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Water Quality Indicators and the Risk of Illness at Beaches With Nonpoint Sources of Fecal Contamination

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Background: Indicator bacteria are a good predictor of illness at marine beaches that have point sources of pollution with human fecal content. Few studies have addressed the utility of indicator bacteria where nonpoint sources are the dominant fecal input. Extrapolating current water-quality thresholds to such locations is uncertain.

Methods: In a cohort of 8797 beachgoers at Mission Bay, California, we measured baseline health at the time of exposure and 2 weeks later. Water samples were analyzed for bacterial indicators (enterococcus, fecal coliforms, total coliforms) using both traditional and nontraditional methods, ie, chromogenic substrate or quantitative polymerase chain reaction. A novel bacterial indicator (Bacteroides) and viruses (coliphage, adenovirus, norovirus) also were measured. Associations of 14 health outcomes with both water exposure and water quality indicators were assessed.

Results: Diarrhea and skin rash incidence were the only symptoms that were increased in swimmers compared with nonswimmers. The incidence of illness was not associated with any of the indicators that traditionally are used to monitor beaches. Among nontraditional water quality indicators, associations with illness were observed only for male-specific coliphage, although a low number of participants were exposed to water at times when coliphage was detected.

Conclusions: Traditional fecal indicators currently used to monitor these beaches were not associated with health risks. These results suggest a need for alternative indicators of water quality where nonpoint sources are dominant fecal contributors.

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Editors' note: A commentary on this article appears on page 21.

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Fecal indicator bacteria are monitored at marine recreational bathing beaches to assess the risk of swimming-related illnesses. In southern California, more than 85,000 samples are collected and $3 million is spent annually to assess this public health risk.[1] The focus on bacteria as a public health monitoring tool is based on the relationship between the density of fecal indicator bacteria and the occurrence of illnesses among persons with water exposure.

Numerous studies have demonstrated the relationship between fecal indicator bacteria at marine beaches and swimming-related illnesses.[2,3] Cabelli et al[4,5] reported a relationship between enterococcus and illness at several beaches. Haile et al[6] reported an association between enterococcus, fecal, and total coliforms and swimming-related illnesses in Santa Monica Bay, California. These studies contributed to the establishment of water-quality thresholds at marine beaches using fecal indicator bacteria.

Although previous studies demonstrated the value of fecal indicator bacteria, virtually all were conducted at locations at which human sewage was the predominant contamination source. Only the study by Haile et al[6] focused on urban runoff as a source, but even this nonpoint source was known to contain nearby human sources of fecal contamination.[6] Most water-quality problems on California beaches are attributable to nonpoint source runoff,[7,8] and it is not certain that waterborne bacterial indicators would be as predictive when nonhuman sources predominate.[9] Animals can shed bacterial indicators without certain accompanying human pathogens.[10] For this reason, there is uncertainty about the current practice of extrapolating water-quality thresholds based on studies of human point source to nonpoint sources dominated by animal-associated fecal contamination. A poor correlation between bacterial indicators and virus concentrations has been found in urban runoff,[11,12] in contrast to the substantial relationships in water bodies polluted by human fecal sources (eg, septic tanks).[13] This discrepancy is further complicated by the differential survival of bacteria relative to viruses, particularly in marine water. Enteric viruses and bacterial viruses (ie, coliphage) are promising indicators of fecal contamination, but they have been inadequately studied as predictors of health effects in bathers.[14] The human specific viruses most commonly associated with symptoms in swimmers include adenovirus and norovirus. Coliphages are viruses that infect *Escherichia coli* bacteria. As such, they may be more useful than *E. coli* alone, since coliphage survival may be more akin to virus survival than fecal-indicator bacteria. The F+ coliphages, in particular, are most commonly associated with fecal material and sewage.

We conducted a cohort study in Mission Bay, California, where state water-quality standards have been exceeded approximately 20% of the time.[15] Several million dollars have been expended to reduce human contamination by inspecting and repairing the sanitary sewerage system surrounding the bay and diverting larger storm drains away from the bay. Recent source-tracking studies suggested that human fecal material constitutes a minor proportion (<10%) of fecal inputs to the Bay.[16] However, Mission Bay continues to exceed California water quality standards.[15,17]

To address the need for faster, more specific water-quality measurements, microbiologists are developing robust new test methods. Chromogenic substrate assays for fecal indicators have become increasingly popular because they are faster and easier than traditional methods while producing comparable results.[18] Gene-based techniques are not yet commercially available for fecal indicator bacteria, but researchers are capable of obtaining results in a matter of hours.[19] Finally, researchers are exploring new microbial indicators, such as Bacteroides, a group of obligate anaerobes that are abundant in intestinal flora.[20,21] Gene-based techniques also provide new tools for directly measuring pathogens, including human specific viruses.[22–24] Regardless of rapidity, specificity, or cost, the efficacy of any new public health monitoring tool can be evaluated only through epidemiologic studies that document relationships to the incidence of swimming-related illness.

