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Water ingestion during water recreation☆

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ABSTRACT

Quantitative risk assessments have estimated health risks of water recreation. One input to risk assessment models is the rate of water ingestion. One published study estimated rates of water ingestion during swimming, but estimates of water ingestion are not available for common limited contact water recreation activities such as canoeing, fishing, kayaking, motor boating, and rowing. In the summer of 2009 two related studies were conducted to estimate water ingestion during these activities. First, at Chicago area surface waters, survey research methods were utilized to characterize self-reported estimates of water ingestion during canoeing, kayaking, and fishing among 2705 people. Second, at outdoor swimming pools, survey research methods and the analysis of cyanuric acid, a tracer of swimming pool water, were used to characterize water ingestion among 662 people who engaged in a variety of full-contact and limited-contact recreational activities. Data from the swimming study was used to derive translation factors that quantify the volume of self-reported estimates. At surface waters, less than 2% of canoers and kayakers reported swallowing a teaspoon or more and 0.5% reported swallowing a mouthful or more. Swimmers in a pool were about 25–50 times more likely to report swallowing a teaspoon of water compared to those who participate in limited-contact recreational activities on surface waters. Mean and upper confidence estimates of water ingestion during limited-contact recreation on surface waters are about 3–4 mL and 10–15 mL, respectively. These estimates of water ingestion rates may be useful in modeling the health risks of water recreation.

1. Introduction

Water recreation has been associated with outbreaks of acute gastrointestinal illness caused by viruses, bacteria, and protozoa (Dziuban et al., 2006; Yoder et al., 2004). Higher rates of acute gastrointestinal illness (AGI) have been reported among swimmers compared to non-swimmers (USEPA, 1983, 1984; Seyfried et al., 1985; McBride et al., 1998; Wade et al., 2008; Colford et al., 2007). Controlled immersion trials have demonstrated higher rates of AGI among those randomized to perform head immersion compared to a non-immersion group (Kay et al., 1994; Wiedenmann et al., 2006; Fleisher et al., 2010).

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Epidemiologic studies require substantial resources and time, and may generate results that have limited generalizability to settings with different types of recreational use or pollutant sources. Quantitative microbial risk assessment (QMRA) offers an alternative method for evaluating health risks for a particular water quality measure or for a range of water quality measures (Wong et al., 2009; Ashbolt et al., 2010). Conversely, reverse QMRA has can performed to identify an acceptable level of water quality for a given targeted risk level and has recently been utilized to estimate the contribution of specific pathogens to known rates of recreational waterborne illness (Soller et al., 2010).

Limited-contact recreation activities are popular, particularly at inland waters. The number of people who engage in limited-contact activities per year in the US (in millions) are: fishing (71), motor boating (52), canoeing (20.7), rowing (9.4), and kayaking per year (6.4) (Cordell et al., 2004). Despite the large number of people exposed through limited-contact recreation, very little is known about the health risks of these activities. Recently site-specific standards for limited (or "secondary") contact recreation have been explored in the United States for waters that do not support full-contact recreation. These include efforts in Idaho (Idaho Department of Environmental Quality, 2004), Illinois (Illinois Pollution Control Board, 2010), Kansas (USEPA, 2003), Missouri (Missouri Coalition for the Environment, 2010), Texas (Texas Commission on Environmental Quality, 2009) and Utah (Utah Department of Environmental Quality, 2008). Estimated rates of water ingestion could serve as inputs in risk assessments that model the health risks of limited contact water recreation. The most recent version of USEPA's Exposure Factor Handbook (USEPA, 2009), available in draft form, does not address the volume of water ingested during recreational activities other than swimming. The ingestion rate during swimming was estimated by Dufour et al. (2006), who utilized cyanuric acid (CYA), routinely added to outdoor swimming pools to stabilize chlorine, as a tracer of swimming pool water. In this work we report the volume of water ingested during a variety of water recreational activities using survey research methods and through the measurement of CYA.

