Do Traditional Measures of Water Quality in Swimming Pools and Spas Correspond with Beneficial Oxidation Reduction Potential?

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SYNOPSIS

Objectives. Oxidation reduction potential (ORP) is a more direct measure of water quality in swimming pools and spas than free chlorine. However, ORP is not considered in some state pool codes, including Minnesota's. This study examined whether compliance with the Minnesota Pool Code assured an ORP $\geq$650 millivolts (mV), a value defined in the literature as adequate to kill viral and bacterial pathogens within seconds. We also examined predictors of ORP.

Methods. Water samples from public swimming pools and spas in Hennepin County, Minnesota, were collected during routine health inspections from May through August 2004 and assessed for compliance with the state pool code. ORP values were also recorded. A Chi-square test was used to evaluate the association between code compliance and ORP. Analysis of covariance (ANCOVA) and logistic regression models were used to determine predictors of ORP.

Results. The study included 132 pools and 30 spas. Compliance with the Minnesota Pool Code did not assure an ORP$\geq$650 mV ($p<0.01$). Outdoor pools had significantly lower ORP values than indoor pools ($p<0.001$). ANCOVA and logistic regression models showed that ORP decreased with increasing cyanuric acid, increasing pH, and decreasing free chlorine.

Conclusions. Compliance with the Minnesota Pool Code did not coincide with adequate ORP values, particularly for outdoor pools and spas. Therefore, it may be appropriate for states to include a minimum ORP standard of $\geq$650 mV in their swimming pool regulations. Doing so would likely benefit the health of swimmers.

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During 2003–2004, the Centers for Disease Control and Prevention (CDC) reported 62 waterborne disease outbreaks associated with recreational water.[1] Forty-three (69.4%) of those outbreaks occurred at treated water venues such as swimming pools and spas (pools and spas will hereafter be referred to as "pools" unless distinguished), of which 18 (42.0%) were associated with chlorine-sensitive pathogens such as methicillin-resistant S*taphylococcus aureus*, *Pseudomonas aeruginosa*, *Legionella pneumophila* serogroup 1, *Shigella sonnei*, *Norovirus,* and Echovirus 9. Outbreaks at treated water venues accounted for 2,446 cases of illness, but this is likely an underestimate of the true incidence of recreational waterborne illness due to underreporting and exclusion of endemic illness.

In Minnesota, five recreational waterborne disease outbreaks of gastroenteritis associated with swimming pools were reported from 2002 through 2005.[2–5] In the absence of national regulations, states assume responsibility for establishing and enforcing regulations for the safe operation and disinfection of public swimming pools and spas. The aforementioned reports suggest that states consider improving interventions to reduce the risk of waterborne illness in treated water venues.

The current Minnesota Pool Code (MPC) emphasizes free available chlorine and pH as critical indicators of pool water quality.[6] However, experimental and theoretical evaluations of the disinfection process indicate that oxidation reduction potential (ORP) is superior to water chemistry parameters as an indicator of water quality.[7–11] ORP measures effectiveness or quality of disinfectant in the water, whereas free chlorine measures quantity.[7] This distinction is important because chlorine exists in various forms in pool water that are not equally effective as disinfectants. Furthermore, tests commonly used to detect chlorine are not always able to distinguish among the various forms. ORP avoids this limitation by measuring in millivolts (mV) the capacity of the disinfectant to oxidize (sanitize) unwanted material regardless of the source of disinfectant.

Research on poliovirus indicated that the relationship between chlorine residual and ORP is variable, and ORP is more reliable in determining the rate of inactivation of poliovirus than chlorine residual.[12] Additional research supported the finding that ORP is superior to chlorine residual as a measure of viral and bacterial inactivation, particularly in swimming pools.[8–10,13,14] Swimming pools were monitored continuously over a short period of time (hours to days) to observe the association among bacterial count, free chlorine, and ORP. In all instances, ORP was a more reliable indicator of bacterial contamination than free chlorine residual.[8–10]