The goal of this study was to examine health effects experienced by swimmers and the relationship of these effects to water quality indicators in water in which nonhuman fecal sources dominate. The study was designed to determine whether water contact increased the risk of illness in the 2 weeks after exposure to water and whether the risk of illness increased with increasing levels of traditional microbial indicators of water quality. As a corollary question, we also considered the risk of illness with increasing levels of new, nontraditional microbial methods or indicators of water quality.

METHODS

The study was designed as a prospective cohort, similar in design to many prior beach studies.[3,10] Participants were recruited each sampling day, and their current health and degree of exposure to the water were recorded. Swimmer exposure was measured by sampling water quality at multiple sites per beach and multiple time periods per day. Ten to 14 days later, participants were contacted by phone and interviewed about symptoms of illness that occurred after their beach visit. We used regression models to evaluate the association between exposure to water quality indicators and illness, and to compare the risk of illnesses between swimmers and nonswimmers.

Sampling Sites

Beach-goers were recruited at 6 Mission Bay beaches on weekends and holidays in 2003, beginning Memorial Day weekend and continuing through Labor Day. Water quality samples were collected at the same 6 beaches. Eighteen sampling sites were targeted, with the number of sites per beach ranging from 2 to 5, depending upon beach length and anticipated swimming activity. Data were collected on 29 days.

Water Quality Data Collection and Analysis (Indicator Organisms)

Three traditional indicators (enterococcus, total coliforms, fecal coliforms) were measured by traditional membrane filtration methods as well as by the chromogenic substrate method. Enterococcus was also determined by quantitative polymerase chain reaction (qPCR). Five measures were new indicators (Bacteroides, somatic coliphage, male-specific coliphage, adenovirus, and norovirus).

Water samples were collected with varying frequency, depending on the specific indicator. The indicators, sampling frequency, and laboratory analysis methods are shown in Appendix A (available with the online version of this article). Additional details regarding laboratory procedures are available in the project technical report.[25]

Human Health Data Collection

All study instruments and protocols were approved by the Committee for the Protection of Human Subjects at the University of California, Berkeley.

Beach Recruitment

Eligibility criteria included: (1) no previous participation in the study; (2) at least one family member of the household at the beach age 18-year-old or older; (3) home address in the United States, Canada, or Mexico; and (4) no history of swimming (face or head under water) in the ocean or in a lake in the previous 7 days. If an individual or household was eligible and agreed to participate, participants provided signed consent. Adults gave signed consent for children under 18. Interviewers recorded which water sampling site was closest to the location of the individual or family on the beach. Participants were given beach balls and asked to complete a questionnaire prior to their departure that day. The questionnaire assessed possible exposures at the beach, and exposures or illnesses experienced during the previous 2–3 days. Participants who failed to complete the survey at the beach were contacted within 3 days by telephone.

Follow-Up Interview

Approximately 14 days after their beach visit, participants were telephoned and asked to complete a 10- to 15-minute interview. This interview included questions on: (1) demographic information (2); swimming and other exposures since the beach day; (3) pre-existing health problems (e.g., chronic diarrhea); and (4) acute health conditions experienced since the visit to the beach. The head of household answered questions for children younger than 18 years of age.

Health Outcomes Measured

Health outcomes included gastrointestinal (GI) illness, respiratory symptoms, dermatologic symptoms, and other nonspecific symptoms. GI symptoms included nausea, vomiting, diarrhea, and stomach cramps. In addition, 2 categories of highly credible gastrointestinal illness (HCGI) were measured. One (HCGI-1) was defined as either: (1) vomiting; (2) diarrhea and fever; or (3) cramps and fever. The second (HCGI-2) was defined as vomiting plus fever, which is consistent with categories of GI illness defined by Haile et al[6,25] Respiratory outcomes included cough, cough with phlegm, nasal congestion or runny nose, sore throat, and significant respiratory disease, defined as: (1) fever plus nasal congestion; or (2) fever plus sore throat; or (3) cough with phlegm. This definition is also consistent with Haile et al[6] Dermatologic outcomes included skin rashes and infected cuts or scrapes. Nonspecific symptoms included fever, redness or eye irritation, earache, and ear discharge. Respondents who reported a symptom associated with one of the health outcomes at baseline (within 72 hours prior to the beach visit) were excluded from analysis of that particular outcome, but not of other outcomes.

Data Analysis

We initially evaluated any differences in illness rates between swimmers and nonswimmers. The analyses were conducted for 2 definitions of swimming: any water contact at the beach, and swallowing any water. Nonswimmers were those who had no contact with water during their day at the beach.

The second group of analyses consisted of regression models to evaluate the association between risk of illness in swimmers and water quality (as measured by the various indicators). In these models, the main outcome was a binary indicator of illness and a continuous measure of exposure, modeled as the geometric mean (on a logarithmic scale) for the indicator at the time and place of the swimmer's exposure. As a secondary analysis, enterococcus was treated as a dichotomous variable using California state water quality thresholds as cutpoints (>35 versus ≤35 in one analysis and >104 vs. ≤104 in a separate analysis). In all models involving water quality indicators, a value of zero was used for water quality exposure values below the detection limit of the test.