2. Materials and methods

2.1. *Overview*

Two groups of participants were enrolled in the spring and summer of 2009. The first group of surface water participants was enrolled in a prospective cohort study of limited contact water recreation, the Chicago Health, Environmental Exposure, and Recreation Study (CHEERS). Participants in the surface water study were recruited at Chicago area locations including piers, harbors, and beaches of Lake Michigan; the Chicago area waterways system (CAWS); several inland lakes; and rivers (excluding the CAWS). Most of the flow in the CAWS is wastewater effluent that has undergone secondary treatment (activated sludge with aeration) but has not been disinfected. A second study group of participants was enrolled into the swimming pool study at participating outdoor public pools. Participants in both studies (surface water and swimming pool) completed post-recreation interviews that addressed water ingestion during recreation. Those in the swimming pool study collected urine samples for 24 h following recreation, to be analyzed for CYA. The surface water study was an observational design; the swimming pool study was a controlled exposure design.

2.2. *Participants*

Data analysis was limited to those age six years or greater. In the swimming pool study, people who had used a swimming pool in the prior four days were excluded, as were those with underlying renal disease, which may influence the elimination half-life of CYA.

2.3. *Recreational activities*

Surface water study participants engaged in one of five activities: canoeing, fishing, kayaking, motor boating, or rowing. There were no constraints on the duration of recreation for the surface waters group. Swimming pool participants engaged in canoeing, kayaking, simulated fishing, wading/splashing, head immersion, or swimming. Head immersion involved standing in the water and immersing one's head three times over a 10 min interval. The duration of all other swimming pool activities was 60 min. Canoes and kayaks were placed in a large swimming pool, and participants were asked to paddle around the pool. During specific study sessions, canoe and kayak instructors were present so that interested participants could practice "rolling" to recover from capsize. Additionally, capsize occurred accidentally and, at times, teenagers and young adults intentionally capsized each other's kayaks. Simulated fishing involved casting a fishing rod with a toy fish on a plastic hook, reeling in the toy fish, removing it from the hook, replacing it, and repeating the procedure every 5 min. Wading/splashing took place in shallow swimming pools ("splash pools"), some of which had fountains. Participants were instructed to walk around, play, or splash in the water, but not to swim. Swimming took place in large swimming pools and, like the study by Dufour et al. (2006), was limited to lap swimming. In the surface waters study, participants were recruited at boat launches, piers, harbors and, in the case of sea kayakers, at beaches. Neither the choice of recreational activity nor the duration of recreation was assigned to surface waters participants.

2.4. *Data collection*

Following recreational activity, participants in the surface water and swimming pool studies were interviewed about water ingestion. Those who reported water ingestion were asked whether they swallowed "a drop or two", "a teaspoon", or "one or more mouthfuls". All interviews were conducted using computer-assisted personal interview methods on laptop computers running BLAISE® software (Westat, Inc). The programming of the questionnaires and the consolidation of survey datasets were performed by the UIC Survey Research Laboratory. Following their field interview, participants were given 2 L amber bottles and instructed to collect their urine for the next 24 h. Upon completion of urine collection, urine samples were transferred from participants' homes to the UIC laboratory by a courier service.

2.5. Measurement of CYA

Previously described methods for measuring CYA in swimming pool water by Cantu et al. (2001a, 2001b) and in urine by Patel and Jones (2007) were the basis for a series of method optimization studies. The method optimization studies and a detailed description of the CYA analysis methods are provided in the Supplementary material. Briefly, Chem-Elut cartridges and the solvent MTBE were used in urine sample preparation. The major analytical instrument was an Agilent Model 1100 HPLC system equipped with a vacuum degasser, a quaternary pump, a thermostated column compartment and a diode-array UV detector. A porous graphite carbon (PGC) column, 110 mm × 3.0 mm, 5 μm particle size (Hypercarb, Thermo-Fisher) was used. The HPLC was operated in an isocratic mode with a flow rate of 0.8 mL/min. The wavelength of the UV detector was set at 213 nm.

