$$

式中，D 表示摄入病原微生物的数量，I 表示摄入海水的体积，C 表示病原微生物在海水中的浓度。

1.3.2 剂量-反应模型

剂量-反应模型通常用于已知病原微生物的数量，并以此为基础构建一个可以与感染疾病的可能性产生关联的数学函数，并且通过构建的剂量-反应模型实现对人体健康风险的评估。根据 Haas 等的研究，由粪大肠菌群所引起的肠道疾病的风险符合 β-possion 分布[49]。暴露于一定数量的粪大肠菌群后日患肠道疾病的风险根据公式(2)得出。

$$P_{FC}=1-[1+(D_{FC}/N_{50})\times(2^{1/a}-1)]^{-a} \tag{2}$$

式中，P_{FC} 表示与粪大肠菌群相关胃肠道疾病的日发生概率，D_{FC} 表示摄入的粪大肠菌群的数量，N_{50} 表示引起 50%暴露于粪大肠菌群海水的游泳人群感染剂量的中位数，a 表示斜率。根据 Hass 等的研究，N_{50} 和 a 的取值分别为 5.96×10^5 和 0.49。

1.4 数据分析

使用 Canoco V5.0 软件对粪大肠菌群浓度与水质指标、气象指标等进行相关性分析。使用 Matlab R2019 软件对所得与粪大肠菌群相关日患肠道疾病的风险数据抽样，进行 10 000 次蒙特卡洛模拟。

2 结果与分析

2.1 典型海水浴场水质情况

表 1 给出了 2003−2018 年 6 个海水浴场环境因子及粪大肠菌群浓度范围。由表 1 可知，6 个海水浴场的粪大肠菌群浓度整体在 1.0×10^1−9.2×10^4 CFU/L，气温、水温、pH 值、降雨量和溶解氧(dissolved oxygen, DO)整体在 9.4−38.6 °C、6.9−36.0 °C、7.15−8.96、0−255.6 mm 和 4.05−32.09 mg/L。位于南方的深圳大梅沙海水浴场及海口假日海水浴场的气温、水温、降雨量等环境因子整体均高于北方海水浴场。

图 1 分别显示了 6 个典型海水浴场中粪大肠菌群浓度分布情况。由图 1 结果可以看出，海口假日海滩海水浴场粪大肠菌群浓度分布较其他 5 个海水浴场集中，并且浓度明显高于其他浴场。

根据国内现行标准[50]，海水中粪大肠菌群的浓度小于 200 CFU/100 mL 时水质为“优”；大于 200 CFU/100 mL 且小于 2 000 CFU/100 mL 时水质为“良”；大于 2 000 CFU/100 mL 时水质为“差”。深圳大梅沙海水浴场水质为“优”

表 1　我国 6 个海水浴场环境因子及粪大肠菌群浓度范围

Table 1　Concentration ranges of environmental factors and fecal coliforms in six bathing beaches in China

Name of the bathing beach	Fecal coliforms (CFU/L)	Air temperature (°C)	Water temperature (°C)	pH value	Rainfall (mm)	DO (mg/L)
Shenzhen Dameisha bathing beach	10−2.9×10^4	19.5−37.4	21.3−36.0	7.80−8.96	0−255.6	4.05−17.91
Haikou holiday bathing beach	20−9.2×10^4	21.9−38.6	22.0−33.3	7.45−8.76	0−253.6	4.46−9.90
Huludao Suizhong Dongdaihe bathing beach	10−2.4×10^4	9.6−32.6	12.1−30.8	7.49−8.91	0−158.2	4.09−32.09
Dalian Jinshitan bathing beach	20−2.4×10^4	9.4−31.9	6.9−26.3	7.15−8.84	0−86.0	4.08−11.72
Qinhuangdao Laohushi bathing beach	10−4.2×10^4	11.9−33.7	18.4−28.2	7.45−8.34	0−105.3	4.05−9.71
Qingdao No.1 bathing beach	20−2.4×10^4	12.6−36.5	12.4−28.0	7.50−8.33	0−126.1	5.31−9.60

