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Exposure Assessment and Risk of Gastrointestinal Illness Among Surfers

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Surfing is a unique recreational activity with the possibility of elevated risk for contracting gastrointestinal (GI) illness through ingestion of contaminated water. No prior studies have assessed exposure from ingestion among surfing populations. This study estimated the magnitude and frequency of incidental water ingestion using a Web-based survey and integrated exposure distributions with enterococci distributions to predict the probability of GI illness at six Oregon beaches. The mean exposure magnitude and frequency were 170 ml of water ingested per day and 77 days spent surfing per year, respectively. The mean number of enterococci ingested ranged from approximately 11 to 86 colony-forming units (CFU) per day. Exposure-response analyses were conducted using an ingested dose model and two epidemiological models. Risk was characterized using joint probability curves (JPC). At the most contaminated beach, the annualized ingested dose model estimated a mean 9% probability of a 50% probability of GI illness, similar to the results of the first epidemiological model (mean 6% probability of a 50% probability of GI illness). The second epidemiological model predicted a 23% probability of exceeding an exposure equivalent to the U.S. Environmental Protection Agency (EPA) maximum acceptable GI illness rate (19 cases/1000 swimmers). While the annual risk of GI illness for Oregon surfers is not high, data showed that surfers ingest more water compared to swimmers and divers and need to be considered in regulatory and public health efforts, especially in more contaminated waters. Our approach to characterize risk among surfers is novel and informative to officials responsible for advisory programs. It also highlights the need for further research on microbial dose-response relationships to meet the needs of quantitative microbial risk assessments (QMRA).

Coastal waters are frequently contaminated with pathogenic organisms from a variety of natural and anthropogenic sources. Contamination may be more prevalent along beaches and near shore areas that receive high recreational use (Dwight et al., 2004; Turbow et al., 2003). Exposure to pathogens in recreational waters is associated with an increased risk of gastrointestinal (GI) illness, respiratory, ear, eye, and skin infections, meningitis, and hepatitis (Cabelli et al, 1983; Corbett et al., 1993; Dewailly et al., 1986; Dwight et al., 2004; Haile et al., 1999; Kay et al., 1994). Pruss (1998) demonstrated that the worldwide body of evidence clearly showed exposure-response relationships linking fecal indicator concentrations with rates of minor illnesses, although this has been recently disputed by Colford et al. (2007).

In 1986, the U.S. Environmental Protection Agency (U.S. EPA) published recommended water quality criteria for recreational waters, which proposed the use of enterococci as indicators in marine waters (U.S. EPA, 1986). These have been upheld in the U.S. EPA Final Rule promulgating water-quality criteria for bacteria in coastal recreation waters (U.S. EPA, 2004). Allowable enterococci density values are based on specific levels of risk for acute GI illness as criteria for protection of public health. The acceptable swimming associated GI illness rate of 1.9% or 19 illnesses per 1000 swimmers is calculated at a steady-state geometric mean indicator density of 35 CFU/100 ml or a single sample density of 158 CFU/100 ml, which corresponds to the U.S. EPA “Moderate Full Body Contact Recreation” category (U.S. EPA, 1986, 2004). The latter single sample density is the Oregon Action Level (Oregon Department of Human Services [DHS], 2004). The World

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Health Organization (WHO) guidelines for microbial quality of recreational waters established an upper 95th percentile value of ≤ 40 CFU/100 ml as a level that relates to an average probability of less than 1 case of GI illness per 100 exposures, 200 CFU/100 ml to ~1 case per 20 exposures, and >500 CFU/100 ml to >10% chance of GI illness in a single exposure (WHO, 2003).

In 1997, the U.S. EPA began the Beaches Environmental Assessment and Coastal Health (BEACH) Program in response to increased concern over bacterial and pathogen-induced disease among recreational users in fresh and marine waters (U.S. EPA, 2002). With the passage of the BEACH Act of 2000, coastal states are mandated to assess and sample coastal recreational waters for bacterial ambient water quality parameters. In 2002, the Oregon Beach Monitoring Program (OBMP) began sampling near-shore marine waters and freshwater outfalls for the presence of fecal bacteria using enterococci as an indicator organism (DHS, 2004).

Oregon has 362 miles of coastline, with public access to all of its beaches. Overall, 23% of state residents report participating in beach activities with approximately 6 million annual visits (Oregon Parks and Recreation Department [OPRD], 2003). Between 2003 and 2007, over 100 beach advisories were issued in Oregon. Despite the cold annual water temperatures, surfing is a popular year round activity at numerous Oregon beaches, including locations where beach advisories were issued as a result of elevated enterococci detections (Benedict & Neumann, 2004). Surfers represent a distinct exposure scenario compared with other aquatic recreational activities such as wading or swimming, given the frequency of unanticipated head submersions, chaotic wave activity, and the potential for longer duration exposures (Turbow et al., 2008). In addition, surfers may comprise a disproportionately large fraction of marine bathers, particularly in some regions of the United States (Turbow et al., 2008). Although the routes of exposure to waterborne pathogens are identical for surfers and swimmers, surfers are likely to have higher exposure compared to swimmers by virtue of more frequent and longer contact with fecal-contaminated water (Dwight et al., 2004; Schijven & de Roda Husman 2006).

In a California study, symptoms of GI illness, sore throat, and eye and skin infections were observed in surfers, with reported symptoms increasing by 10% for each 2.5 h of weekly water exposure as estimated by contact time in the water (Dwight et al., 2004). In addition, increased illness was reported during years in which there was greater coastal water pollution due to increased rainfall runoff, as measured by mean monthly total coliform counts (Dwight et al., 2004). Other research focused on ear problems (Kroon et al., 2002), surfer injuries (Nathanson et al., 2002), and seabather's eruptions (Kumar et al., 1997). In previous studies investigating swimmer illnesses, exposure generally includes head immersion, splashing, or water ingestion (WHO, 2003). However, few studies measured the frequency or magnitude of exposure in swimmers (Wade et al., 2003), and no studies determined this in surfers. According to WHO (2003), epidemiological data on exposures other than swimming (e.g., high-exposure activities such as surfing, sailing, or whitewater canoeing) are currently inadequate to assess defined risks. Thus, the results from past studies may not accurately assess the health risks to special interest groups such as surfers, given their higher probability of ingesting recreational waters.

There were two primary objectives in this study. The first was to estimate the magnitude and frequency of ingestion of marine waters among surfers, who are a potentially high exposure group. The second was to model exposure distributions to determine the probability of GI illness related to surfing. To our knowledge, this is the first exposure assessment of surfers in which volume and frequency of water ingested have been used to calculate exposure. A previous surfer study (Dwight et al., 2004) used surrogate information (contact time in the water) to estimate exposure. Our approach to characterizing risk among surfers is novel and should provide meaningful input to public health and environmental officials who are responsible for implementing beach sampling and advisory programs. This study also has implications for other recreational water activities in which there may be increased potential for incidental ingestion of contaminated waters.