A subset of urine samples were analyzed by liquid chromatography tandem mass spectrometry (LC/MS/MS), with the intention of confirming the results obtained using the HPLC/DAD method. The procedure of urine sample pretreatment for LC/MS/MS analysis is similar to that described above for HPLC/DAD, except that 100 ng/mL $^{13}C_3$ $^{15}N_3$ labeled CYA was spiked in each urine sample as the first step. The Waters MicroMass Quattro LCZ LC/MS/MS system equipped with a SeQuant ZIC HILIC column (2.1 × 150 mm PEEK, 5 micron) was used. The operational conditions were developed based on those previously reported by Smoker and Krynitsky (2008). For each sample, a 20 μL full-loop injection was made at 8 μL/min. The electron spray ionization MS was operated in negative mode with multiple reaction mechanism (MRM). The native CYA was monitored with primary transition m/z 128→42 and secondary transition m/z 128→85. The labeled CYA was monitored with transition m/z 134→44. Quantitation of CYA was based on integrated peak area of the primary transition.

2.6. Data analysis

2.6.1. Water ingestion estimated from tracer chemical methods

Estimated water volumes were calculated using the following mass-balance approach, as described by Dufour et al. (2006):

$$\text{Volume ingested(mL)} = \frac{\text{Urine CYA conc.}(\mu\text{g/mL}) \times \text{Urine Volume(mL)}}{\text{Pool CYA conc.}(\mu\text{g/mL})}$$

If less than 20% of the expected 24-urine output was provided, the urine sample volume was considered insufficient. These thresholds for sufficient volume were 150 mL for those age 10 and younger, 200 mL for those age 11–16, and 300 mL for those age 17 and older based on estimates of urine volume being 60% of daily weight-based fluid requirements (Greenbaum, 2007).

2.6.2. Statistical methods

Individuals were permitted to participate in the study more than once, but not within four days of prior participation. For those who participated more than once it was necessary to determine whether each round of participation could be considered an independent event. If repeat participation events were independent, relatively simple statistical methods such as logistic regression would be used. If, on the other hand, repeat participation events were not independent, mixed-effects regression models would be necessary to account for correlations between repeated events of individuals.

The SAS NLMIXED procedure (SAS Institute, Cary, NC) was used to evaluate the independence of repeated measurements within individuals. In this analysis we employed logistic (for dichotomous and ordinal outcomes) and linear regression models with a random individual effect. A variance parameter for the random individual effect was estimated to account for the covariance between repeated measurements from the same individual. A likelihood ratio test on the significance of this individual variation parameter reveals whether repeated events from the same participant can be assumed to be independent. The outcomes of interest included (1) any self-reported water ingestion (vs. none), (2) the estimated volume of water ingested reported (four ordinal categories), and (3) the calculated volume of ingestion based on results of CYA measurement. Age, gender, recreational activity, and the time of enrollment were included as fixed-effect covariates for all models. For the dichotomous outcome (any water ingestion), model selection was performed using likelihood ratio tests to compare between a random-intercept logistic model and random-trend logistic model. For ordinal outcomes (estimated volume of water ingested), the proportional odds assumption was checked by the likelihood ratio test. If the proportional odds assumption was shown to be violated, non-proportional odds ordinal logistic model would be compared to non-proportional odds ordinal logistic model with random intercepts to check whether significant correlations existed between repeated measurements. For the continuous outcome, volume of water ingested, log transformation was performed first to normalize the data. Likelihood ratio tests were employed to choose between mixed-effects regression models with different random effects covariates (random intercept vs. random-trend), as well as appropriate error variance-covariance structures. Model fits were evaluated using Akaike's information criterion (AIC) and Bayesian information criterion (BIC). Using the selected model with best fit, Wald tests of the random-effect parameters were performed to evaluate independence of the repeated measurements.

Translation factors: As described in the "Results" section, reliable measures of cyanuric acid were only available for a subset of urine samples. Using the calculated ingestion volumes from those samples, as well as the self-reported ingestion estimates from the participants who provided those samples, translation factors were calculated. Two types of translation factors were calculated. The mean estimate was the mean calculated volume of water ingested for a given level of self-reported ingestion. For each level of self-reported ingestion an upper confidence estimate was calculated as:

$$\text{Upper confidence estimate} = \text{Mean estimate} + (1.96)(\text{standard deviation}).$$