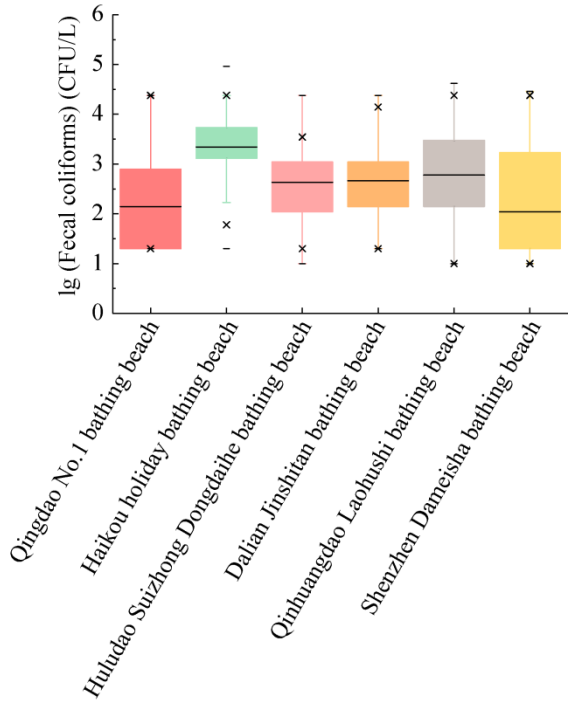

图 1　我国 6 个海水浴场粪大肠菌群浓度分布情况

Figure 1　Concentration distribution of fecal coliform in six bathing beaches in China.

“良”“差”的占比分别为 75.39%、16.88%和 7.73%；海口假日海滩海水浴场水质为“优”“良”“差”的占比分别为 43.71%、53.45%和 2.84%；葫芦岛海水浴场水质为“优”“良”“差”的占比分别为 94.24%、5.71%和 0.06%；大连金石滩海水浴场水质为“优”“良”“差”的占比分别为 94.41%、5.19%和 0.40%；秦皇岛北戴河老虎石海水浴场水质为“优”“良”“差”的占比分别为 70.14%、27.14%和 2.73%；青岛第一海水浴场水质为“优”“良”“差”的占比分别为 83.87%、12.64%和 3.49%。由图 2 结果可以看出，相较于其他 5 个海水浴场，海口假日海滩海水浴场的水质情况整体较差。其中，6 个典型海水浴场中水质为“差”的站位当天均有降雨，并根据 Pearson 相关性检验结果显示，发生降雨与粪大肠菌群超标存在极显著相关关系(P<0.001)。

2.2　典型海水浴场粪大肠菌群浓度变化影响因素

使用 SPSS 软件对全国典型海水浴场中粪大肠菌群浓度与其各自的环境因子进行共线性检验，VIF 值在 0−3 之间，均小于 10，表明粪大肠菌群浓度与环境因子间均不存在明显的共线性关系。之后对粪大肠菌群与环境因子进行相关性分析，结果如表 2 所示。在 6 个海水浴场中，粪大肠菌群浓度均与水温、气温及总云量呈显著正相关 (P<0.01)；仅深圳大梅沙海水浴场、海口假日海滩海水浴场及青岛第一海水浴场中粪大肠菌群浓度与降雨量具有显著相关性(P<0.05)。

2.3　国内游泳人群游泳习惯特征

问卷调查过程中，对被调查者在性别分布方面与国内普通人群进行卡方检验，结果显示并无显著差异(P>0.05)，表明被调查者很好地代表了国内普通人群。

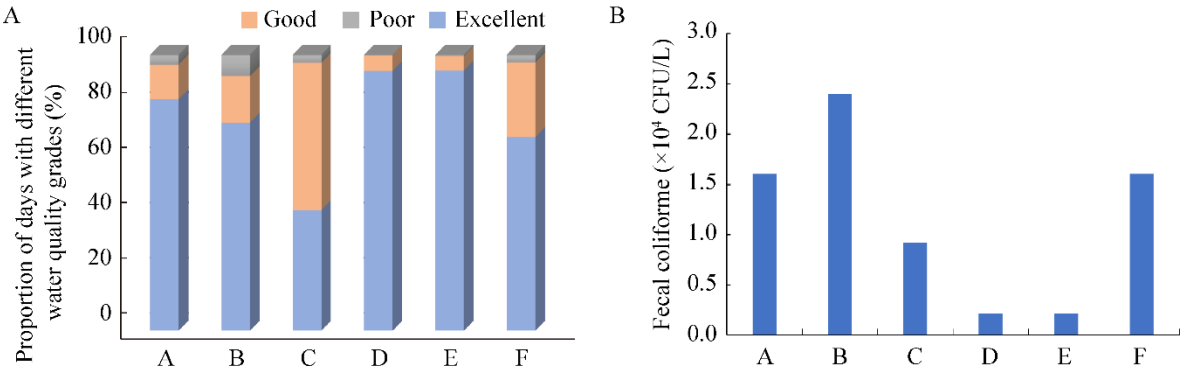

图 2　我国 6 个海水浴场不同水质等级天数比例(A)及粪大肠菌群浓度第 95 百分位数(B)　A：青岛第一海水浴场；B：深圳大梅沙海水浴场；C：海口假日海滩海水浴场；D：葫芦岛绥中海水浴场；E：大连金石滩海水浴场；F：秦皇岛北戴河老虎石海水浴场