MATERIALS AND METHODS

Our evaluation of the risk to surfers at each of six Oregon beaches (Figure 1) from exposure to enterococcus group bacteria followed the conceptual model shown in Figure 2, which included: (1) an exposure analysis to estimate the volume of water ingested by surfers and the density (as colony-forming

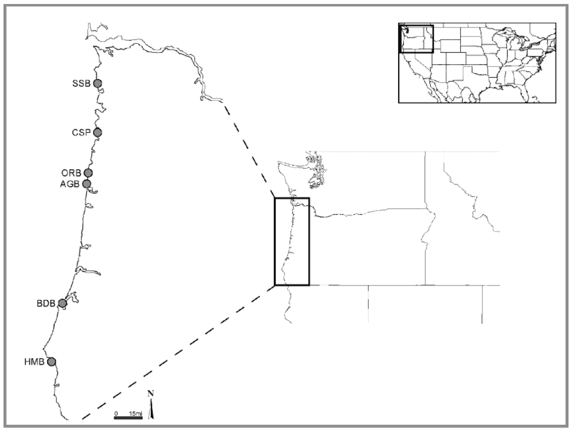

FIG. 1. Geographic distribution of beaches in Oregon used to model exposure for surfers, based on enterococcus densities. The beaches, in order from north to south, were Short Sands Beach (SSB), Cape Kiwanda State Park (CSP), Agate Beach (AGB), Otter Rock Beach (ORB), Humbug Mountain Beach (HMB), and Bastendorff Beach (BDB).

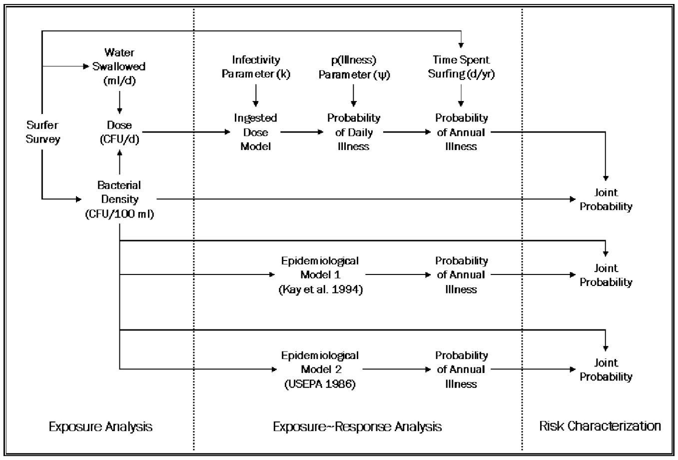

FIG. 2. Conceptual model for the assessments of surfer exposure to enterococci group bacteria and of risk of gastrointestinal (GI) illness, using three different exposure-response models.

units [CFU] per 100 ml) of enterococci group bacteria; (2) an exposure-response analysis that used two epidemiological and one ingested dose model to predict the probability of GI illness given bacterial density or dose, respectively; and (3) a risk characterization that utilized a joint probability curve (JPC) methodology to integrate the probability of GI illness with the probability of exposure to a dose or density that may result in illness.

Exposure Analysis

A Web-based survey was designed to query surfers about the volume of water ingested while surfing. The survey was developed with assistance from the Oregon State University (OSU) Survey Research Center and administered via the Internet from May through July 2007. The survey was posted on a secure OSU site, which was linked to the Surfrider Foundation (www.surfrider.org/oregon/) and Oregon Surf (www.oregonsurf.com) websites. Participants were 18 yr or older, and were primarily recruited by self-visitation to the websites. Participants were also recruited through mailings to coastal surf shops that announced the study and requested that surf shop owners direct interested participants to the websites. Potential participants were not required to be paid members of the Surfrider Foundation to participate in the survey. The survey was administered via the Internet to a pilot group of 25 surfers prior to conducting the study, and adjustments were made to the survey based on the feedback that was received from the pilot group. The pilot participants reported that the categories of ingestion were readily understandable, and did not recommend any changes. The study was approved by OSU's Institutional Review Board for the protection of human subjects.

The survey collected information in four general areas: exposure assessment parameters—route, magnitude, duration, and frequency; risk behaviors (e.g., surfing during a posted advisory, surfing prior to or following a rain event); demographic characteristics (e.g., residency, location of beaches used, years of experience as a surfer, age, gender, occupation, etc.); and risk perception related to surfing. This study is limited to the information from surfers that is relevant to a quantitative exposure assessment.

Qustions regarding the magnitude and frequency of incidental ingestion were included in the survey. Surfers were asked to estimate the amount of water that was incidentally ingested through the mouth or nose based on choices adapted from Schijven and de Roda Husman (2006) in their study of water ingestion by divers. Surfers were asked to estimate the amount of water ingested by selecting from these categories: "a few drops," "1–3 teaspoons," "the amount in a shot glass" (1–2 ounces), or "the amount in a small juice glass" (4 ounces). To estimate the frequency of surfing (the number times per month a surfer used an Oregon beach) respondents were asked to select one of 4 categories: "once or twice per month," "3–4 times per month," "5–10 times per month," or " >10 times per month."

From May through September, ocean water is sampled by the OBMP either once per week, every 2 wk, or monthly based on the priority ranking of the beach (DHS, 2004). The priority is determined by beach use, pollution hazards, previous monitoring results, and input from coastal stakeholders. When a sample exceeds the state standard (158 CFU/100 ml), a water contact advisory is issued and resampling occurs within 96 h. During the winter, water is sampled every 2 wk at the beaches that are used most for winter water recreation. No resampling is conducted during the winter. The detection limit for enterococcus in the OMBP is 10 CFU/100 ml. Concentrations of enterococci were analyzed using Enterolert (IDDEX, Westbrook, ME).

Study participants were also asked to identify where they had surfed in the previous 12 mo from a list of popular surfing beaches. The six beaches chosen to model exposure assessments were, therefore, beaches that were frequented by surfers and beaches for which there was OMBP enterococci monitoring data. OMBP results from January 2004 through December 2007 were then queried for these 6 beaches, which include, in order from north to south, Short Sands Beach (SSB), Cape Kiwanda State Park (CSP), Agate Beach (AGB), Otter Rock Beach (ORB), Humbug Mountain Beach (HMB), and Bastendorff Beach (BDB) (Figure 1). Between 2004 and 2007, the density of enterococci in marine water was analyzed at SSB, CSP, ORB, AGB, BDB, and HMB (Figure 3). Because these data sets were moderately to heavily censored (approximately 40–80% of sample results were below the detection limit) these density measurements were fit to lognormal distributions using a maximum likelihood estimator for censored distributions, modified for left censoring (Schneider, 1986). This technique was required to estimate the probability of densities below the detection limit, and provide a close fit between measured and estimated densities above the detection limit. The parameters for these distributions are described in Table 1.