Logistic regression models were used to evaluate variables associated with dichotomous categories of water ingestion. The three outcomes (evaluated in three separate models) were (1) any water ingestion (vs. none), (2) a teaspoon or more ingested (vs. none or a drop), and (3) a mouthful or more ingested (vs. none, a drop, or a teaspoon). Multivariate models included gender and age category (less than age 18 years vs. 18 years or more) as predictor variables. For recreational activities that took place in both the swimming pool study and the surface water study, models included a variable to evaluate whether estimates of ingestion were different in the pool than in the surface water study. For surface water study participants, water ingestion was also evaluated as a function of whether recreation took place in the CAWS vs. other area waters. All data analyses were conducted using SAS version 9.1 (SAS Institute, Cary, NC).

2.7. *Human subject research*

This research was approved by the Institutional Review Board of the University of Illinois at Chicago. Adult participants provided written documentation of informed consent. Parents or guardians provided written documentation of informed consent for participation of their children. Children above the age 8 years provided written assent to participate.

3. Results

3.1. *Study participants*

Of the 662 swimming pool study participants, 410 (62%) participated more than once; 9% participated four or more times. An analysis of random effects in models of survey and CYA-based estimates of water ingestion determined that the covariance of observations from same individual are not significant, and hence, each repeated event from the same participant can be considered independent. Only 6% of participants in the surface water study enrolled more than once, too infrequent for within-individual covariance to be a concern. Therefore the 3367 sets of water ingestion data were treated as though they came from 3367 different individuals. Subject demographics and recreational activities are summarized in Table 1. A comparable proportion of participants were children in the surface water and swimming pool studies.

3.2. *Self-reported water ingestion*

Self-reported water ingestion is summarized in Table 2, by recreational activity and study setting, as frequencies, and as relative frequencies. Pool study fishers and participants who walked around the swimming pool reported no water ingestion. No more than 5% of participants in any given activity on surface waters reported ingesting water. Those who canoed and kayaked in swimming pools tended to report water ingestion more frequently than those who engaged in these same activities in surface waters. Swimmers more frequently reported water ingestion than those who performed head immersion.

Table 1 – Recreational activities and demographics of study participants.

	Surface waters					Swimming Pool				
	Adult		Child		Total	Adult		Child		Total
	M	F	M	F		M	F	M	F	
Comparison activity										
Walking						12	11			23
Limited contact										
Canoeing	243	410	51	62	766	29	37	3	7	76
Boating	129	140	26	21	316					0
Fishing	190	236	87	87	600	78	26	6	11	121
Kayaking	346	372	31	52	801	31	47	4	22	104
Rowing	75	101	23	23	222					0
Wade/splash						59	35	6	12	112
Full contact										
Immersion						52	45	9	6	112
Swimming						49	46	11	8	114
Total	983	1259	218	245	2705	310	247	39	66	662
Percent	36.3	46.5	8.1	9.1	100.0	46.8	37.3	5.9	10.0	100.0
Grand total	3367									

M: male; F: female.

Table 2 – Self-reported water ingestion of 3,367 recreators, by activity, and study setting.

	Surface water study					Pool study				
Activity	*n*	Drop	Tsp	Mouthful	Relative ingestion	*n*	Drop	Tsp	Mouthful	Relative ingestion
Canoeing	766	5	1.4	0.5	1.5	76	7.9	6.6	3.9	6.9
Fishing	600	0.3	0.3	0.3	0.4	121	0	0	0	0
Immersion						112	20.5	9.8	0.9	10.3
Kayaking	801	4.2	1.1	0.2	1.2	104	15.4	11.5	6.7	12.1
Motor boating	316	2.2	0.9	0.3	1.0					
Rowing	222	4.5	1.8	0.5	1.9					
Swimming						114	53.5	50.9	27.2	53.6
Wade/splash						112	2.7	2.7	0	2.8
Walking						23	0	0	0	0

Numbers in the "Drop" "Tsp" and "Mouthful" columns refer to the percent of participants reporting that volume of ingestion. Relative refers to the proportion of participants in study-activity category, who ingested at least a teaspoon, relative to motor boaters.