Furthermore, it was found that an ORP≥650 mV (measured with a platinum/calomel electrode) was sufficient to kill *Escherichia coli* and inactivate poliovirus within 30 seconds.[10,11] Water quality in pools is dynamic and changes with organic load as people enter and leave the pool. Continuous monitoring of ORP in a swimming pool maintains water quality throughout the day, despite variations in bather load.[8]

ORP has been suggested as an effective measure of disinfection in food safety, drinking water, and wastewater treatment.[7,15,16] Germany has enforced an ORP standard for swimming pools since 1982. The World Health Organization mentions ORP as a valuable measure of water quality in its guidelines for safe recreational waters,[17] and at least eight states (Arizona, Colorado, Iowa, Idaho, Ohio, Maine, Montana, and Wyoming) address ORP in their state pool codes as a supplement to traditional measures of water quality (e.g., free chlorine and pH) that, if measured, should be a minimum of 650 mV.[18–25] In Iowa, a swimming pool or spa with an ORP<650 mV may be closed immediately, regardless of other water quality parameters.[20]

Despite evidence suggesting that ORP is superior to free chlorine as a measure of water quality, the MPC does not include an ORP standard.[6] Furthermore, data are not available in the literature to indicate whether compliance with the state pool code assures an ORP regarded as adequate to protect health (≥650 mV). The primary purpose of this study was to establish whether compliance with the MPC assured adequate ORP. In particular, we sought to answer two questions: (*1*) Do pools that comply with the state pool code have an ORP≥650 mV? and (*2*) What factors predict ORP? Knowing what factors influence ORP can help guide solutions to its management.

METHODS

We considered 170 public indoor and outdoor pools in Hennepin County, Minnesota, for which ORP data were collected during routine inspections, for inclusion in this study. Pools were located in multiple cities and owned by hotels, apartment complexes, schools, athletic clubs, country clubs, and cities.

In instances in which a pool was inspected multiple times due to a serious code violation that required follow-up (n=1) or because it was inspected early in the summer and the inspector had time to visit the pool a subsequent time (n=27), only data from the first inspection were used.

Data collection

Pool water samples were collected and analyzed by environmental interns and sanitarians with Hennepin County Environmental Health during routine swimming pool inspections from May through August 2004. The majority (80%) of inspections were conducted by a single environmental intern to reduce operator variability. Inspections were unannounced and took place between 8 a.m. and 4 p.m. Monday through Friday. Water samples were collected from the deepest end of the pool and away from areas where water circulation was poorest, such as near corners or steps. Samples were collected from about 1 foot below the water surface and as far away from the pool wall as the observer was able to reach. Water samples were analyzed on-site immediately after collection.

Water quality was assessed based on the following six criteria: chlorine residual (free and combined), pH, alkalinity, ORP, cyanuric acid, and water temperature. Free and total chlorine, pH, alkalinity, and cyanuric acid were determined using the LaMotte PRO DPD test kit model PRO250-NJ (Chestertown, Maryland). ORP was measured in mV with a handheld Waterproof ORPTestr® (OAKTON Instruments, Vernon Hills, Illinois), which included a platinum electrode and double-junction design against a Kynar® reference junction. ORP was measured by immersing the electrodes about 1 inch into the pool water and swirling slowly until the potential stabilized (3 to 5 minutes). Water temperature was measured with a digital thermometer and reported in degrees Fahrenheit.

Compliance with the MPC was defined in terms of water quality. A pool was considered code compliant if it met all of the criteria listed in Table 1.

Table 1. Minnesota pool rules for pool water condition[a]

Pool water condition	*Rule*
Free chlorine residual	0.5–5.0 ppm 2.0 ppm minimum (spas) 1.0 ppm minimum (wading pools) 1.0 ppm minimum (pools with cyanuric acid >30 ppm) 1.0 ppm minimum (pools with temperature >84°F) 1.0 ppm minimum (pools with pH>7.7)
pH	7.2–8.0
Alkalinity	>50 ppm
Combined chlorine	<0.5 ppm
Cyanuric acid	<100 ppm
Water clarity	Main drain is visible