Multivariate models included the following potential confounding factors: age, sex, ethnicity, income, allergies, swimming after the beach interview, collecting shells at the beach, digging in sand, playing with seaweed or algae, chronic or pre-existing illnesses, contact with other sick people, use of insect repellant at the beach, use of sunblock, showering immediately after swimming, consumption of raw or undercooked eggs or meat, and consumption of food at the beach. All variables except age were categorized as 1 or 0. Race was dichotomized as white or nonwhite.

All analyses were conducted using a nested interaction model that effectively assigned nonswimmers a zero exposure value, while including an indicator of swimming. The model permits comparisons among swimmers with different levels of indicator exposure as well as comparisons of swimmers versus nonswimmers independent of indicator level. This model is parameterized as follows:

$$\ln(p/(1-p)) = \alpha + \beta_1 x_1 + \beta_2 (x_1 * x_2) + \beta_3 x_3 + \beta_4 (x_3 * x_2)$$

where p = probability of illness; $x_1 = 1$ if any contact with water, 0 otherwise; x_2 is a water quality indicator value (continuous); and x_3 is a 1/0 indicator of other specific water exposure (body contact, head under water, etc.). In the multivariate analyses, we used a backwards deletion procedure to identify factors that most affected the water quality/illness relationship.[26]

The risk of illness was expressed as an adjusted odds ratio (OR), with the associated 95% confidence interval (CI). For models comparing swimmers and nonswimmers, the OR can be interpreted as the odds of a specific illness in swimmers divided by the odds of illness in nonswimmers. For models assessing the association between water-quality indicators among swimmers, the OR can be interpreted as the increase in the odds of illness per unit of increase in the water-quality measure among swimmers. ORs were calculated by exponentiation of the regression coefficient provided by the model output.

Models adjusted for relevant covariates were used to estimate the percentages of swimmers and nonswimmers ill for any health outcomes. The adjusted attributable-risk estimates were determined by estimating adjusted probabilities of swimmers and nonswimmers from a multivariate logistic model, weighting the covariates as the mean value for each covariate. The adjusted attributable risk was then calculated as the difference between the probability of illness among swimmers with mean levels of covariates and nonswimmers with mean levels of covariates. These results are expressed as the number of excess cases of illness predicted among 1,000 swimmers (along with a 95% confidence interval of this estimate).

RESULTS

Water Quality

This beach was open for recreational use during the entire study period. A total of 1897 water samples were collected. All but 5 of these samples were analyzed successfully in the laboratory. The majority of samples had quantifiable levels of indicator bacteria. (See Appendix B, which is available with the online version of the Journal at www.epidem.com.) Approximately 16% of the samples exceeded state water quality thresholds for traditional fecal indicator bacteria, with enterococcus accounting for most of the exceedances (96%) and total coliforms the least (2%). These percents are similar to historical results from Mission Bay and from other studies.[15,6] Pathogenic virus was detected in only one sample. The majority of samples had quantifiable levels of somatic coliphage, but not of male-specific coliphage. The range of concentrations for virus measurements is shown in Appendix B.

Health Outcomes

A total of 12,469 individuals from 5,062 households were enrolled in the study. Of these, 8797 (71%) of the enrolled participants and 3501 (69%) of the households completed the follow-up telephone interview. Fifty-seven percent (n = 4971) of those who completed the follow-up interview were swimmers. Tables 1 and 2 show the individual and household sociodemographic characteristics of the study group.

TABLE 1. Individual Sociodemographic Characteristics Collected From Study Participants at All Beaches From Mission Bay

Characteristic	All (n = 8797) No. (%)	Swimmers (n = 4971) No. (%)	Nonswimmers (n = 3742) No. (%)	Missing (n = 84) No. (%)
Age (yrs)				
0–5	1214 (14)	870 (18)	326 (9)	18 (21)
5.1–12	1808 (21)	1461 (29)	332 (9)	15 (18)
12.1–30	2366 (27)	1215 (24)	1127 (30)	24 (29)
30.1–55	2928 (33)	1251 (25)	1654 (44)	23 (27)
>55	332 (4)	76 (2)	253 (7)	3 (4)
Missing	149 (2)	98 (2)	50 (1)	1 (1)
Sex				
Male	4761 (54)	2624 (53)	2100 (56)	37 (44)
Female	3948 (45)	2292 (46)	1609 (43)	47 (56)
Missing	88 (1)	55 (1)	33 (1)	0 (0)
Race				
White	2495 (28)	1,181 (24)	1,307 (35)	7 (8)
Black	369 (4)	165 (3)	194 (5)	10 (12)
American Indian/Alaskan Native	62 (1)	35 (1)	27 (1)	0 (0)
Asian/Pacific Islander	463 (5)	177 (4)	281 (8)	5 (6)
Hispanic/Latino	4723 (54)	3052 (61)	1616 (43)	55 (66)
Mixed race	407 (5)	241 (5)	163 (4)	3 (4)
Other	227 (3)	96 (2)	128 (3)	3 (4)
Missing	51 (1)	24 (1)	26 (1)	1 (1)

TABLE 2. Household Sociodemographic Characteristics Collected From Study Participants at All Beaches From Mission Bay (n = 3501 Households)