3.3. *Predictors of self-reported water ingestion*

Multivariate logistic regression models were used to identify and evaluate predictors of ingesting a teaspoon or more of water, by self-report among surface water recreators (Table 3). After adjusting for activity and age category, males tended to report water ingestion more frequently than females. Age category was not associated with self-reported water ingestion. The odds of ingesting a teaspoon or more of water were substantially higher among swimmers than among those who performed head immersion (in the pool study) or limited-contact activities on surface waters. Odds ratios and confidence intervals similar to those reported in Table 3 were noted for swallowing any water and for swallowing at least a mouthful of water (data not presented).

Capsizing occurred among 41/766 (5.4%) surface water and 21/76 (27.6%) of swimming pool canoers. Capsizing occurred among 27/801 (3.4%) surface water and 40/104 (38.5%) swimming pool kayakers. One of 222 surface water rowers (0.5%) reported capsizing as well. Swallowing water among canoers, kayakers, and rowers was evaluated using a multivariate logistic model with capsizing, age category, gender, activity, and study setting (CAWS vs. other surface waters). The only significant predictor of water ingestion was capsizing. Compared to those who did not capsize, the odds (95% CI) of ingesting any, a teaspoon or more, or a mouthful or more among those who did capsize were 4.83 (2.42, 9.64), 24.57 (9.32, 64.75), and 247.22 (17.45, 3501.85), respectively.

Table 3 – Multivariate odds ratios for ingesting at a teaspoon or more of water, by self-report.

Variable	Reference category	Odds ratio (95% CI), swallowed $\geq$ teaspoon
Child	Adult	0.81(0.43, 1.50)
Male	Female	2.0 (1.3, 3.2)
Swimming	Motor boating	125.0 (35.7, 333.3)
Swimming	Canoeing	62.5 (33.3, 125.0)
Swimming	Fishing	333.3 (90.9, 1000.0)
Swimming	Immersion	10.0 (4.8, 20.8)
Swimming	Kayaking	50.0 (27.0, 90.9)
Swimming	Rowing	62.5 (21.7, 200.0)
Swimming	Wade/splashing	38.5 (11.5, 125.0)

Given the strong association between capsizing and ingesting water, a logistic regression model was run to identify predictors of capsizing. The only significant predicator was that capsizing was much more likely to occur on general use waters compared to CAWS, as presented in Table 4.

3.4. *CYA in pool water and urine samples*

A total of 130 pool water samples were analyzed using the HPLC/DAD method. As detailed in the Supplementary material, quality-monitoring data indicate excellent performance of the method for pool samples. Urine samples were collected from 665 of the 685 study participants (97.1%). Excellent agreement between self-reported water ingestion and the estimates obtained from CYA measurement using LC/MS/MS was observed for the subset ($N = 27$) of the urine samples collected from participants who enrolled in the study on four dates in July, 2009. These participants used a total of four pools, and represented five of the six recreational activities (none fished). The mean age of these participants was comparable to those whose samples were not analyzed by MS (34.8 vs. 34.3 years, $p = 0.85$). The means $\pm$ standard deviations are 1.4 $\pm$ 0.8, 9.4 $\pm$ 11.0, and 26 $\pm$ 37 mL for the participant groups with self-reported injection volumes of none, drop to teaspoon, and mouthful, respectively, showing strong agreement between the self-reported results and those based on CYA measurement using LC/MS/MS. However, quality control data for HPLC/DAD analysis indicated a strong matrix effect, particularly when the CYA concentration level in the swimming pool water was low. The correlation between CYA concentrations measured by the two instrument systems was very poor ($r^2 = 0.1$). In addition, the estimates of ingestion

Table 4 – Multivariate predictors of capsize in surface waters.

Variable	Reference category	Odds ratio	95% confidence interval
Male	Female	1.34	(0.80,2.25)
Child	Adult	0.64	(0.29,1.43)
Kayaking	Canoeing	0.75	(0.45,1.24)
Rowing	Canoeing	0.20	(0.03,1.50)
Other surface waters	CAWS	9.26	(3.32, 25.64)

Table 5 – Translation factors for self-reported ingestion (mL) based on LC/MS/MS measures of CYA.

	n	Mean	Standard deviation	Median	Minimum	Maximum	UCL
None	15	3.5	3.6	2.0	0.3	12.7	10.6
Drop/teaspoon	6	10.8	10.5	7.9	0.7	27.6	31.4
Mouthful	6	20.3	30.1	11.1	1.2	80.9	79.3

UCL: 95% confidence limit.

from measured CYA in urine using HPLC/DAD were inconsistent with the self-reported information (refer to the online Supplement for details). Therefore, the results of HPLC/DAD analysis were not explored further.