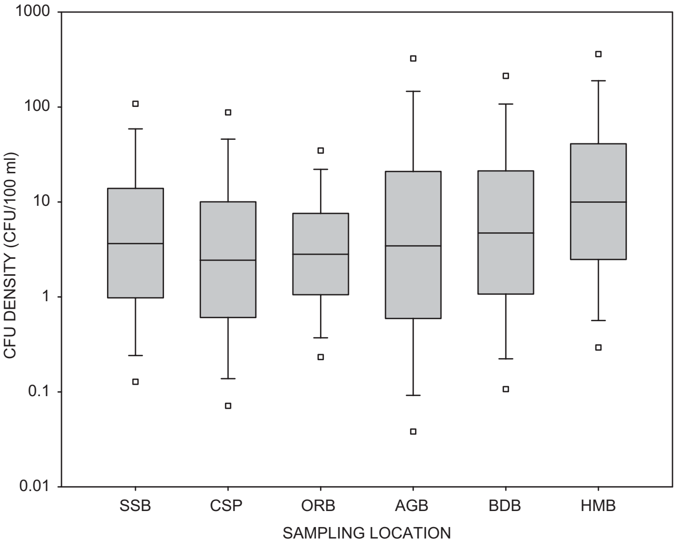

FIG. 3. Box and whisker plots of enterococci densities among six selected beaches in Oregon (bottom □: 25th percentile, lower whisker: 10th percentile, bottom of box: 75th percentile, centerline of box: 50th percentile, top of box: 75th percentile, upper whisker: 90th percentile, top □: 95th percentile). Note that the *y* axis (density) is a log scale.

Exposure-Response Analysis

Models are available to relate the density of enterococcus group bacteria in water to the probability of GI illness (Cabelli et al., 1982; Kay et al., 1994, 2004; U.S. EPA, 1986). Although these epidemiological-based models provide different functional relationships between density and excess risk of GI illness (Given et al., 2006), they do not explicitly relate ingested dose (number of enterococci organisms consumed) to risk of GI illness. Because there are few examples in the literature of ingested dose models for fecal enterococci (Donovan et al., 2008; Ottoson & Stenström, 2003), one based on methods used in other quantitative microbial risk assessments was developed (Hope et al., 2002). This ingested dose model was used to evaluate the probability of GI illness among surfers as a result of incidental ingestion of enterococci at each of the 6 beaches. For discussion purposes, these risk estimates were compared with those from two epidemiological models. These models estimate the probability of excess GI illness and the incidence of GI illness per 1000 swimmers as a function of enterococci densities in water (Cabelli et al., 1982; Kay et al., 1994, 2004; U.S. EPA, 1986). Exposure estimates were also compared to regulatory guidelines for enterococci group bacteria (U.S. EPA, 1986; WHO, 2003).

Ingested dose model. The probability of GI illness from ingestion of fecal enterococci was estimated with an exponential exposure-response model (Haas et al., 1999):

$$p(\text{ill})_{\text{day}} = \{1-\exp(-D_{\text{oral}}/\text{k})\}\cdot\Psi \qquad (1)$$

$$D_{\text{oral}} = I_{\text{oral}}\cdot(c/100) \qquad (2)$$

$$p(\text{ill})_{\text{year}} = 1-(1-p(\text{ill})_{\text{day}})^{d} \qquad (3)$$

where $p(\text{ill})_{\text{day}}$ is the daily probability of GI illness, D_{oral} is the number of CFU ingested per day, k is an organism-specific infectivity parameter, ψ is the ratio of illness to infection, I_{oral} is a random variable drawn from the distribution of water ingestion rates (ml/d, Figure 4A; see also Results section), c is a random variable drawn from the distribution of enterococci density (CFU/100 ml, Figure 3 and Table 1), $p(\text{ill})_{\text{year}}$ is the annual probability of GI illness, and d is a random value drawn from the distribution of days spent surfing per year (Figure 4B; see also Results section). Sensitivity analysis of Eq. (3) found that the volume of water ingested (I_{oral}) made the largest contribution to variance (~40%), followed, in order, by the CFU density (c, ~36%), the number of days spent surfing annually (d, ~13%), the infectivity parameter (k, ~10%), and the illness:infection ratio (ψ, ~1%).

Equation (1) calculates the daily probability of illness, while Eq. (3) estimates this probability on an annual basis (Haas et al., 1993). The infectivity parameter (k) was drawn from a triangular distribution with minimum of 177 (Ottoson & Stenström, 2003), a mode of 1442, and a maximum of 14,427. The mode and maximum values equate to median infectious dose (ID_{50}) values for the known waterborne pathogens cholera and *Salmonella*/shigellosis, respectively (Burrows & Renner, 1999). Given that very low enterococci densities have been associated with appreciable high illness rates (Cabelli et al., 1982) or none at all (Colford et al., 2007), it is uncertain whether these choices for k would yield over- or underestimates of risk. The ratio parameter (ψ) was drawn from a triangular distribution with minimum 0.1, mode 0.2, and maximum 0.3, based on infection to illness conversion probabilities for ingestion of *Salmonella* (Hope et al., 2002). These values are less than those reported for more virulent waterborne pathogens (Havelaar & Melse, 2003). The daily dose-response relationship generated by Eq. (1) is shown in Figure 5A.

Epidemiological model 1. The relationship between the density of enterococci in marine waters and the probability of excess GI illness from bathing (i.e., surfing) in those waters was estimated by (Kay et al., 1994, 2004; Wyer et al., 1999):

$$b = 0.20201\cdot\sqrt{(c-32)}-2.3561 \qquad (4)$$

$$p(\text{ill}) = (1/(1+e^{-b}))-0.0866 \qquad (5)$$

TABLE 1
Enterococcus Group Bacteria Density, Exposure, Risk and Rate of Illness, by Location

	Beach[a]					
Parameter	SSB	CSP	ORB	AGB	BDB	HMB
Density distribution (CFU/100 ml)[b]	LN{1.30, 1.75}	LN{0.89, 1.85}	LN{1.04, 1.30}	LN{1.24, 2.35}	LN{1.55, 1.97}	LN{2.30, 1.85}
Estimated density (CFU/100 ml)[c]	17 ± 2 [1–64]	13 ± 2 [1–51]	7 ± 1 [1–24]	51 ± 14 [1–165]	31 ± 6 [1– 120]	53 ± 8 [1–208]
Estimated dose (CFU/d)[c]	37 ± 18 [1–75]	19 ± 6 [1–68]	11 ± 2 [1–40]	49 ± 14 [1–138]	39 ± 10 [1–111]	86 ± 24 [1–251]
Probability of 50% risk of illness (annual) (ingested dose model)[d]	2% [<1–25%]	2% [<1–22%]	1% [<1–19%]	6% [<1–27%]	5% [<1–30%]	9% [<1–40%]
Probability of 50% risk of illness (epidemiology model 1)[e]	2%	1%	<1%	5%	3%	6%
Probability of 19 or more cases of excess illness per 1000 swimmers[f] (epidemiology model 2)	9%	7%	2%	15%	14%	23%
Probability of exceeding 158 CFU/100 ml[g] (regulatory guidelines)	< 1%	< 1%	< 1%	~7%	~3%	~9%
Probability of exceeding 40 CFU/100 ml[h] (regulatory guidelines)	~10%	~10%	<1%	~15%	~15%	~25%

[a] Short Sands Beach (SSB), Cape Kiwanda State Park (CSP), Otter Rock Beach (ORB), Agate Beach (AGB), Bastendorff Beach (BDB), Humbug Mountain Beach (HMB).