Characteristic	No. (%)
Household size (No. of persons)	
1	1269 (36)
2	649 (19)
3	532 (15)
4	511 (15)
5	290 (8)
≥6	250 (7)
Missing	0 (0)
Country of residence	
United States	3170 (91)
Mexico	66 (2)
Canada	2 (0)
Missing	263 (8)
Average annual household income ($)	
<10,000 to 20,000	923 (26)
20,001 to 40,000	804 (23)
40,001 to 60,000	525 (15)
60,001 to 80,000	391 (11)
80,001 to 100,000	229 (7)
>100,000	309 (9)
Missing	321 (9)

Health Outcomes for Swimmers Versus Nonswimmers

Swimmers had a significant increase in diarrhea (OR = 1.4; 95% CI = 1.0–1.8) and skin rash (2.3; 1.6–3.2) when swimming was defined as having any water contact (Table 3). When swimming was defined as having swallowed water, the risk of diarrhea was increased (1.9; 1.3–2.7), with risks also for cramps (1.5; 1.1 – 2.2), skin rash (2.1; 1.4–.2), and eye irritation (1.7; 1.2–2.3; Table 3).

We explored the relationship between participant age and health outcomes after water exposure (Table 4). Among participants with any water contact, the strongest association with diarrhea was among children ages 5 to 12 years (OR = 2.8; 95% CI = 1.1–7.3). The OR increased with increased exposure in the 5- to 12-year-old age group (5.3; 2.0–14). In several age groups, skin rash was significantly associated with any water contact or with swallowing water. Associations also were found among those who swallowed water and who reported skin rash (ages 0–5 and 5–12 years) and eye irritation (ages 5–12 years). Similar patterns were seen within strata of race/ethnicity (Appendix C, available with the online version of this article).

Attributable risk was calculated for diarrhea, stratified by age group. (See Appendix D, which is available with the online version of the Journal at www.epidem.com.) The estimated excess of cases among swimmers versus nonswimmers was greatest in participants age 5–12 years with any water contact (27 excess cases per 1000 swimmers) and

TABLE 3. Association of Water Exposure With Health Outcomes

	Nonswimmers†		Any Water Contact			Water on Face			Swallow Water		
Health Outcome*	No.‡	% With Symptoms	No.‡	% With Symptoms	Adjusted OR (95%CI)	No.‡	% With Symptoms	Adjusted OR (95%CI)	No.‡	% With Symptoms	Adjusted OR (95%CI)
Gastrointestinal											
Diarrhea	3581	3.4	4798	4.5	1.4 (1.0–1.8)	3575	4.6	1.5 (1.2–2.1)	1021	6.1	1.9 (1.3–2.7)
HCGI-1	3581	2.3	4798	2.9	0.96 (0.68–1.4)	3575	3.2	1.0 (0.71–1.5)	1021	3.6	1.0 (0.62–1.7)
HCGI-2	3457	0.60	4612	1.0	0.93 (0.49–1.8)	3428	1.3	1.1 (0.57–2.1)	971	1.4	1.1 (0.51–2.5)
Nausea	3577	2.6	4797	2.3	0.88 (0.64–1.2)	3575	2.6	1.1 (0.77–1.6)	1021	3.4	1.4 (0.91–2.2)
Cramps	3581	4.0	4796	4.5	1.1 (0.81–1.4)	3574	4.7	1.1 (0.86–1.5)	1021	6.6	1.5 (1.1–2.2)
Vomiting	3581	1.7	4797	1.9	0.85 (0.58–1.3)	3575	2.2	0.92 (0.61–1.4)	1021	2.4	0.86 (0.49–1.5)
Skin rash	3642	1.6	4850	3.9	2.3 (1.6–3.2)	3602	4.5	2.4 (1.7–3.3)	1043	4.9	2.1 (1.4–3.2)
Eye irritation	3682	4.0	4904	5.1	1.2 (0.93–1.5)	3637	5.4	1.3 (0.99–1.7)	1041	7.1	1.7 (1.2–2.3)
Ear											
Earache	3695	1.8	4908	2.3	0.96 (0.65–1.4)	3635	2.4	1.0 (0.64–1.6)	1041	2.7	1.1 (0.63–1.9)
Ear discharge	3695	0.54	4909	0.33	0.40 (0.16–1.0)	3636	0.33	0.47 (0.19–1.1)	1041	0.48	0.82 (0.22–3.0)
Fever	3514	3.0	4726	3.8	0.96 (0.70–1.3)	3525	4.3	1.0 (0.74–1.5)	1015	5.3	1.2 (0.76–1.8)
Respiratory											
SRD	3514	3.6	4726	4.1	1.1 (0.80–1.5)	3525	3.9	1.0 (0.75–1.4)	1015	4.0	0.99 (0.62–1.6)
Sore throat	3513	4.5	4725	4.2	0.89 (0.69–1.2)	3525	4.3	0.96 (0.71–1.3)	1015	4.0	0.87 (0.56–1.3)
Cough	3514	2.7	4725	2.1	0.74 (0.54–1.0)	3525	2.2	0.77 (0.54–1.1)	1015	2.7	0.82 (0.47–1.4)

*Numbers of subjects reporting baseline illness (excluded from analysis): gastrointestinal, 392; respiratory/fever, 619; rash, 235; ear, 85; eye, 124.
†Reference category (adjusted OR = 1.0).
‡Inconsistencies in numbers are a result of missing values for particular responses.
HCGI-1 is defined as (1) vomiting, or (2) diarrhea and fever, or (3) cramps and fever.
HCGI-2 is defined as vomiting plus fever.
SRD (Significant Respiratory Disease) is defined as (1) fever plus nasal congestion or (2) fever plus sore throat or (3) cough with phlegm.

among those who had swallowed water (59 excess cases per 1000 swimmers).