3.5. *Translation factors for self-reported water ingestion*

Among participants whose urine samples were analyzed by LC/MS/MS, because few reported swallowing a drop or a teaspoon of water, these two categories were collapsed into a single category. Log_{10}-transformed values of MS-based calculations of ingestion were associated with the ordinal levels of self-reported ingestion (none, drop-teaspoon, mouthful), with an r^2 of 0.24, $p = 0.009$. Table 5 summarizes the values of calculated ingestion for each level of self-reported ingestion.

The translation factors (Table 5) were used to estimate the volume of water ingested for recreational activities. The absolute estimated ingestion volumes for the mean and upper confidence level by activity are summarized in Table 6. The table also summarizes the mean ingestion volume relative to that observed during surface water fishing and rowing. Generally, the mean estimates are about 50% greater than the median estimates. This occurs because the distribution of mean ingestion volumes is skewed in a positive direction, with most of the values found near the minimum value (0.3 mL, corresponding to "no water ingestion" in Table 5), consistent with a lognormal distribution. Three categories of recreational activities are apparent based on ingestion estimates for the 95th percentile (the upper confidence limit). The low ingestion category is comprised of rowing, motor boating, fishing, wading/splashing, and non-capsizing kayaking and canoeing. These activities have an upper confidence estimate of about 10–12 mL/h. Those who capsized during canoeing or kayaking comprise a middle ingestion category, with an upper confidence limit estimate of about 17–20 mL/h. Swimmers were the high ingestion category, with an estimated upper confidence estimate of ingesting about 35 mL/h.

4. Discussion

In this first study designed to evaluate water ingestion during limited-contact recreational activities, less than 5% of limited-contact recreators on surface waters reported swallowing any water, compared to more than 50% of swimmers in a pool. Compared to those who canoed or kayaked in a swimming pool, swimmers in a pool were about four to seven times more likely to report swallowing at least a teaspoon of water. Compared to those who canoed or kayaked on surface waters, swimmers in a pool were more than 50 times as likely to report swallowing a teaspoon of water. Because the vast majority of limited-contact recreators on surface waters denied swallowing any water, less dramatic differences were observed in the estimated mean volume of water ingested: canoeing, 3.9 mL; fishing 3.6 mL; kayaking, 3.8 mL; motor boating, 3.7 mL; and rowing 3.9 mL. These are all about

Table 6 – Estimated water ingestion in mL, by activity, study, and capsize status.

Activity	Capsize	Surface water study				Swimming pool study			
		Median	Mean	UCL	Relative to surface water fishing and rowing mean	Median	Mean	UCL	Relative to surface water fishing and rowing mean
Boating	No	2.1	3.7	11.2	1.0				
Canoeing	No	2.2	3.8	11.4	1.1	2.1	3.6	11	1.0
Canoeing	Yes	3.6	6	19.9	1.7	3.9	6.6	22.4	1.8
Canoeing	All	2.3	3.9	11.8	1.1	2.6	4.4	14.1	1.2
Fishing	No	2.0	3.6	10.8	1.0	2.0	3.5	10.6	1.0
Immersion	NA					3.2	5.1	15.3	1.4
Kayaking	No	2.2	3.8	11.4	1.1	2.1	3.6	10.9	1.0
Kayaking	Yes	2.9	5	16.5	1.4	4.8	7.9	26.8	2.2
Kayaking	All	2.3	3.8	11.6	1.1	3.1	5.2	17	1.4
Rowing	No	2.3	3.9	11.8	1.1				
Rowing	Yes	2.0	3.5	10.6	1.0				
Rowing	All	2.3	3.9	11.8	1.1				
Swimming	NA					6.0	10	34.8	2.8
Wading/splashing	NA					2.2	3.7	11.2	1.0
Walking	NA					2	3.5	10.6	1