Figure 2　The percentage of days with different water quality grades and the 95 th percentile of the concentration of fecal coliforms in six beaches in China. A: Qingdao No.1 bathing beach; B: Shenzhen Dameisha bathing beach; C: Haikou holiday bathing beach; D: Huludao Suizhong Dongdaihe bathing beach; E: Dalian Jinshitan bathing beach; F: Qinhuangdao Laohushi bathing beach

表 2　我国 6 个海水浴场粪大肠菌浓度与环境因子 Pearson 相关性分析

Table 2　Correlation analysis of fecal coliform concentrations and environmental factors Pearson in six bathing beaches in China

Name of the bathing beach	pH value	DO	Water temperature	Wave height	Wind speed	Wind direction	Air temperature	Visibility	Total cloud amount	Rainfall
Shenzhen Dameisha bathing beach	0.039*	−0.002	0.125**	−0.050**	−0.053**	−0.025	0.063**	0.022	0.131**	0.199**
Haikou holiday bathing beach	−0.022	−0.017	0.051**	0.204**	0.092**	−0.081**	0.049**	0.089**	0.106**	0.118**
Huludao Suizhong Dongdaihe bathing beach	0.004	0.041**	0.150**	0.002	−0.030	−0.021	0.130**	0.016	0.066**	0.008
Dalian Jinshitan bathing beach	0.000	−0.052**	0.154**	−0.016	−0.055**	−0.011	0.162**	0.023	0.037**	0.004
Qinhuangdao Laohushi bathing beach	−0.016	−0.039*	0.039**	−0.030	−0.030	−0.030	0.061**	0.007	0.060**	0.009
Qingdao No.1 bathing beach	−0.014	−0.029	0.038*	0.017	−0.097**	0.015	0.022	0.073**	0.068**	−0.040*

Note: *: $P<0.05$; **: $P<0.01$.

对调查问卷进行描述性统计，结果如表 3 所示。儿童组与成人组的游泳习惯、游泳时长及游泳后的不适症状均存在显著性差异($P<0.01$)。在对游泳过程中单次下水吞咽海水量的调查中，不吞咽的情况在儿童和成人中均占比最高，分别为 41.74%、44.55%。对调查问卷中的游泳时长及游泳后不适症状使用独立样本 t 检验进行统计分析，发现儿童更有可能持续更久的游泳时间，并更有可能在游泳后发生相关疾病($P<0.01$)。

表 3 对被调查者的描述性统计

Table 3 Descriptive statistics of responders to inquiries

Questionnaire options	Children (<20 years)		Adults (>20 years)	
	Number	Percentage of options among children (%)	Number	Percentage of options among children (%)
The questionnaire	1 181		312	
Male	602	51.00	159	51.00
Female	579	49.00	153	49.00
Swallow times during one swimming event				
No swallowing	493	41.74	139	44.55
One swallow	347	29.38	115	36.86
Two swallows	154	13.04	34	10.90
Three swallows	58	4.91	8	2.56
More than three swallows	129	10.92	16	5.13
Swimming duration				
Less than one hour	471	39.88	185	59.29
1−2 hours	412	34.89	117	37.50
2−3 hours	158	13.38	7	2.24
More than three hours	140	11.85	3	0.96
Discomfort after swimming				
No discomfort	1 092	91.08	288	89.44
Conjunctivitis	24	2.00	10	3.11
Tympanitis	30	2.50	13	4.04
Nasosinusitis	15	1.25	4	1.24
Pharyngitis	8	0.67	0	0.00
Diarrhea	30	2.50	7	2.17

将单口吞咽水的体积、单次下水的吞咽口数与对应的下水次数相乘得到单次沐浴事件的吞咽量，并通过适合优度测试，得到单次沐浴事件的吞咽量符合伽马分布，与 Schets 等的研究结果[47]相同。儿童单次沐浴事件吞下海水的体积为 35.1 mL (95%置信区间为 32.4−37.8，α=0.578，β=0.016)，成年男性单次沐浴事件吞下海水的体积为 45.0 mL (95%置信区间为 31.1−59.3，α=0.532，β=0.012)，成年女性单次沐浴事件吞下海水的体积为 35.7 mL (95%置信区间为 29.7−41.8，α=0.753，β=0.032)。