[a]Minnesota Office of the Revisor of Statutes. Minnesota Administrative Rules Chapter 4717.0100-4717.3975 [cited 2007 Aug 27]. Available from: URL: http://www.revisor.leg.state.mn.us/arule/4717/

ppm = parts per million

Analyses

Statistical analyses were performed using SPSS.[26] Analysis of covariance (ANCOVA) was used to determine water quality variables that best predicted ORP. Continuous predictor variables entered into the ANCOVA model were (*1*) free available chlorine in parts per million (ppm), (*2*) pH, (*3*) alkalinity in ppm, and (*4*) water temperature in degrees Fahrenheit. Categorical variables entered into the model were (*1*) cyanuric acid (<20 ppm or ≥20 ppm), (*2*) combined chlorine (≤0.5 ppm or >0.5 ppm), (*3*) whether the swimming structure was a pool or spa, (*4*) whether the pool was indoor or outdoor, (*5*) whether the pool was disinfected with stabilized (chlorine and cyanuric acid) or unstabilized (no cyanuric acid) chlorine product, and (*6*) whether or not the pool had an automatic controller. Values for cyanuric acid and combined chlorine were modeled as categorical due to limitations of test kit sensitivity. Estimates are reported in Table 2 as the point estimate (ß) ± standard error (SE). Colinearity of variables was assessed using matrices of Pearson and Spearman rank correlations.

The predictor variables entered into the ANCOVA models were also entered into a logistic regression model to identify variables that best predicted an ORP ≥650 mV. All predictor variables were included in the initial ANCOVA and logistic models, and then sequentially removed from the model based on significance until all predictors were significant at $p \leq 0.05$. The Pearson Chi-square test was used to test the association of MPC compliance (yes/no) with adequate ORP (≥650 mV vs. <650 mV). The proportion of pools complying with the state pool code but with inadequate ORP, and the proportion of pools with adequate ORP but not complying with the state pool code, were noted.

RESULTS

The analysis included 132 pools and 30 spas. Outdoor pools comprised the majority of the sample (n=93; 57%). Of the 170 pools considered for study, one pool and six spas were excluded because they were disinfected with bromine rather than chlorine to avoid potential variability in the analysis due to disinfectant chemical. One pool was excluded because of uncertainty whether the pool was disinfected with a stabilized or unstabilized chlorine product.

Table 2. Significant predictors of ORP based on an ANCOVA model

Predictor	*All pools/spas* (n=155)[a] *Adjusted* R^2 = *0.673* *F* (p-value)	*β ± SE*	*Indoor pools/spas* (n=60)[a] *Adjusted* R^2 = *0.636* *F* (p-value)	*β ± SE*	*Outdoor pools/spas* (n=95)[a] *Adjusted* R^2 = *0.306* *F* (p-value)	*β ± SE*
Cyanuric acid[b]	18.4 (<0.001)	−67.6 ± 15.8	8.4 (0.005)	−99.8 ± 34.5	27.4 (<0.001)	−75.7 ± 14.5
Indoor/outdoor[c]	78.3 (<0.001)	−105.8 ± 12.0	Ref.	Ref.	Ref.	Ref.
Unstabilized/stabilized[d]	5.3 (0.023)	−35.8 ± 15.6	4.6 (0.036)	−62.4 ± 29.0	Not significant	Ref.
Free chlorine	54.7 (<0.001)	15.5 ± 2.1	29.9 (<0.001)	16.6 ± 3.0	26.3 (<0.001)	14.4 ± 2.8
pH[e]	33.6 (<0.001)	−10.0 ± 1.7	41.3 (<0.001)	−14.5 ± 2.3	5.5 (0.021)	−5.9 ± 2.5

[a]Three indoor pools are missing values for alkalinity. Four outdoor pools are missing values for alkalinity, cyanuric acid, or water temperature.

[b]Reference is cyanuric acid <20 ppm.

[c]Reference is indoor pools.

[d]Reference is unstabilized.

[e]Estimates are per 0.1 unit increase in pH.

