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Cryptosporidium risk from swimming pool exposures

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ABSTRACT

Background: Infection risk estimates from swimming in treated recreational water venues are lacking and needed to prioritize public health interventions in swimming pools. Quantitative infection risk estimates among different age groups are needed to identify vulnerable populations. High risk populations can be targeted during public health interventions, like education campaigns and pool operation improvements.
Objectives: This study estimated per-swim and annual *Cryptosporidium* infection risks in adults (>18) and children (≤18) using new experimental data collected in the U.S. on swimmer behavior.
Methods: Risks were estimated using oocyst concentration data from the literature, and data collected in this study on pool water ingestion, swim duration and pool use frequency. A sensitivity analysis identified the most influential model variables on infection probability.
Results: The average estimated risk of *Cryptosporidium* infection was 2.6×10^{-4} infections/swim event. The per-swim risk estimate in the present study differed from others because behavior data (ingestion rates, swim duration, and visit frequency) were collected in different countries and varied from U.S. estimates. We found swimmer behaviors influence infection risk. This is the first study to report annual risk of *Cryptosporidium* infection among swimmers by age group. Using U.S. exposure data, annual risk was estimated at 2.9×10^{-2} infections/year for children and 2.2×10^{-2} infections/year for adults. Annual risk for all swimmers was estimated at 2.5×10^{-2} infections/year from swimming in treated recreational water venues. Due to increased ingestion and swim duration, child swimmers had the highest annual risk estimate. *Cryptosporidium* concentration is the most influential variable on infection probability.
Conclusions: Results suggest the need for standardized pool water quality monitoring for *Cryptosporidium*, education, development of interventions to reduce ingestion, consideration of behaviors unique to swimming populations in future risk assessments and improvement of oocyst removal from pool water. Child swimmers were the most vulnerable sub-population, and should be targeted in healthy swimming education campaigns.

1. Introduction

Documented swimming pool-related outbreaks in the United States have increased since reporting began in 1978 (Hlavsa et al., 2014; Yoder et al., 2008). Pool-related outbreaks occur when common symptoms are reported by two people in separate parties who also report visiting the same pool facility within a given timeframe relative to symptom manifestation. In the most recent surveillance publication of waterborne disease outbreaks associated with recreational water (2011–2012), the Centers for Disease Control and Prevention (CDC) reported 69 pool-related outbreaks that accounted for 1,309 illnesses (Hlavsa et al., 2015). Forty-two outbreaks began in the peak swim season (June-August) and 34 of the 42 outbreaks were associated with Acute Gastrointestinal Illness (AGI) (Hlavsa et al., 2015). AGI causes diarrhea, abdominal cramps, vomiting, and/or nausea, and can be life-threatening in sensitive populations which represent 20–25% of the U.S. population and includes children <5 (Chen et al., 2002; Dupont et al., 1995; Hunter et al., 2011; Okhuysen et al., 1998; Reynolds et al., 2008). The majority of AGI outbreaks in swimming pools during peak swim season (32 of 34) between 2011 and 2012 were associated with *Cryptosporidium* spp., primarily *Cryptosporidium parvum*. Cryptosporidiosis incidence in the U.S. is more than double in children compared to adults (5.6/100,000 among children 1–4 years of age, and 2.5/100,000 among adults during 2009), and infections predominantly occur following exposures to pool water

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contaminated with *Cryptosporidium* shed by infected swimmers (CDC, 2011; Yoder and Beach, 2010). Greater infection rates in young children may be because their immune systems are underdeveloped and they ingest more pool water than adults (Dufour et al., 2006; Suppes et al., 2014; Teunis et al., 2002). Further, the incidence of illness may be greater because children (≤18) are more likely to participate in swimming activities that lead to pool water ingestion, like playing, splashing, or diving (Suppes et al., 2014). *Cryptosporidium* is the primary cause of AGI outbreaks in pools because oocysts are resistant to chlorine disinfection, transmitted through the fecal-oral route, excreted by ill swimmers in high amounts (up to 10^9 oocysts/fecal release), and have a low infectious dose (ingesting 10 oocysts can elicit response in humans) (Dufour et al., 2006; Teunis et al., 2002; Yoder and Beach, 2010). The higher incidence of cryptosporidiosis in treated water venues compared to other gastrointestinal illnesses makes *Cryptosporidium* the ideal reference pathogen for assessing AGI risk from swimming in pool water.

Quantitative infection risk estimates among different age groups are needed to identify vulnerable populations to target during public health interventions, like education campaigns and pool operation improvements. Currently, no estimates have been reported for annual risk of *Cryptosporidium* infection among swimmers of any age group. Per-swim risk estimates are available, but have been estimated using behavior data from countries other than the U.S. (Canada and the Netherlands) where swimming activities like duration and frequency of pool visits differ due to culture, climate, access and other variables. This study estimates both annual and per-swim risk of *Cryptosporidium* infection using behavior data collected in the U.S. Annual risk estimates reflect the influence of pool visit frequency, and are useful when comparing risk across groups. We estimated per-swim and annual risk of *Cryptosporidium* infection among all swimmers, adults (>18) and children (≤18).