Water Quality and Health Outcomes Among Swimmers

No correlation was observed between traditional water quality indicator levels for enterococcus, fecal coliform, or total coliform and the risk of illness. Using diarrhea as an example, there were no notable elevations in risk with enterococcus (Table 5). This result persisted even with numerous approaches to assigning water quality exposure (eg, combining or separating sites at a beach) or to calculation of indicator metrics (daily geometric mean, daily maxima, or various cutpoints). Of particular note, exposure to indicator measures above the 2 different California state water quality thresholds did not show increased risk of illness (Table 6).

We found no correlation of Bacteroides, enterococcus using rapid methods (qPCR), human pathogenic virus (adenovirus and norovirus), or somatic phage with increased risk of illness (results available in technical report).[25] The relationship with viruses could not be adequately evaluated because no norovirus was found, and adenovirus was detected in only one sample. These low counts were consistent with the absence of risk for other health outcomes evaluated.

Our data suggest associations between the levels of male-specific coliphage and gastrointestinal illnesses, nausea, cough, and fever (Table 7). However, a low number of participants were exposed to the water at times when male-specific coliphage was detected. (See Appendix E, which is available with the online version of the Journal at www.epidem.com.)

DISCUSSION

Swimmers (those having any water contact) experienced more diarrhea and skin rash than nonswimmers in Mission Bay. The incidence of these symptoms increased with greater exposure categories (eg, swallowing water), further suggesting that these symptoms were mediated by water contact. However, increased risk was not observed for more severe symptoms such as fever, vomiting, or HCGI-1 or HCGI-2. These latter symptoms have been the foundation for Federal and State water quality thresholds[5,6] and have been the focus of most previous epidemiology studies.[3] Symptoms such as HCGI are considered more relevant because multi-symptom reactions that include fever are typically pathogen-mediated, whereas symptoms such as rash and diarrhea could potentially result from saltwater irritation.

Previous studies have observed a fairly broad range of illnesses, probably reflecting diversity in study populations as well as differences in illness definitions and methods of data collection. The illness incidence observed at Mission Bay falls within the range previously reported, although GI symptom incidence occurred in the lower part of the range. For example, diarrhea was reported by 4–6% of swimmers in Mission Bay compared with 5–6% in Santa Monica, Califor-