[b] LN{ , σ}=A lognormal distribution, with log mean, log standard deviation.

[c] Arithmetic mean [5th–95th percentile range].

[d] Bracketed [ ] values show effect of uncertainty in the dose-response model (Figure 5A) on risk estimates.

[e] Model not constrained between 32 and 158 CFU/100 ml.

[f] A rate of 19 cases or less per 1000 swimmers is U.S. EPA guidance (U.S. EPA, 1986).

[g] Oregon beach advisory guideline.

[h] WHO 2003 guideline.

where *b* is the $\log_n$ odds of gastroenteritis, *c* is a random variable drawn from the distribution of enterococci density per 100 ml, and *p*(ill) is the excess probability of GI illness. In Eq. (5), the constant 0.0866 adjusts the relationship to reflect the probability of excess GI illness for those who swim versus those who do not (Wyer et al., 1999). Kay et al. (1994, 2004) assumed that excess risk was zero below 32 CFU/100 ml (which equates to a background risk of approximately 14%)

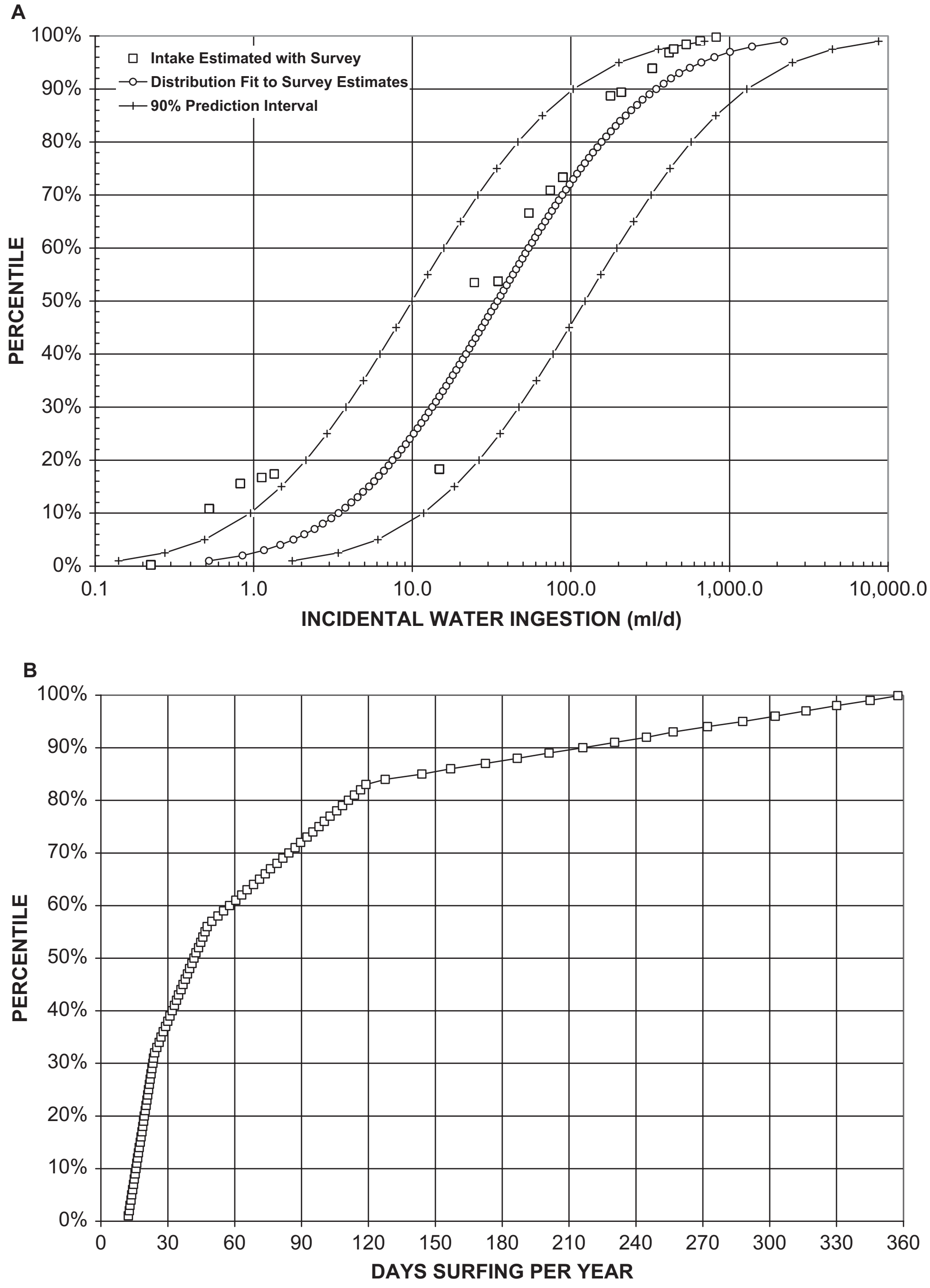

FIG. 4. (A) Distribution of the volume of seawater incidentally ingested per surfing day. (B) Cumulative distribution of the number of days spent surfing per year across all six beaches.

and that the value of p(ill) is constant when c exceeds 158 enterococci CFU/100 ml, with the probability of GI illness at higher levels being unknown. This assumption is likely to underestimate risk (WHO, 2003). In this analysis, probabilities were calculated for CFU densities <32 [i.e., the −32 term was removed from Eq. (4)] and >158 CFU/100 ml, to provide information for public health risk management decisions when enterococci concentrations may not fall within these thresholds. The exposure-response relationships generated with Eq. (5) ("constrained" with the "–32" term in the equation, "unconstrained" with it removed) are shown in Figure 5B, left y-axis.