35–40% of the 10.0 mL estimated to occur during swimming in a pool. The mean volume of water ingested during canoeing or kayaking among those who capsized was about 60% higher than among those who did not capsize. Canoers and kayakers were about 5–10 times more likely to capsize in a swimming pool than on surface waters. These observations may have been due to a perception of safety in a pool with lifeguards and kayaking instructors in attendance. Among surface waters, study participants, capsizing was nine times more common on general use waters than on the CAWS. Again, this may have been due to the recognition of unique physical hazards and the presence of wastewater at the CAWS, which are communicated to the public at CAWS boat launches via posted signs. The fact that capsizing is less common on the CAWS suggests that efforts to communicate health and safety hazards to the public have resulted in risk reduction. Work by Fleisher and Kay (2006) suggests that risk perception influences the occurrence of self-reported gastrointestinal illness; our findings suggest that this may occur despite the ingestion of smaller volumes of water. The LC/MS/MS method resulted in calculated volumes of ingestion that were consistent with self-reported data, supporting the validity of the survey instrument for evaluating water ingestion.

4.1. *Significance of the results*

QMRA analyses are probabilistic, utilizing a distribution of values for each of the following key inputs: (1) the volume of water ingested during recreation, (2) the density of microbes in the water, (3) the relationship between the dose of microbes ingested and probability of illness. The volume of water ingested can be calculated as a function of the rate of ingestion (volume per unit time) and the duration of recreation. As a consequence of this research, estimates of water ingestion during a variety of water recreational activities are now available, which should reduce the uncertainty in quantitative estimates of health risk due to water recreation. The measurement of CYA in urine (but not in swimming pool water) was problematic using HPLC/DAD, and future efforts to quantify CYA in urine should rely on LC/MS/MS.

Several epidemiologic studies have identified associations between self-reported water exposure during full-contact water recreation and the development of illness. Exposure has previously been categorized based on the occurrence of head immersion (Seyfried et al., 1985; McBride et al., 1998; Wade et al., 2006) or body immersion (Wade et al., 2008). A study of windsurfers evaluated the influence of the number of times participants fell into the water (Dewailly et al., 1986). Other studies analyzed the occurrence of illness as function of self-reported water ingestion for controlled exposure (Wiedenmann et al., 2006) and for observational studies of limited-contact (Fewtrell et al., 1994; Lee et al., 1997) and full-contact (Colford et al., 2007) recreation. In general, health risks are higher in association with increased exposure, though not for all outcomes and not for all definitions of exposure.

Two broad categories of study designs - randomized trials of controlled exposure and observational studies - have been employed to evaluate the health risks of water recreation. It has not been possible to directly compare results of the two approaches because of differences in the definition of exposure used in each of the approaches. In the randomized trials exposure has been defined as three head immersions during a 10-min interval (Kay et al., 1994; Wiedenmann et al., 2006; Fleisher et al., 2010). In the observational studies (USEPA, 1983, 1984; Wade et al., 2006, 2008) exposure was not determined by the investigators, but rather, participants swam or played in the water for as long and in whatever ways they chose. We found that head immersion results in about half the mean volume of ingestion and about 1/5th the likelihood of swallowing at least a teaspoon of water compared to swimming. This information should be useful in synthesizing the findings generated by the two study designs. It should be noted, however, that we evaluated head immersion in a swimming pool while the other studies evaluated immersion in surface water. It is possible that those in swimming pool may have perceived a lesser risk of ingesting pool water and may not have avoided water ingestion as they may have in surface waters, particularly in marine waters.