TABLE 4. Association of Water Exposure With Health Outcomes, by Age Group

	Age Group (Years)			
	0–5 Adjusted OR (95%CI)	>5–12 Adjusted OR (95%CI)	>12–30 Adjusted OR (95%CI)	>30 Adjusted OR (95%CI)
		Any water contact		
Gastrointestinal				
Diarrhea	0.75 (0.40–1.4)	2.8 (1.1–7.3)	1.7 (0.96–3.1)	1.3 (0.85–1.9)
HCGI-1	0.86 (0.45–1.6)	1.3 (0.56–3.1)	0.73 (0.36–1.4)	1.4 (0.60–3.2)
HCGI-2	0.74 (0.31–1.8)	2.3 (0.28–18)	0.64 (0.15–2.7)	2.1 (0.30–15)
Nausea	1.9 (0.62–5.8)	1.4 (0.52–3.8)	0.46 (0.26–0.83)	1.1 (0.63–2.0)
Cramps	1.2 (0.53–2.7)	1.6 (0.77–3.4)	0.57 (0.34–0.94)	1.5 (0.93–2.4)
Vomiting	0.58 (0.31–1.1)	1.6 (0.54–4.7)	0.68 (0.31–1.5)	1.5 (0.64–3.3)
Skin rash	5.9 (1.8–19)	3.3 (1.3–8.2)	1.6 (0.89–2.9)	1.8 (1.0–3.3)
Eye irritation	0.53 (0.27–1.0)	1.8 (0.94–3.6)	1.2 (0.81–1.8)	1.2 (0.8–1.9)
Ear				
Earache	0.86 (0.31–2.4)	1.1 (0.37–3.5)	0.62 (0.30–1.3)	1.5 (0.73–3.0)
Ear Discharge	0.12 (0.010–1.7)	0.22 (0.030–1.6)	0.58 (0.14–2.4)	0.63 (0.10–3.9)
Fever	0.68 (0.39–1.2)	1.7 (0.67–4.2)	0.83 (0.44–1.6)	1.4 (0.73–2.8)
Respiratory				
SRD	0.63 (0.32–1.2)	1.2 (0.57–2.7)	1.0 (0.58–1.8)	1.4 (0.86–2.4)
Sore throat	0.74 (0.33–1.7)	1.2 (0.57–2.6)	0.82 (0.51–1.3)	0.90 (0.61–1.4)
Cough	0.52 (0.27–1.0)	0.84 (0.38–1.9)	0.78 (0.41–1.5)	0.84 (0.49–1.5)
		Swallow water		
Gastrointestinal				
Diarrhea	0.97 (0.47–2.0)	5.3 (2.0–14)	1.8 (0.79–3.9)	1.8 (0.86–3.7)
HCGI-1	0.61 (0.25–1.5)	1.7 (0.65–4.6)	1.3 (0.49–3.7)	0.70 (0.08–6.3)
HCGI-2	0.74 (0.23–2.4)	2.8 (0.32–25)	0.92 (0.13–6.5)	3.2 (0.18–54)
Nausea	2.3 (0.76–6.8)	2.3 (0.84–6.2)	0.56 (0.21–1.5)	2.1 (0.81–5.3)
Cramps	2.1 (0.88–4.8)	2.5 (1.2–5.3)	0.52 (0.23–1.2)	1.8 (0.85–3.9)
Vomiting	0.41 (0.14–1.2)	2.2 (0.57–8.1)	1.3 (0.43–3.8)	1.1 (0.12–10)
Skin rash	10 (2.3–46)	4.1 (1.4–12)	1.2 (0.46–2.9)	1.3 (0.39–4.5)
Eye irritation	0.89 (0.41–1.9)	2.9 (1.4–5.7)	1.5 (0.82–2.7)	1.5 (0.72–3.3)
Ear				
Earache	0.25 (0.03–2.2)	2.1 (0.65–6.8)	0.78 (0.26–2.3)	0.89 (0.18–4.3)
Ear discharge	—	—	—	—
Fever	0.73 (0.36–1.5)	2.4 (0.88–6.3)	1.5 (0.64–3.6)	1.0 (0.22–4.9)
Respiratory				
SRD	0.62 (0.24–1.6)	1.2 (0.46–3.0)	1.0 (0.41–2.6)	0.71 (0.15–3.3)
Sore throat	0.81 (0.26–2.5)	1.0 (0.42–2.5)	0.90 (0.38–2.1)	0.69 (0.25–1.9)
Cough	0.44 (0.15–1.3)	1.3 (0.48–3.7)	1.5 (0.53–4.3)	

—, indicates too few individuals for analysis.

nia,[27] approximately 2% in New York,[5] 10–13% in the Great Lakes (for GI illness without fever),[28] and 14% in the United Kingdom.[29]

With regard to levels of pollution, a fairly wide range has been previously reported as a result of the differences in the beach sites, the sources of pollution affecting these sites, and aspects of water sampling (for example, frequency of sample collection, depth, and time of collection). The levels observed in Mission Bay are, however, broadly within the range reported in other studies at marine locations. In Santa Monica, between 0% and 45% of samples exceeded 106 enterococci cfu/100 mL depending on the sample location, whereas in Mission Bay, 14% of all samples exceeded the current California enterococcus threshold of 104 cfu/100 mL.[27] In Mission Bay, we observed a geometric mean of 29 enterococci cfu/100 mL. Cabelli et al,[5] in the New York studies, observed a range of 16–91 fecal streptococci cfu/100 mL, a group very similar to the enterococci group. In New Zealand, a median of 3.5 enterococci cfu/100 mL was reported, although in this study 2 "pristine" beaches were included in the analysis.[30] (Note that the median and the geometric mean are fairly commensurate measures, and the geometric mean equals the median when the data are lognormally distributed.) In Australia, Corbett and colleagues[31]

TABLE 5. Association of Enterococcus, Fecal Coliform and Total Coliform Levels (the unit change in exposure in these models was set to represent a change of 3.4 ln increase per 100 ml [equivalent to an increase from 0–30 in the geometric mean] for enterococcus, and 5 ln per 100 ml [equivalent to an increase of 0–148 in the geometric mean] for both fecal and total coliforms)