2.4 人体健康风险评估结果

根据 6 个海水浴场的粪大肠菌群浓度，分别绘制感染胃肠道疾病的中位数概率和四分位数范围，并将结果与美国环境保护署(Environmental Protection Agency，EPA)规定的可接受的风险阈值 19‰ (即每 1 000 名游泳者中有 19 个患病病例)[51]进行比较(图 3)。由图 3 可以看出，相较于其他 5 个浴场，海口假日海滩海水浴场游泳者患胃肠道疾病风险更高。在 6 个海水浴场中，儿童的患病风险均低于成人。

使用 Matlab 软件对 6 个海水浴场的患病风险通过蒙特卡洛模拟，随机进行 10 000 次迭代，结果如图 4 所示。由图 4 可见，6 个海水浴场中海口假日海滩海水浴场的患病风险较高，但儿童、男性及女性的患病风险均未超过 EPA 规定的可接受的风险阈值，最高为 10‰，并且海口假日海滩海水浴场的患病风险与其纬度相近的深圳大梅沙海水浴场存在较大差异。

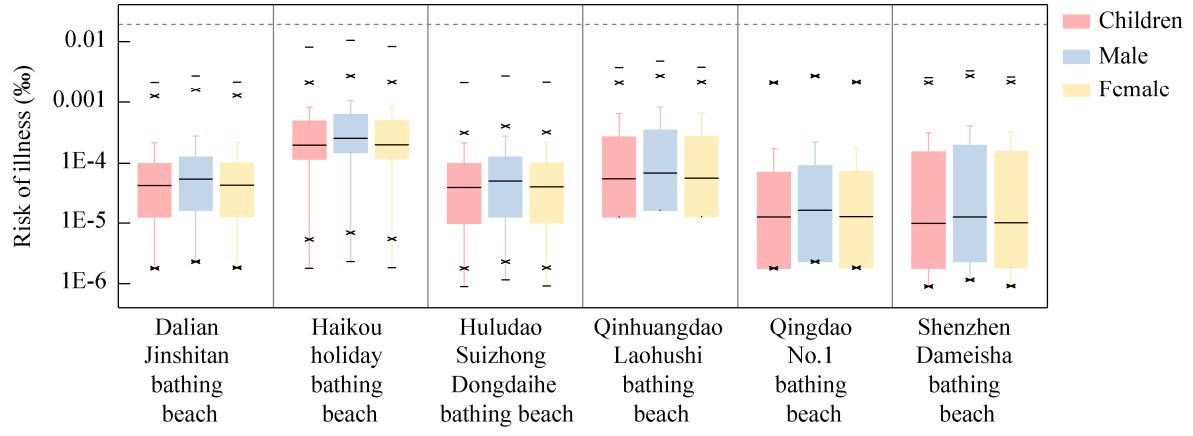

图 3　基于粪大肠菌群的我国 6 个海水浴场的患病概率

Figure 3　Probability of illness in six beaches based on fecal coliforms in China.