ORP = oxidation reduction potential

ANCOVA = analysis of covariance

SE = standard error

Ref. = reference group

Code compliance in relation to ORP

Compliance with the MPC did not consistently correspond with an ORP ≥650 mV. Thirty-six (40%) of the 90 code-compliant pools had inadequate ORP (<650 mV), while 52 (80%) of the 65 noncompliant pools had adequate ORP (≥650 mV, χ^2=6.98, p<0.01). Of the 62 outdoor pools that were code-compliant, the majority of them (n=35, 56%) had poor ORP, in contrast with indoor pools, of which only one of the 28 (4%) code-compliant pools had poor ORP.

Predictors of ORP

Among all pools in the study, significant predictors of ORP included cyanuric acid, indoor/outdoor location, type of chlorine (stabilized or unstabilized), free chlorine, and pH (Table 2). Water temperature and alkalinity were not significantly associated with ORP after adjusting for other variables. The strongest predictor of ORP was indoor/outdoor location. ORP values of outdoor pools were on average 106 mV less than indoor pools after adjusting for cyanuric acid, free chlorine, pH, and type of chlorine used as disinfectant (p<0.001). Strength of predictor variables differed by indoor/outdoor location.

The effect of cyanuric acid on ORP was consistent whether it was modeled continuously in ppm or categorically by type of chlorine (stabilized or unstabilized). Indoor pools disinfected with stabilized chlorine had a lower mean ORP than indoor pools disinfected with unstabilized chlorine. Similarly, the mean ORP of indoor pools with detectable cyanuric acid (≥20 ppm) was approximately 100 mV less than that of indoor pools with <20 ppm cyanuric acid.

In contrast with indoor pools, the strongest predictor of ORP among outdoor pools was cyanuric acid. Adjusted ORP values in outdoor pools with detectable cyanuric acid were on average 76 mV less than that of outdoor pools with undetectable cyanuric acid. Free chlorine was also a strong predictor of ORP among outdoor pools.

The independent variables in the final ANCOVA models explained more ORP variance in indoor than outdoor pools (adjusted R^2 of 0.636 vs. 0.306), but the models demonstrate that ORP decreases with increasing cyanuric acid, increasing pH, and decreasing chlorine regardless of a pool's indoor/outdoor location in either setting.

In the logistic regression analysis, free chlorine, pH, cyanuric acid, and indoor/outdoor location were significant predictors of whether a pool achieved an ORP ≥650 mV (Table 3). Logistic modeling was attempted on indoor and outdoor pools separately, but the models did not converge.

DISCUSSION

Results of this study suggest that compliance with the MPC does not assure that pools achieve an ORP ≥650 mV, a level of disinfection described in the literature as adequate to kill viral and bacterial pathogens within seconds.[10,11] We found that 40% of code-compliant pools had ORP values <650 mV and may pose a risk to public health despite being deemed adequate by code standards. Interestingly, 97% of the pools that fell into this category were located outdoors. Outdoor pools consistently had lower ORP values than

indoor pools; however, regardless of indoor/outdoor location, ORP decreased with increasing cyanuric acid, decreasing free chlorine, and increasing pH. These results correspond with prior research demonstrating that these same variables affect chlorine's kill time of viral and bacterial pathogens in the same fashion (i.e., increasing cyanuric acid, decreasing free chlorine, and increasing pH result in longer kill times).[27–29] More difficult to explain is why after adjusting for these variables, the mean ORP of outdoor pools was 106 mV lower than it was for their indoor counterparts, and why outdoor pools accounted for nearly all of the pools that complied with the state pool code but failed to achieve adequate ORP.

The difference in bather load between indoor and outdoor pools at the time of inspection is one variable that may have been responsible for the lower ORP in outdoor pools vs. indoor pools. Because information on bather load was not recorded at the time of inspection, estimation of its effects on the ORP of pools was not possible. If outdoor pools had higher bather loads than indoor pools during the period of study (summer), this may have contributed to lower ORP levels outdoors. Previous research has demonstrated clearly how the ORP of a swimming pool decreased at times of high bather load when chlorine was not adequately increased to compensate for the chlorine being lost to oxidation of the contaminants.[8]