	Enterococcus		Fecal Coliform		Total Coliform	
Health Outcome	Any Water Contact Adjusted OR (95%CI)	Swallow Water Adjusted OR (95%CI)	Any Water Contact Adjusted OR (95%CI)	Swallow Water Adjusted OR (95%CI)	Any Water Contact Adjusted OR (95%CI)	Swallow Water Adjusted OR (95%CI)
Gastrointestinal						
Diarrhea	0.77 (0.33–1.8)	0.31 (0.06–1.6)	0.41 (0.18–0.93)	0.33 (0.07–1.5)	0.34 (0.15–0.77)	0.47 (0.09–2.5)
HCGI-1	0.76 (0.28–2.0)	1.6 (0.23–12)	0.65 (0.25–1.7)	1.5 (0.22–11)	0.58 (0.21–1.6)	0.64 (0.08–4.9)
HCGI-2	0.97 (0.18–5.2)	1.7 (0.09–31)	0.59 (0.11–3.1)	3.5 (0.20–62)	0.48 (0.09–2.7)	0.43 (0.02–8.8)
Nausea	0.72 (0.22–2.4)	0.79 (0.10–6.4)	0.56 (0.19–1.7)	1.3 (0.17–9.7)	0.39 (0.12–1.3)	0.35 (0.04–2.9)
Cramps	0.87 (0.38–2.0)	0.67 (0.14–3.1)	0.58 (0.26–1.3)	0.62 (0.14–2.7)	0.84 (0.34–2.1)	0.56 (0.12–2.6)
Vomiting	0.69 (0.22–2.2)	2.0 (0.18–22)	0.76 (0.23–2.6)	2.6 (0.26–27)	0.48 (0.14–1.6)	0.69 (0.06–8.2)
Skin rash	0.84 (0.34–2.0)	0.65 (0.11–3.9)	0.86 (0.36–2.1)	0.67 (0.12–3.7)	1.4 (0.52–3.5)	3.5 (0.59–21)
Eye irritation	0.74 (0.34–1.6)	0.79 (0.17–3.7)	0.69 (0.33–1.4)	0.67 (0.15–2.9)	0.64 (0.29–1.4)	1.2 (0.24–6.1)
Ear						
Earache	1.1 (0.34–3.8)	0.45 (0.04–5.2)	1.5 (0.51–4.4)	0.38 (0.04–3.4)	1.9 (0.53–6.5)	0.46 (0.04–5.0)
Ear discharge	1.5 (0.05–42)	1.1 (0.01–189)	7.1 (0.31–165)	0.79 (0.00–130)	6.3 (0.27–145)	5.2 (0.02–1140)
Fever	0.98 (0.39–2.4)	1.1 (0.21–5.8)	0.57 (0.24–1.4)	0.72 (0.14–3.8)	0.79 (0.29–2.1)	0.40 (0.07–2.2)
Respiratory						
SRD	1.2 (0.47–2.8)	1.5 (0.23–9.3)	0.58 (0.25–1.3)	1.1 (0.16–7.8)	0.68 (0.26–1.8)	0.78 (0.10–6.1)
Sore throat	1.3 (0.52–3.1)	0.34 (0.05–2.1)	1.4 (0.6–3.3)	0.25 (0.06–2.0)	1.5 (0.59–3.8)	0.40 (0.06–2.6)
Cough	0.50 (0.14–1.8)	0.06 (0.01–0.70)	0.44 (0.14–1.4)	0.16 (0.02–1.6)	0.37 (0.10–1.4)	0.14 (0.01–1.5)

TABLE 6. Association of 2 Dichotomous Measures Of Enterococcus Exposure With Health Outcomes

	Enterococcus Exposure (per 100 mL)	
Health Outcome	>35 vs ≤35 Adjusted OR (95% CI)	>104 vs ≤104 Adjusted OR (95% CI)
Gastrointestinal		
Diarrhea	1.0 (0.73–1.4)	1.2 (0.85–1.8)
HCGI-1	0.74 (0.51–1.1)	1.1 (0.73–1.8)
HCGI-2	0.69 (0.38–1.3)	0.80 (0.37–1.7)
Nausea	0.78 (0.51–1.2)	1.1 (0.65–1.9)
Cramps	0.91(0.66–1.2)	1.4 (0.95–2.0)
Vomiting	0.67 (0.43–1.0)	1.1 (0.67–1.9)
Skin rash	0.83 (0.61–1.2)	1.0 (0.67–1.5)
Eye irritation	0.97 (0.72–1.3)	0.77 (0.53–1.1)
Ear		
Earache	1.1 (0.68–1.7)	1.2 (0.70–2.0)
Ear discharge	1.2 (0.30–4.4)	0.94 (0.19–4.6)
Fever	0.92 (0.65–1.3)	0.89 (0.58–1.4)
Respiratory		
SRD	0.96 (0.67–1.4)	1.1 (0.73–1.7)
Sore throat	1.1 (0.80–1.5)	1.2 (0.77–1.7)
Cough	0.65 (0.40–1.1)	0.51 (0.25–1.0)

TABLE 7. Association of Any Water Contact to Male-Specific Coliphage (per unit increase) With Health Outcomes

Health Outcome	Adjusted OR (95% CI)
Gastrointestinal	
Diarrhea	1.1 (0.97–1.4)
HCGI-1	1.3 (1.1–1.5)
HCGI-2	1.4 (1.1–1.8)
Nausea	1.3 (1.2–1.6)
Cramps	1.0 (0.83–1.3)
Vomiting	1.2 (0.96–1.5)
Skin rash	1.0 (0.77–1.3)
Eye irritation	1.1 (0.95–1.4)
Ear	
Earache	—
Ear discharge	—
Fever	1.3 (1.1–1.4)
Respiratory	
SRD	1.1 (0.85–1.3)
Sore throat	1.0 (0.83–1.3)
Cough	1.2 (1.0–1.5)

—, indicates too few individuals for analysis.

reported median fecal streptococci measures of 16 cfu/100 mL for morning and 11 cfu/100 mL for afternoon samples, and Von Schirnding and colleagues[32] in South Africa reported median enterococci levels of 2 cfu/100 mL at a relatively unpolluted beach, and 50 cfu/100 mL at a beach affected by fecal waste.