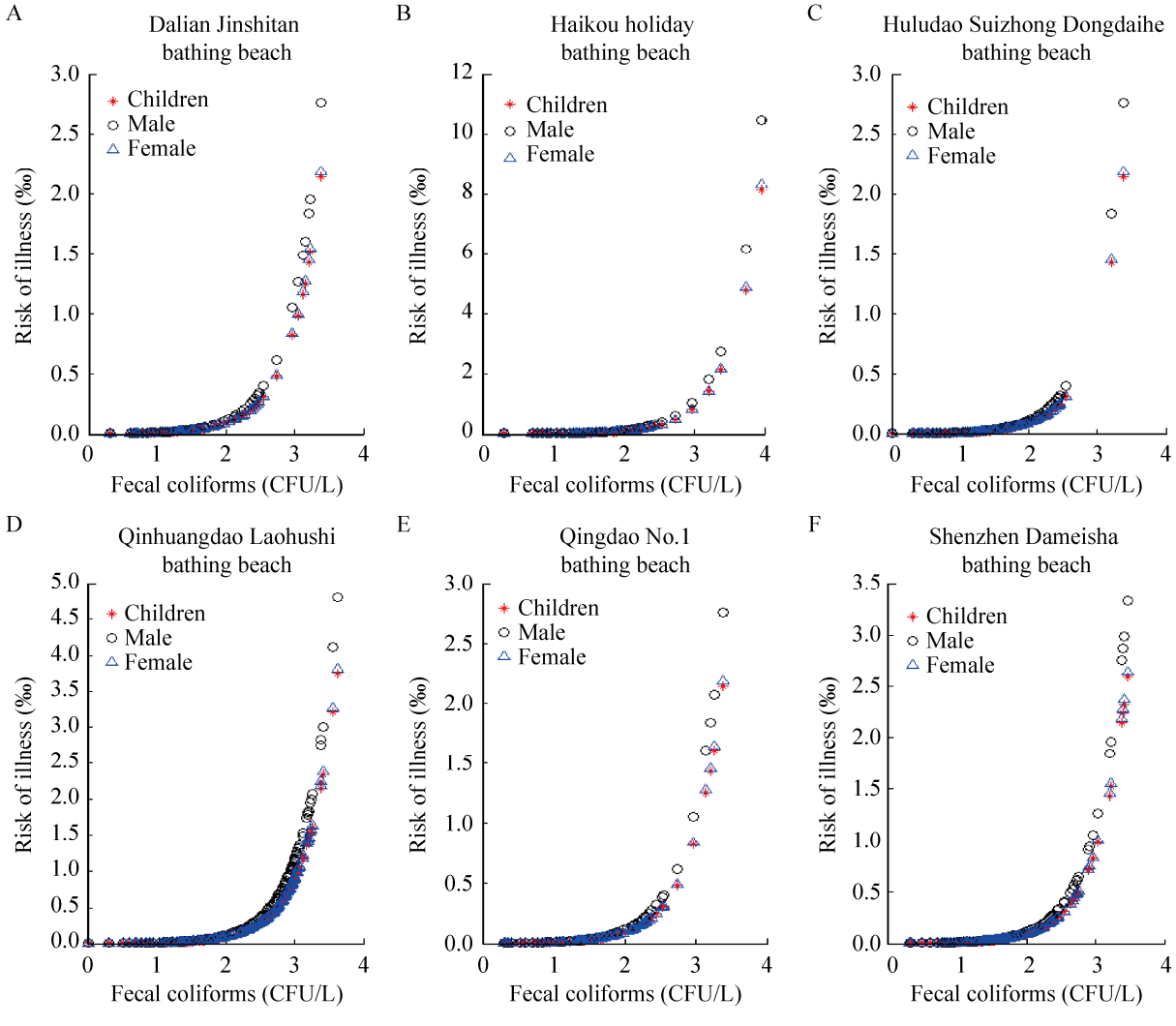

图 4　我国 6 个海水浴场粪大肠菌群健康风险蒙特卡洛模拟结果

Figure 4　Monte Carlo simulation results of fecal coliform health risks in six bathing beaches in China.

3 讨论

3.1 海水浴场中粪大肠菌群浓度影响因素

本研究通过对我国 6 个海水浴场中粪大肠菌群浓度与环境因子进行相关性分析，发现在 6 个海水浴场中，5 个典型浴场海水中粪大肠菌群浓度均与水温、气温及总云量具有显著相关性。水温是微生物生长繁殖的重要理化因子之一，粪大肠菌群作为革兰氏阴性无芽孢杆菌可以在 44 °C 培养生长[52]。6 个海水浴场的水温变化范围在 6.9−36.0 °C 之间，均低于其最适生长温度，因此在该水温范围内温度越高，粪大肠菌群的活性越高，在水体中生长繁殖越快。气温对粪大肠菌群的活性也具有相同的影响效果，气温的升高会导致表层水温升高。此外，总云量对海水浴场中粪大肠菌群浓度的影响主要体现在太阳辐射，太阳辐射是影响微生物在水体中活性的主要原因，而太阳光到达水体的辐射量与高空中的云量有关，云量的多少可显著影响太阳光的辐射量[53]。位于南方的深圳大梅沙海水浴场及海口假日海滩海水浴场的粪大肠菌群浓度不仅与上述三类环境因子有关，还与降雨量存在显著相关性。因为在海水浴场中，不仅海水是病原微生物的储存库，沙滩也同样具有强大的储存病原微生物的能力[54]。降雨会通过影响地表径流，将原本附着在沙粒上的粪大肠菌群水平或者垂直冲刷入海水中。同时，由于南北方海水浴场中沙滩的沙粒情况可能存在较大差异，因此在降雨过后南方海水浴场中的粪大肠菌群会呈现大幅度增加的趋势[55-57]。