Epidemiological model 2. Based on work by Cabelli et al. (1982), the U.S. EPA (1986) developed a linear regression

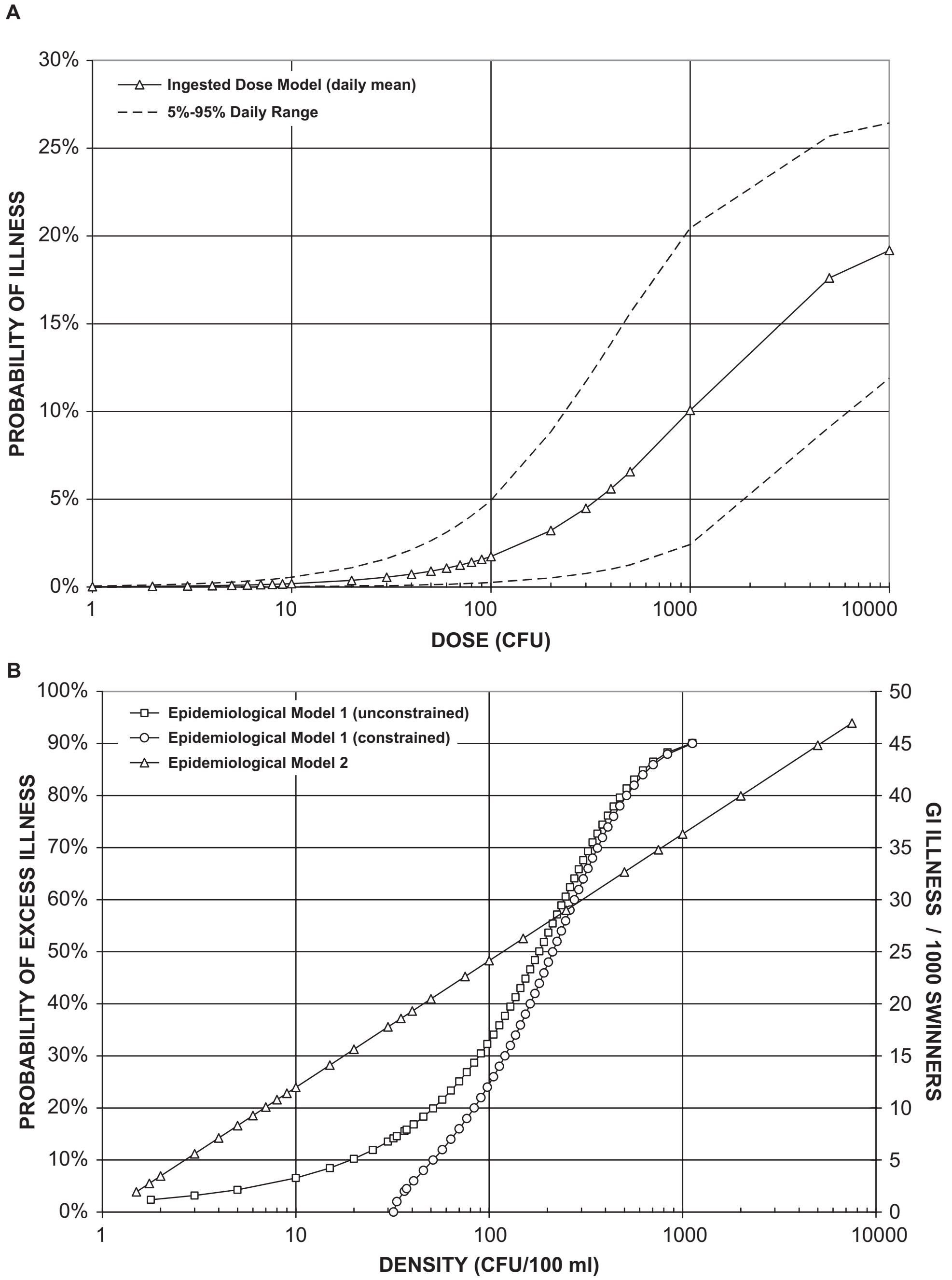

FIG. 5. (A) Daily probability of GI illness attributable to ingestion of enterococcus group bacteria. (B) Probability of GI illness attributable to density of (and implicit exposure to) enterococcus group bacteria (□, epidemiological model 1 (unconstrained, i.e., "–32" term removed from Eq. 4); (○, epidemiological model 1 (constrained between 32 and 158 CFU/100 ml); Δ, epidemiological model 2).

relationship that relates the rate of GI illness per 1000 swimmers to the density of enterococci in marine waters as:

$$p(\text{ill}) = -0.20 + 12.17[\log_{10}(c)] \tag{6}$$

where p(ill) is the rate difference of illness between swimmers and nonswimmers and c is the mean enterococci density per 100 ml. This exposure-response relationship is shown in Figure 5B, right y-axis.

Risk Characterization

Risk was characterized as the joint probability of exposure and response using a joint probability curve (JPC) methodology (Aldenberg & Jaworska, 2000; Giesy et al., 1999; Hendley &

Giddings, 1999; U.S. EPA, 2001). This method combines the probability of a given exposure occurring (from the exposure assessment) with the probability of that exposure eliciting a response (from the exposure-response assessment) should that exposure occur. For example, the risk of GI illness to a surfer is determined jointly by the value of D_{oral} in Eq. (1) and the probability of that value of D_{oral} occurring. The rationale for use of the JPC method is that it integrates exposure and response, thus providing a more accurate representation of risk and a better basis for decision making compared with "risk-free" quotients or other simple ratio methods.

The type of JPC used here (specifically an exceedance probability plot) was constructed by first representing both exposure and response as distributions, using the exponential model to estimate the probability of illness. These distributions for exposure and response at a given exposure were plotted against the same horizontal (x) exposure axis. Each exposure on the horizontal axis could thus be related to both the probability of its occurrence at a given beach and the probability of a response (illness) at that exposure. The exposure distribution was then cast as a complementary ($1 - p$) cumulative distribution function, which showed that high exposures (i.e., those likely to yield large responses) have a low probability of occurring. Because these two distributions share the same horizontal (x) axis (exposure), they could be combined to form a JPC by plotting the complementary exposure probability on the vertical (y) axis and the illness associated with that probability on the horizontal (x) axis. The area under the curve was taken as the measure of risk, with a smaller area equating to a lower risk. The closer a JPC comes to its axes, the lower the probability of a response of a given magnitude, and hence the lower the concern about adverse outcomes; conversely, the farther it lies from the axes, the higher is the concern. Exposure-response modeling, exposure and enterococci distributions, joint probability curves, and sensitivity analyses were conducted suing Crystal Ball Professional 2000 v5.2 (Decisioneering, Inc., Denver, CO) software.

RESULTS

Exposure Assessment

Five hundred nineteen (519) individuals completed the questions on the Web-based survey, with 93% of the respondents from 21 counties in Oregon. The age of respondents ranged from 18 to 64 yr, with a mean of 33 yr. The average number of years that respondents have been surfing was 12.4 yr.

Magnitude and Frequency of Ingestion

All (100%) of the respondents reported that they had swallowed water while surfing in the last 12 months, and 91% responded to the question regarding how much water is ingested for each swallow. Of these, 16.6% reported "a few drops," 51.3% reported "1–3 teaspoons," 21.1% reported "the amount in a shot glass" (2 ounces), and 1.8% answered "the amount in a small juice glass" (4 ounces). Individuals who could not estimate volume swallowed (9.1%) were excluded from further analysis. There were 487 responses to the question of how many times an individual swallowed water per day. Of these, 61.8% reported 1–2 times per day, 21.6% reported 3–4 times per day, 10.5% reported 5–6 times per day, 3.7% reported 7–8 times per day, and 2.5% reported 9 or more times per day. These descriptive survey estimates of exposure were aggregated into 442 quantitative estimates of the volume of water incidentally ingested daily (ml/d) while surfing, then fitted to a lognormal distribution so that ingested intake (I_{oral}) = LN{3.54, 1.80} ml/d. This distribution gave a median intake of 34.4 ml/d, an arithmetic mean intake of 170.6 ml/d, and a 5th–95th percentile intake range of 1.8–664.9 ml/d (Figure 4A).