Another potential explanation for why the mean ORP of outdoor pools was much lower than that of indoor pools is that cyanuric acid, which inversely affects ORP, was ubiquitous in outdoor pools, but methods we used to detect cyanuric acid were too insensitive to model this effect accurately. This explanation is supported by prior research that suggests that chlorine combined with cyanuric acid produces a lower ORP than chlorine without cyanuric acid.[14] If cyanuric acid affects ORP in a dose-response manner, this association may have been missed by broadly categorizing cyanuric acid as <20 ppm and ≥20 ppm in the ANCOVA models. Therefore, indoor and outdoor pools with <20 ppm cyanuric acid were treated similarly, although this categorization scheme may not have characterized cyanuric acid concentration accurately because the majority of indoor pools with cyanuric acid measuring <20 ppm probably had no cyanuric acid present. In contrast, the majority of outdoor pools in the same category likely had at least some, though undetectable, amounts of cyanuric acid. This misclassification would have led to underestimation of cyanuric acid's effect on ORP and perhaps help explain why outdoor pools had a lower ORP than indoor pools even after adjustment for cyanuric acid. Finally, results may have been confounded by an unknown factor or factors distributed disproportionately between indoor and outdoor pools.

If the pools in the present study are representative of pools around the state, these study results indicate that it may be worth reevaluating the way pools are inspected for safety in Minnesota and perhaps in other states without ORP standards. Adding an ORP standard to the state pool code would improve the state's ability to ensure safe water in public pools and spas by assuring effectiveness of disinfection.

Because the amount of chlorine needed to maintain a constant ORP will fluctuate with the demands of the pool, it may be necessary for the free chlorine concentration to rise above the current standard of 5.0 ppm to achieve a set ORP. Therefore, enforcing a minimum ORP standard may not be possible without

Table 3. Significant predictors of ORP ≥650 mV based on a logistic regression model (*n*=161)[a,b]

Predictor	*ß ± SE*	*Wald (p-value)*	*Odds ratio (95% CI)*
Cyanuric acid[c]	−2.9 ± 0.6	20.9 (<0.001)	0.06 (0.02, 0.20)
Indoor/outdoor[d]	−3.1 ± 0.8	14.9 (<0.001)	0.04 (0.01, 0.22)
Free chlorine	0.8 ± 0.2	22.6 (<0.001)	2.30 (1.64, 3.25)
pH	−2.7 ± 1.0[e]	8.0 (0.005)	0.07 (0.01, 0.44)

[a]One outdoor pool is missing a value for cyanuric acid.

[b]Nagelkerke R^2 = 0.635

[c]Reference is cyanuric acid <20 ppm.

[d]Reference is indoor pools.

[e]Value per 1 unit increase in pH

ORP = oxidation reduction potential

mV = millivolt

SE = standard error

CI = confidence interval

simultaneously raising the maximum level of free chlorine allowed in a pool, particularly in pools that use cyanuric acid.

Whether a swimming structure was a pool or spa or located indoors or outdoors was not an a priori determinant of study design. Therefore, some structures were not well represented, precluding more in-depth analysis of their relationship to ORP. No microbiological tests were performed on the pool water to support previous research suggesting that an ORP ≥650 mV is sufficient to assure microbiological purity of the water.

Several states are already advocating ORP as a supplemental measure of water quality in their state pool codes but, curiously, little has been published on the role of ORP in pool sanitation since the 1970s. In fact, Medline and PubMed searches on "oxidation reduction potential," "ORP," and "redox potential" produced no peer-reviewed data on the role of ORP in pool water sanitation in the United States. The existing, though limited use of ORP as a measure of pool sanitation in the U.S. combined with a scarcity of data suggest that there are many opportunities for future research on this topic. Future research might focus on evaluating whether states that currently enforce an ORP standard see fewer recreational waterborne illnesses than those that do not, whether an ORP ≥650 mV is sufficient as a minimum standard, and how bather load affects ORP.

CONCLUSIONS

This study demonstrated that compliance with the MPC, which does not currently include an ORP standard, did not coincide with ORP levels generally regarded as safe, particularly among outdoor pools. Therefore, it may be appropriate to include a minimum ORP standard of at least 650 mV in pool code regulations. Maintaining a safe ORP will accommodate the changing disinfection demands in swimming pools, thereby improving water quality and benefiting the health of swimmers.

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