3.2 国内游泳人群暴露参数特征

对 6 个海水浴场以粪大肠菌群浓度为指标进行人体健康风险评估，得到的结果与石岩的研究结果[58]不同，石岩通过对全国 23 个重点海水浴场的人体健康风险进行评估，得出在 23 个海水浴场中儿童患胃肠道风险的概率均高于成年人。推测可能是由于单次游泳事件吞咽海水量的估计值不同导致，石岩的研究采用国外的统计数据，而本研究采用前期对国内游泳人群发放的调查问卷所得数据[58]。使用国外的吞咽海水数据作为估计值，会因国内外游泳人群的游泳习惯差异对人体健康风险评估的结果造成直接影响。同时在对海水浴场患病风险进行评估的过程中，不同年龄的游泳人群均采用同一剂量-反应模型，而儿童的免疫力较成人更低，摄入相同数量的粪大肠菌群可能会导致更高的患病风险，使计算所得的健康风险评估结果与实际情况具有较大的偏差，从而影响浴场管理者对管理措施的有效制定，建议下一步根据游泳者不同的年龄段将剂量-效应模型参数进行优化。

3.3 粪大肠菌群作为健康风险指标可行性分析

对 6 个海水浴场的粪大肠菌群浓度情况进行分析，结果表明 6 个海水浴场均存在粪大肠菌群浓度超标的情况。位于南方的深圳大梅沙海水浴场与海口假日海滩海水浴场中水质等级为“优”的比例均低于其他 4 个海水浴场，并且这 2 个海水浴场中粪大肠菌群浓度第 95 百分位数达 2 900 CFU/100 mL，均高于水质等级为“差”的阈值(2 000 CFU/100 mL)，表明南方海水浴场受粪便污染可能较北方严重。同时纬度相近的秦皇岛北戴河老虎石海水浴场与葫芦岛绥中海水浴场、深圳大梅沙海水浴场与海口假日海滩海水浴场中各等级水质所占比例及粪大肠菌群浓度第 95 百分位数存在较明显的差异，推测海水浴场的水质状况不仅受南北方差异的影响，还受浴场所处地理及人文环境如地形、海流、地表径流及海水浴场人流量等的影响。然而对 6 个海水浴场应用 QMRA 方法进行人体健

康风险评估，得到的结果显示游泳者在 6 个海水浴场游泳后患胃肠道疾病的风险均远低于 EPA 规定的可接受的风险阈值,最高仅为 10‰。上述结果表明，粪大肠菌群虽然对粪便污染具有良好的指示作用，但不适用作为健康风险评估的指标。同时已有的流行病学调查结果显示，海水中粪大肠菌群浓度与胃肠道疾病症状的相关性较差，并且粪大肠菌群作为粪便污染指示菌的一种，其与海水中病原菌的浓度无显著相关性。因此，美国环境保护署在 2012 年颁布的标准中用肠球菌代替粪大肠菌群进行人体健康风险评估[59-61]。Fan 等对大连星海海水浴场的研究也表明，粪大肠菌群与海水中其他病原菌的相关性均较差，而肠球菌和人源拟杆菌在多数情况下可指示主要病原菌(金黄色葡萄球菌、粪链球菌和腔气单胞菌)的污染情况，建议国内海水浴场选用肠球菌与人源拟杆菌作为海水浴场水质评价指标，开展海水浴场风险评价[62-63]。

4 结论

本研究分析了国内游泳人群的游泳习惯特征、6 个海水浴场中粪大肠菌群与环境因子关系及基于粪大肠菌群浓度的人体健康风险评估，结果发现：(1) 深圳大梅沙海水浴场、海口假日海滩海水浴场、葫芦岛绥中海水浴场、大连金石滩海水浴场、秦皇岛北戴河老虎石海水浴场和青岛第一海水浴场中粪大肠菌浓度均与水温、气温及总云量呈现显著正相关关系；(2) 不同年龄游泳人群的游泳时长、泳后不适症状具有显著差异，儿童更有可能持续更久的游泳时间，并更可能在泳后发生相关疾病；(3) 虽然基于粪大肠菌群数量评价高温、降雨后海口假日等海水浴场水质较差，但是基于 QMRA 方法评价的病原微生物患病概率均远低于美国环保署规定的可接受风险阈值，建议选取肠球菌与人源拟杆菌作为指示微生物开展海水浴场风险评价，保护公众亲海安全。

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