The majority of respondents (503) answered the question on the frequency of surfing days per year. Of these, 31.8% reported 1–2 days per month, 24.5% reported 3–4 days, 27.0% reported 5–10 days, and 16.7% reported 10 or more days. The survey did not ask for any further breakdown of the time spent surfing between 10 and 30 days per month; thus, a simple linear relationship was assumed between 10 and 30 days per month, and the resulting distribution had a minimum of 1 day per month (12 days per year) and a maximum of 30 days per month (360 days per year). This distribution gave a median of 42 d/yr, an arithmetic mean of 77 d/yr, and a 5th–95th percentile range of 12–288 d/yr (Figure 4B). This distribution was also assumed to apply to all beaches, and the majority of respondents indicated that they surfed Oregon beaches year round.

Ingested Dose Model

Figure 6A shows the annualized joint probability curves (JPC) using Eq. (3), for each beach with exposure expressed as the number of CFU ingested. The area under the curve for HMB is the largest, indicating the most risk of illness for surfers, while the area under the curve for ORB is the lowest, indicating the least risk of illness for surfers. The relative risk among beaches is HMB > BDB > AGB > SSB > CSP > ORB. Intuitively, the risk of illness increases dramatically if the timeframe considered is surfing over 1 yr. For annual surfing at HMB, an exposure (dose) equivalent to a 10% probability of illness has approximately 27% probability of occurring, one equivalent to a 50% probability of illness has approximately 9% probability of occurring, and one equivalent to a 90% probability of illness has approximately 4% probability of occurring (Figure 6A). In other words, the levels of exposure that are more likely to occur are those that are also less likely to produce GI illness. Conversely, high exposures, those virtually certain to lead to illness, have a low probability of occurrence.

Epidemiology Model 1

Figure 6B shows JPC using Eqs. (4) and (5), for each beach with exposure expressed as CFU density. As with the ingested

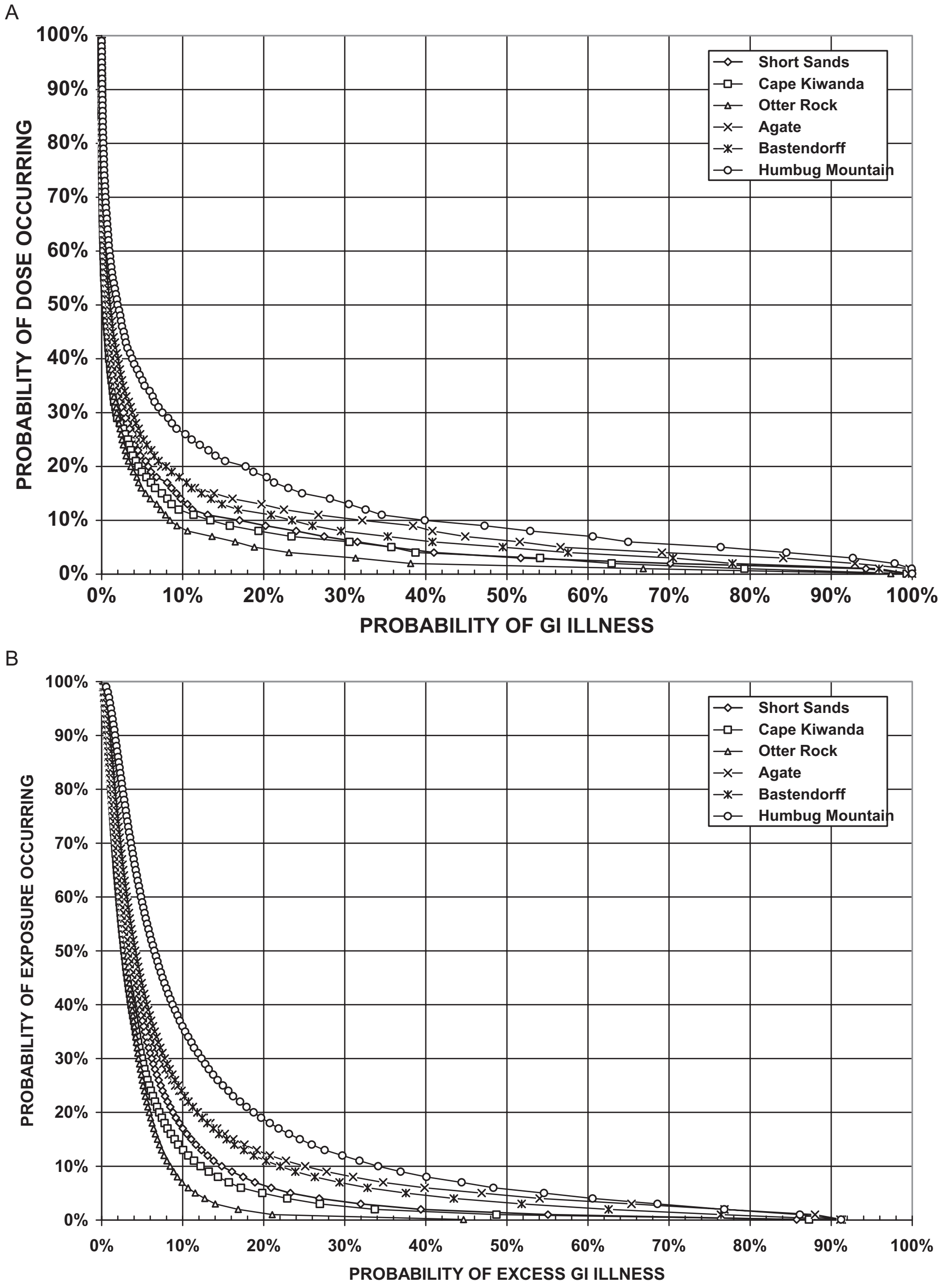

FIG. 6. Joint probability curves of median risk based on the annualized ingested dose model (A) and epidemiological model 1 (B) at various beach locations on the Oregon coast.

dose model, the area under the curve for HMB is the largest, indicating the most risk of illness for surfers, while the area under the curve for ORB is the lowest, indicating the least risk of illness. For surfing at HMB, an exposure equivalent to a 10% probability of illness has approximately 35% probability of occurring, one equivalent to a 50% probability of illness has approximately 6% probability of occurring, and one equivalent to a 90% probability of illness has approximately 1% probability of occurring.