Risk estimates are also useful for improving pool management and operation. The CDC published a Model Aquatic Health Code (MAHC) in 2014 consisting of pool management and operational guidelines state and local health departments can adopt (CDC, 2016). Risk-based recommendations for water quality improvement are needed to evaluate and support standard pool management and operational guidelines. State and local health departments in the U.S. lack swimming pool safety regulations standardizing water quality monitoring, water treatment, and pool operations since there is no mandatory federal pool code. Until the MAHC is adopted by all U.S. states and jurisdictions, standardized pool operation will be lacking in the U.S.

2. Materials and methods

2.1. Data collection

One hundred and twenty-six swimmers were recruited at four pool sites in Tucson, Arizona during the peak swimming months (June–September 2013) and issued a swimming activity questionnaire. Free and informed consent of participants was obtained using a form approved by the University of Arizona Human Subjects Research and Institutional Review Board. Swimmers were approached upon arrival at the pool, provided with study objectives, and asked if they would participate by completing a questionnaire via tablet or home computer. The questionnaire was created in DatStat Illume Survey Developer Gateway Version 5.1.1.17347 (Seattle, WA) to collect information on average annual frequency of pool visits, duration of visit, and swimmer age during the observed swim. Age groups were children (≤18) and adults (>18). Average duration of pool visits reported on the questionnaire was used as a surrogate for swim duration per pool visit. Risk differences between child and adult swimmers were explored because statistically significant differences at the 5% significance level between ingestion (Suppes et al., 2014) and swim duration have been found within these groups. Pool water ingestion volumes were estimated in 38 of the 126 swimmers. Methods for quantifying pool water ingestion rates have been published separately (Suppes et al., 2014). Data on *Cryptosporidium* concentrations from 152 backwash samples collected in the Netherlands at 7 pool sites were used as *Cryptosporidium* concentrations in pool water (Schets et al., 2004). Eighteen of 152 (11.8%) pool water backwash samples were positive for *Cryptosporidium*, ranging from <0.2 to 20.8 oocysts/L (Schets et al., 2004) and 25 of 38 (65.8%) swimmers ingested some pool water ranging from 0.9 to 105.6 mL/h (Suppes et al., 2014).

2.2. Data analysis

Unpaired *t*-tests identified swim frequency and duration differences between groups using STATA Statistics/Data Analysis Version 11.0 Software (College Station, TX). Associations were considered statistically significant at a p-value <0.05 (95% confidence).

Quantitative uncertainty analysis using Monte Carlo simulation was applied to obtain a distribution of oocysts ingestion per-swim with R Version 3 (R Studio add-on Version 0.97.248, Free Software Foundation, Inc., Boston, Massachusetts). Each variable was fit to a distribution for use in the oocyst ingestion exposure model (Table 1), where C = concentration of *Cryptosporidium* oocysts/mL of pool water, I_r = pool water ingestion rate (mL/h), T = swim duration/pool visit (h), and D = oocyst dose/swim event (1). Lognormal distributions were applied to all model variables based on goodness of fit tests (Kolmogorov-Smirnov test statistic p-value > 0.05) and information from previous risk assessments of *Cryptosporidium* infection (Pintar et al., 2010; Schets et al., 2011). Sample sizes for each variable are included in Table 1.

$$D = C \times I_r \times T \quad (1)$$

Monte Carlo samples (10,000 iterations) from each variable were multiplied to create a distribution of oocysts ingested per-swim (D) by all swimmers, child swimmers (D_c) and adult

Table 1
Model variable, symbol, and sample size, distribution parameters, and goodness of fit test *p*-values (Kolmogorov-Smirnov test statistic).

Variable	Units	Symbol	Sample Size	Lognormal Distribution Parameters:Meanlog, SDlog	P-Value
Cryptosporidium oocyst concentration in pool water[a]	oocysts/mL	C	152	−5.862, 1.123	0.224[b]
Pool water ingestion	mL/h	I_r	38	1.751, 2.036	0.4914[b]
Pool water ingestion, children	mL/h	$I_{r,c}$	17	1.642, 1.575	0.6404[b]
Pool water ingestion, adults	mL/h	$I_{r,a}$	21	1.802, 2.218	0.3582[b]
Pool visit frequency	visits/year	F	96	3.702, 1.335	0.00165
Time per visit	h	T	97	0.3008, 0.5654	0.00024
Time per visit, adults	h	T_a	51	0.0891, 0.5084	0.0043
Time per visit, children	h	T_c	46	0.5416, 0.5291	0.1269[b]

[a] Data re-fit from Schets et al. (2004). All other model variables were collected by Suppes et al. (2014).
[b] Failure to reject the null hypothesis that data are consistent with the specified distribution.