Although levels of contamination and rates of illness were comparable with previous studies, we found no relationship between fecal indicator bacteria and illness rates.[3,6] This result is unlike most previous marine recreational epidemiology studies. Wade et al[3] reviewed 27 relevant marine recreational water epidemiology studies; most showed increased risk with increasing fecal indicator concentrations, particularly with enterococcus. However, in essentially all of these studies, there were known sources of human fecal contamination. There appears to be little human fecal contamination in Mission Bay, as evidenced by a recent source tracking study showing that the predominant source of fecal contamination was avian.[16] Although animal sources can harbor disease-causing agents, they are less likely to serve as sources of some human enteric diseases, especially those diseases caused by enteric viruses.[10] There is, however, no grazing by cattle, sheep, or other animals in this watershed.

The use of bacterial indicators as predictors of swimming-associated illnesses is based on the presumption that the indicator bacteria have survival properties similar to the pathogens that cause disease. This presumption is less likely to be true when water circulation is restricted and bacterial residence times increase, which can be days to weeks in Mission Bay.[33] Increased survival, and perhaps even regrowth of fecal indicator bacteria, has been suggested in the sediments and wrack lining beaches such as Mission Bay.[17,34] Regardless, the lack of relationship of nonhuman sources of fecal indicator bacteria to health risk suggests that the water contact advisories posted at Mission Bay beaches during the course of this study were not predictive of a public health risk. This conclusion was also apparent when traditional bacterial indicators were measured using qPCR. This contrasts with a recent study which observed a relationship between enterococcus measured by qPCR and gastrointestinal illness at Great Lakes beaches.[28] Unlike Mission Bay, however, these beaches had human fecal contamination.

It is uncertain whether viral measures in our study could be used in place of bacterial indicators for health risk assessments in Mission Bay. Male-specific coliphage was correlated with increased incidence of several health outcomes, including HCGI-1, HCGI-2, nausea, cough, and fever (Table 7). This is consistent with the success of this measure in freshwater application and edible bivalve molluscan shellfish.[35,36] However, we interpret these associations cautiously because male-specific coliphage was not detected often, and few subjects were exposed to the water at those times (Appendix E).

The human-specific viruses we measured in Mission Bay were rarely detected, which is consistent with our low rates of swimming-associated illnesses. We did not encounter high virus counts that would have allowed us to assess their effectiveness as predictors. The interpretation of viruses as negative predictors is potentially compromised by technology limitations. We used the most advanced techniques available, but quantifying virus particles in seawater is difficult; DNA and RNA are lost as the result of complexation and interferences when concentrating and extracting nucleic acid material.[12,21,22] Thus, we cannot be certain that the low levels of positive samples we observed were due to their absence, or due to the technical difficulties in recovering and measuring viruses that may have been present. Our results are at least consistent with the possibility that viral measures are more effective than traditional bacterial indicators as predictors of illness when nonhuman sources of contamination are dominant.

Although we found that traditional fecal indicators were ineffective predictors of health effects, it is unclear whether Mission Bay is the exception or the rule. Mission Bay has been subjected to extensive cleanup activities that has reduced human fecal sources, whereas human fecal material may still be an important contributor to nonpoint sources at other beaches.[15–17,37] It would also be inappropriate to extrapolate our results beyond our specific study conditions. We would expect to see an increase in health risks, and likely an association with bacterial indicators of water quality, if large sources of untreated human fecal material such as a sewage overflow entered the Bay. Finally, we examined swimming-related illnesses only during dry weather. No epidemiologic data currently exist for any beach to assess whether health risks are associated with swimming at beaches with nonpoint, nonhuman source inputs following rainfall. Wet weather typically produces transient increases in levels of fecal contamination at beaches, yet most disease outbreaks associated with wet weather have been due to drinking water.[38]

In summary, we found an elevation in rash and diarrhea among swimmers compared with nonswimmers in Mission Bay, California in the summer of 2003. The risk of 12 other illnesses, including highly credible GI illnesses and significant respiratory disease, were not markedly increased. There were no associations between levels of traditional fecal indicator bacteria (total coliforms, fecal coliforms, enterococcus) and illness. The exceeding of California's marine recreational water quality thresholds for traditional fecal indicator bacteria was not associated with increased risk of illness. In addition, there were no associations between Bacteroides, enterococcus using rapid methods (PCR), human pathogenic virus (adenovirus and norovirus), or somatic coliphage and illness. There were associations between male-specific coliphage and illness, but we interpret these associations cautiously because so few subjects overall were exposed.

Our findings do not agree with earlier studies reporting associations between bacterial indicators of water quality and illness. We believe these results are due to a lack of human sources of traditional fecal indicator bacteria, supported by our lack of virus detection and an independent microbial tracking survey. Like Mission Bay, many enclosed marine beaches, in California and elsewhere, suffer from impaired water quality due to nonpoint sources of bacteria and poor circulation. We do not recommend extrapolation to other beaches at this time, however, as we are uncertain if Mission Bay has unique site characteristics. Further studies to confirm the reduced risk of swimming-related illnesses at beaches contaminated by nonpoint sources of fecal pollution appear justified. The predictive abilities of coliphages as microbial indicators of recreational water quality also need further investigation.

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