Epidemiological Model 2

The potential rate of illness of surfers at each beach studied was plotted in the context of the U.S. EPA guidelines for recreational marine waters. Because the rate of illness does not represent a probability, a JPC was not used with this model. Rather, the rate of illness per 1000 swimmers [Eq. (6)] was plotted against the inverse probability of the occurrence of the exposure associated with that rate (Figure 7). At HMB, for example, there is approximately 58% chance that enterococci

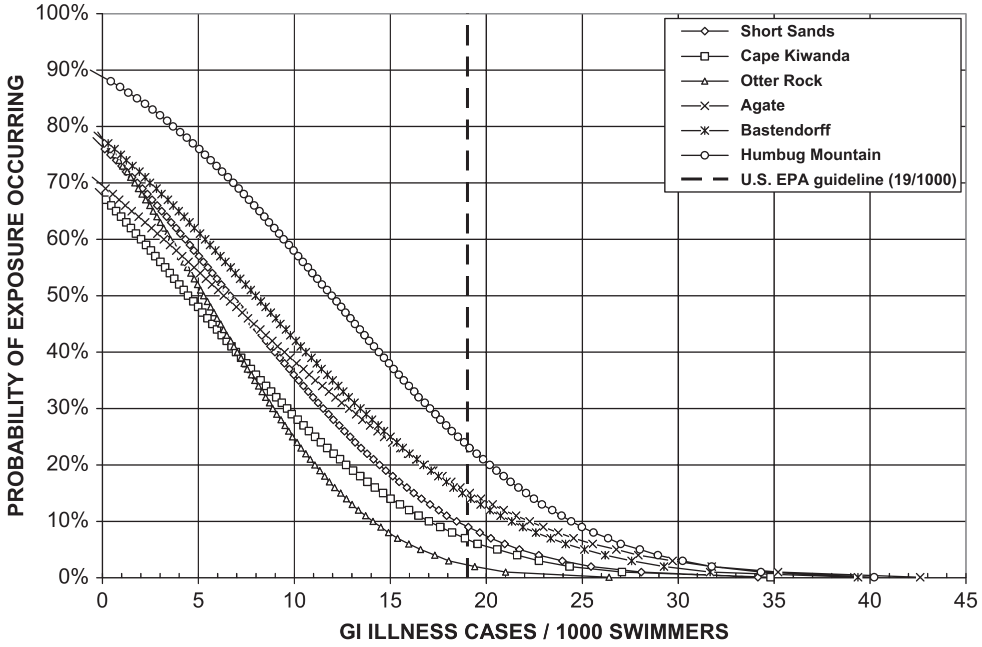

FIG. 7. Relationship between the median rate of GI illness per 1000 swimmers (estimated with epidemiological model 2) and the probability that an enterococcus density (as CFU/100 ml) capable of producing that rate would occur at selected beaches in Oregon. The dashed line indicates the U.S. EPA acceptable rate of illness (i.e., 19 per 1000 people).

densities would be high enough to result in illness in 10 out of 1000 surfers, approximately 20% chance of 20 illnesses, and only approximately 3% chance of 30 illnesses. At ORB, there is essentially no (de minimis) chance of encountering an enterococci density capable of producing 30 cases of illness.

Regulatory Guidelines

The probability of exceeding a density of 40 CFU/100 ml, the WHO guideline, ranges from a low of less than 1% at ORB to a high of 25% at HMB (Table 1). Similarly, the probability of exceeding a density of 158 CFU/100 ml, the Oregon beach advisory level, ranges from less than 1% at ORB to 9% at HMB (Table 1). The probability of exceeding an exposure that is equivalent to an illness rate of 19 per 1000 people ranges from a low of approximately 2% at Otter Rock Beach to a high of approximately 23% at Humbug Mountain Beach (Figure 7).

DISCUSSION

To our knowledge, this study is the first to estimate ingestion rates for surfers. A limited number of other exposure assessments have been developed or utilized for recreational water activities. Examples include the use of exposure estimates to calculate risk from toxigenic cyanobacteria in freshwaters with the assumption that 100 ml water is incidentally ingested over 2 h of swimming (Stone & Bress, 2007; WHO, 2003). A recent pilot study of recreational swimmers calculated an average amount of water swallowed by children and adults to be 37 ml and 16 ml, respectively (Dufour et al., 2006), which is considerably less than the WHO (2003) default estimate. A survey of diving behavior among recreational and occupational divers in the Netherlands revealed ingestion rates of 9 and 9.8 ml marine water per dive, respectively (Schijven & de Roda Husman, 2006). Estimates of water intake for surfers were markedly higher (mean = 170 ml/d) than those for swimmers and divers. Data showed that surfers, like the divers, were able to provide estimates of ingestion when given a familiar volume (teaspoon, shot glass, etc.) as a reference point. The reason given for such low ingestion rates among divers were that divers, unlike surfers, wear either an ordinary diving mask or sometimes a full face mask, which reduced the amount of water swallowed during diving. In addition, although the volumes of ingestion differed between surfers and divers, our findings also showed a low frequency of high-volume ingestions (1.8%) and a high frequency of lower volume ingestions (89.1%). Although these results are plausible when considered on a daily basis, it is acknowledged that there are uncertainties in any self-reported data, and that volumes of water ingested may vary.

Some studies demonstrated success in acquiring much needed empirical quantitative information from recreational participants, and highlighted the need for additional studies estimating ingestion among surfers and other high exposure water activities(Dufour et al, 2006; Schijven & de Roda Husman, 2006). In comparison to these studies, it was found that the magnitude of incidental ingestion among surfers for each recreational event was 1.7-fold higher compared with WHO (2003) estimates, 10.6-fold higher compared with the amount ingested by adult swimmers in a pool (Dufour et al., 2006), and 18-fold higher compared to diver exposure (Schijven & de Roda Husman, 2006). There were no differences in ingestion estimates from our survey between surfers based on surfing experience (number of years); thus, surfers at all skill levels ingested measurable volumes of water during each surfing day. There were also no significant differences in ingestion estimates with surfers based on age (older vs. younger).

The potential for selection bias in our study exists because survey participants self-selected to visit the website (Eysenbach & Wyatt, 2002; Lenert & Skoczen, 2002; Turbow et al., 2008). Our participant sample may be disproportionately comprised of surfers who are more interested in water pollution as it relates to health issues, and thus may not be representative of the entire group of Oregon surfers or those nationally. On the other hand, the survey may represent a broader surfer population in Oregon than expected. Because the survey was posted on the Oregon Surfrider website, it was postulated that the majority of our participants would be members of Surfrider Foundation. However, only 23% of participants indicated they were members of Surfrider, so the survey represents a broader section of surfers than just those who are members of this group.

Another limitation to the current study is that the true response rate for the survey is unknown, because the number of site visits could not be monitored to assess the total number of people who viewed the survey over the study period, but chose not to complete the survey. It is also true that surfers who were interested in completing this survey may have been more frequent surfers (and therefore ingest more water) than those who did not complete the survey, leading to the possibility of overestimating the exposures for surfers.