Our findings of relative rates of water ingestion (as mL/hour or percent that swallow a teaspoon or more) are likely more meaningful than the absolute estimates of ingestion. The mean estimate of water ingestion during limited-contact recreation is about one third of that during swimming (in a pool). Given the mean volume ingestion during swimming relative to limited-contact recreation, rates of illness attributable to limited-contact activities should be about one third of that reported during swimming on the same water, assuming a linear relationship between ingested pathogen dose and illness risk. The fact that self-reported ingestion of a teaspoon or more of water is relatively uncommon (less than 5% of surface water limited-contact recreators) suggests that a small percentage of recreators constitute an at-risk group. We found that capsizing is a strong determinant of ingestion, and should be discouraged in water where water quality is relatively poor. While studies of water recreation have generally focused on infectious hazards, health risk assessments for chemical exposure during water recreation have also been reported (Hussain et al., 1998; Dor et al., 2003). The findings of the present study may also be useful in risk assessments of recreational exposure to mercury, polychlorinated biphenyls, and of recent interest, oil dispersants.

4.2. *Our findings in context*

Two prior studies have attempted to quantify the volume of water ingested during water recreation. Water ingestion among surfers on the Oregon coast was investigated by Stone et al. (2008). In that study participants were also asked to estimate the volume of water swallowed while surfing with response options of a few drops, 1–3 teaspoons, the amount in a shot glass (2 ounces), or the amount in a small juice glass (4 ounces). Based on the self-reported estimates of ingestion volume and ingestion frequency, the authors estimated a median daily ingestion of 34.4 mL, and an arithmetic mean of 170.6 mL. Water ingestion among swimmers was estimated by Dufour and colleagues Dufour et al. (2006) at USEPA using CYA as a tracer of swimming pool water. Over the course of a 45-min swim, the 12 adults in the study swallowed an estimated 16 mL of pool water while the 41 children swallowed an average of 37 mL. The authors followed up with a larger scale study with involving 549 swimmers, the results of which have been presented at a conference by Evans et al. (2006). In that study children were found to swallow more water than adults (47 mL vs. 24 mL), and males swallowed more than females (37 mL vs. 27 mL), differences that were highly significant statistically. Twenty-five percent of the swimmers swallowed 85 mL or more, and some swallowed up to 280 mL. The Dufour estimate of 16 mL/45 min (or 21 mL/h) is intermediate between our mean estimate of 10 mL and the upper confidence estimate of 35 mL.

4.3. *Limitations*

As originally designed, this research sought to generate a calculated volume of water ingestion for each participant, using HPLC measures of CYA in pool water and urine samples. We did not rely on the HPLC measures of CYA in urine because of their limited precision and the frequency of false positives and false negatives. We based our estimates of ingestion volume on the 27 (5%) of participants who provided self-reported estimates of ingestion, as well as urine samples measured by LC/MS. Because that subset of participants was relatively small, the point estimates of the translation factors (Table 5) are limited in their precision. Additionally, because of the small number of participants whose urine samples were analyzed with the gold standard method, we were unable to generate adult-specific and child-specific volumes of ingestion (based on CYA measures) for each level of self-reported ingestion. Another limitation is that the highest category of self-reported water ingestion was “a mouthful or more”. Some participants who reported this level of ingestion may have ingested “a mouthful” while others ingested more than that. The collection of more detailed data about the number of mouthfuls ingested may have generated better agreement between self-reported and CYA-based estimates of ingestion. Because <1% of surface water participants reported ingesting “a mouthful or more” any improvement in categorizing ingestion among that small subset would have minimal impact on the overall findings. Again, because of the relatively small number of participants for whom high quality urine CYA data was available, we were unable to compare the volume of water ingested by adults and by children. Future research could focus on this question. Although it is not known how representative study participants were of surface water recreators in general, there is no reason to believe that participants systematically over- or under-estimated the volume of water that they ingested.

5. Conclusions

The mean volume of water ingested during limited-contact recreation activities, about 3.5–4 mL is about 35–40% of that observed during swimming (about 10 mL). The frequency of swallowing at least teaspoon of water during limited-contact recreation (about 1% of study participants) is about 1/50th the frequency observed during swimming in a pool (51% of participants). In surface waters with high concentrations of chemical or microbial hazards, avoiding capsizing should significantly reduce the percentage of paddlers who swallow a teaspoon or more of water. LC/MS/MS is preferred over HPLC for analyzing CYA in urine samples.

Appendix. Supplementary material

Supplementary data related to this article can be found online at doi:10.1016/j.watres.2010.12.006.

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