Enterococcus density (Figure 3) was analyzed at six Oregon beaches and used to construct exposure distributions for Oregon surfers. Enterococci are regarded as a suitable indicator organism for use in regulating recreational waters to monitor the risk of GI illness, as evidenced in previous studies showing a strong statistical association ($r^2 = .74$) between enterococci density and GI illness risk (Cabelli et al., 1982; U.S. EPA, 1986; Wade et al., 2003). Enterococci density has, however, been recently reported to be unrelated to illness at a specific beach in California (Colford et al., 2007). Enterococci density ranged from an arithmetic mean of 7 CFU/100 ml at ORB to 53 CFU/100 ml at HMB. Sampling results were characterized by a high level (40–80%) of samples below the detection limit (10 CFU/100 ml) and sporadic results above the threshold for issuance of beach advisories in Oregon (158 CFU/100 ml). A prior study of 26 Oregon beaches in 2002 found 9 locations with densities above the U.S. EPA single-sample maximum density of 104 enteroccoci CFU/100 ml, with exceedances ranging from 131 to 4325 CFU/100 ml (Benedict & Neumann, 2004). A follow-up study analyzing Oregon Beach monitoring data from 2002–2005 showed that one-third of the 52 beach locations had enterococci levels exceeding Oregon's action level of 158 CFU/100 ml (Neumann et al., 2006). The probability of exceeding 158 CFU/100 ml was low (<1%) at 3 of the beaches in our study, suggesting that these beaches may present low risks to surfers. However, risk for surfers is increased at several of the beaches that had greater probabilities of exceeding the advisory level (AGB and HMB), especially if these sites are preferred by certain surfing populations.

The distribution of enterococci densities at the six targeted beaches were integrated with the exposure distributions to model the number of enterococci ingested. The estimated mean ingestion among surfers ranged from ~11 CFU/d at ORB to ~86 CFU/d at HMB (Table 1). This wide range of ingestion estimates indicates that the degree of incidental ingestion during surfing and other high-intensity recreational activities is quite variable among both individuals and beaches, thus affecting the probability of developing GI illness. Thus, while Otter Rock Beach (ORB) and Humbug Mountain Beach (HMB) have the lowest and highest risk, respectively, they may present similar risk to a surfer who spends more time at ORB or less time at HMB. Better characterization of the days spent surfing annually at a particular beach might be an important piece of information for more effective management of the risk to recreational users.

An unconstrained (i.e., estimates of illness probability were not truncated at densities of 32 and 158 CFU/100 ml) epidemiological model 1 estimates total, rather than excess, risk, making it more compatible with outputs from the ingested dose model. In addition, a constrained epidemiological model 1 (i.e., no risk of excess illness below 32 CFU/100 ml or increased excess illness above 158 CFU/100 ml) produces results that are not readily compatible with the JPC method. Furthermore, its upper bound truncation was acknowledged to potentially underestimate actual risk (Kay et al., 2004) and raises the possibility that the degree of underestimation might be further increased during high exposure scenarios (i.e., surfing) (WHO, 2003). Overall, epidemiological model 1 (Figure 6B) suggested approximately the same level of risk to surfers as predicted by the annualized ingested dose model (Figure 6A). This suggests that the ingested dose model, despite its inherent uncertainties (Table 1, Figure 5A), is capable of estimating risk of GI illness similar to an epidemiological model based on enterococci density.

The joint probability curve (JPC) methodology is one of several ways to integrate distributions of exposure and exposure-response. It can be applied to many types of distributions and is relatively easy to construct and calculate. If data to characterize the probability of occurrence of a particular exposure and an exposure-response curve are available, they can be combined to yield a JPC that illustrates the probability that a response greater than some specified magnitude would occur. The advantage of this approach is that it gives a clear visual display of both the probability and magnitude of response. Further, the area under the curve is a relative index of the population-level risk (Figure 6, A and B). In addition, comparison of this area across different beaches is helpful in comparing different risk scenarios with respect to both risk characterization and risk management. As illustrated in Figure 6, A and B, HMB is predicted to have a higher probability of GI illness compared to other beaches. Using a risk-based approach, this graphic comparison could be informative in prioritizing the surveillance of recreational sites for advisory programs. One drawback is that it is sometimes difficult for decision makers to understand and interpret risk characterization results presented in this format (U.S. EPA, 2001). Evidence indicates, however, that the results of this foundational research could be readily adapted to provide beach managers with a practical and implementable risk-based management tool. For example, a simple, color-coded, laminated chart that relates CFU density, time spent surfing, and risk on a high–medium–low matrix scale for a given beach could be prepared by beach managers.

The probability of an exposure occurring above the U.S. EPA acceptable rate of 19 GI illnesses per 1000 swimmers ranged from approximately 2% at OMB to approximately 23% at HMB, as shown in Figure 7. All beaches had less than 5% probability of exceeding 30 illnesses per 1000 people and an effectively zero (de minimis) probability of exceeding 40 illnesses per 1000 people over a 1-yr period. While the risk of excess GI illness is not high, it does indicate that people engaged in surfing activities in Oregon coastal waters may not be adequately considered in the context of a health advisory program.

Our approach to assess the risk of GI illness to surfers was based on quantitative exposure assessment and exposure-response modeling. It is possible the enterococci densities used in our calculations were based on somewhat limited sampling within the OBMP. Nevertheless, the results reflect 3 years of sampling data and were conducted on a year-round basis. It is also recognized that quantification of exposure using a survey instrument may not be as accurate as the actual measurement of water ingestion. However, there is confidence that our estimates are more accurate compared to those from past studies that base exposure estimates merely on head submersion. This supposition is supported by the similarity in results from the ingested dose model and epidemiological model 1. Our study also has implications for surfers who are exposed to marine toxins (such as cyanotoxins) in addition to bacterial or viral organisms, as exposure to cyanotoxins may be enhanced through aspiration of water into the lungs and inhalation of mist, as well as oral ingestion (Stone & Bress, 2007). In addition, this study was conducted on surfers who visit cold marine waters that are relatively low in enterococci densities compared with surfing locations in warm waters. Risk for surfers in more contaminated waters may help to explain the large number of reported illnesses in the few studies that have been conducted with surfers or windsurfers in warmer waters (Dewailly et al., 1986; Turbow et al., 2008; Dwight et al., 2004). The risk estimated in our study may not be representative of these locations, suggesting further investigation of these surfers and other marine recreational activities is needed.

CONCLUSIONS

Surfers ingest more water during a typical recreational day compared to swimmers and divers, and need to be considered in the context of public health or regulatory efforts. On an annual basis, an ingested dose model gave similar estimates of risk of GI illness among surfers as was shown in two epidemiological models. While the risk for Oregon surfers was not high for GI illness, our findings suggest that surfers who spend more time in recreational waters or who surf in highly contaminated locations are likely to be at higher risk of GI illness. Our approach to characterize risk among surfers, which integrates the probability of an exposure occurring with the probability of illness, is a novel application of the JPC methodology to microbial risk assessment. The graphic illustration of risk may be useful to public health and environmental officials who are responsible for beach sampling and advisory programs.

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