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Proposed Method for Setting Standards for Recreational Divers Diving in Benzene Polluted Waters

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Abstract There are no recognized standards for recreational diving in benzene polluted waters. If daily absorption is limited to that absorbed from drinking 2-L of water at the recommended maximal contaminant limit concentration (9.7 μg per day), then permissible diving hours can be determined. A formula is proposed that calculates allowable monthly diving time based on dermal absorption, amount of water ingested, benzene concentrations in the water and in the sediment and the proportion of the body exposed.

Keywords Benzene · Recreational divers · Pollution · Standards

Recommendations for diving in chemically contaminated waters are vague (Amson 1991), and for benzene it is stated that exposure should be "absolutely minimal". This creates a problem for recreational divers since benzene is ubiquitous in recreational surface waters primarily due to motorized recreational boating (Heald 2005), where up to 30% of unburned fuel is discharged into lakes. Furthermore industrial efferents also add to benzene concentrations in surface waters and aquatic sediments and can result in extremely high values.

There are however, no recognized standards for recreational diving in benzene polluted waters. Such values might be established by assuming that dermal and gastrointestinal absorption results in an equivalent risk to that from pulmonary absorption. The U.S. Environmental Protection Agency (EPA) has used that assumption to calculate drinking water standards for benzene (U.S. EPA 2005a).

In the following study we propose a method to calculate the hours of diving time permissible in polluted waters for recreational divers. We will determine the concentrations of benzene in water and in sediment that will result in absorption during 1 h of diving that is equal to that absorbed at the proposed maximal contaminant level (MCL) for drinking water. Then we will propose a formula to calculate a threshold value for allowable diving time, based on benzene concentrations in the water and in the sediment, the amount of water ingested, and the proportion of the body surface area exposed. Finally we will calculate the risk to a diver exposed to benzene concentrations in surface water and in sediment thought to pose a serious health risk (Lijzen et al. 2001).

Materials and Methods

We used the proposed MCL for benzene (0.005 mg/L) and assumed a 2-L intake of drinking water per day to calculate acceptable levels of benzene absorption.

Absorption was calculated by the following equations as suggested by the U.S. Environmental Protection Agency (U.S. EPA 2004).

1. Gastrointestinal absorption = Concentration (μg/mL) * proportion absorbed * oral intake (10 mL) (* equals "multiplied by").
2. Water dermal absorption = Concentration (μg/mL (cm^3)) * permeability constant (cm/h) * surface area of the skin (default value, 19,400 cm^2) * exposure hours.

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3. Sediment dermal absorption = Concentration (μg/g soil) * relevant skin surface area (default value, 9,800 cm^2 (50% of body exposed)) * absorption (proportion/24 h) * adherence factor (0.021 g/cm^2) * exposure (hours).

Absorption constants are taken from accepted sources (U.S. EPA 2005c) that are consistently updated.

We determined the concentrations of benzene that could be present in sediment and in water that would lead to absorption during a 1 h dive that was equivalent to drinking 2-L of water per day at the proposed MCL. Based on these values a formula is presented that takes into consideration, actual benzene concentrations in the water and sediment, the amount of water ingested, and the proportion of the body surface area exposed.

Finally we calculate the allowable diving time at concentrations though to pose a serious health risk for humans (serious risk concentrations (SRC), Lijzen et al. 2001). For this example we used an average of 10 mL gastrointestinal intake per dive (Schijven and de Roda Husman 2006), 15% of the body smeared with sediment (Albering et al. 1999), and 12 h of diving per month, the maximal exposure for recreational divers assuming an average of 4 dives per month (St Leger Dowse et al. 2002).

Results and Discussion

The amount of benzene absorbed while drinking 2 L of water with a concentration of benzene at 0.005 mg/L with a 97% gastrointestinal absorption is (5 μg * 0.97 * 2) or 9.7 μg (Table 1).

There are three ways benzene can be absorbed during diving; water dermal absorption, sediment dermal absorption and gastrointestinal water absorption. We calculated separately the concentration of benzene in the water and sediment that would lead to the absorption of 9.7 μg over an 1 h exposure dive. Thus the proposed water standard for a 1 h dive ($\mu g/cm^3$) equals 9.7 μg divided by Kp (cm/h) * 19,600 cm^2 * 1 h (9.7/0.0207 * 19,600) or 0.0024 $\mu g/cm^3$ (24.3 μg/L). In other words a diver's whole body exposed to benzene in the water at a concentration of 24.3 μg/L for 1 h would absorb 9.7 μg of benzene through his skin.

Table 1 Calculated standards for benzene concentrations in water and sediment for professional divers for the various routes of absorption (dermal, gastrointestinal)

Values	Units[a]	Benzene
Water standard	mg/L	0.005
Work standard – TLV-TWA	mg/m^3	1.6
Work standard-action level	mg/m^3	0.8
Short-term exposure limit	mg/m^3	5
Lung retained & absorbed	%	50
Gastrointestinal absorption	%	97
Kp	cm per h	0.0207
ABS-soil	% per 24 h	0.01
Proposed standards for a 1 h dive		
Water standard – gastrointestinal[b]	mg/L	1
Water standard – dermal[b]	mg/L	0.024
Sediment standard – dermal[b]	mg/kg	113

[a] mg, milligram; L, liter; m^3, meters cubed; cm, centimeter; kg, kilogram

[b] Based on oral absorption of benzene at the water standard of 9.7 μg (0.005 mg/L * 2 L * 0.97 absorption) per day

$$\text{hours per day} = \frac{1}{\text{Wc} * \text{BW}/\text{Ws} * 100 + \text{Wc} * \text{D}/\text{Ds} * 10 + \text{SEDc} * \text{BS}/\text{SEDs} * 50}.$$

For sediment absorption (9.7 μg = Concentration (μg/g soil) * relevant skin surface area (9800 cm^2) * absorption (0.01/24 h) * adherence factor (0.021 g/cm^2) * exposure 1 h), the proposed standard would be 9.7 * 24 divided by 9800 * 0.021 * 0.01, or 113 mg/kg.

For gastrointestinal absorption the standard for 10 mL oral intake per dive would be (9.7 μg = Concentration (μg/mL) * 0.97 * 10), concentration = 9.7 μg/0.97 * 10 = 1 μg/mL or 1 mg/L.

To calculate the number of hours that one can dive in a given polluted area, the following equation takes into account the three ways of absorption, the proportion of the body exposed to the water (BW), the amount of water intake (D, mL), and the proportion of the body exposed to sediment (BS). Ws, water standard skin; Ds, water standard – gastrointestinal (oral intake); SEDs, sediment standard – skin; Wc, water concentration; SEDc, sediment concentration; BS, average percent of body smeared with sediment over the dive; BW, average percent of body exposed to polluted water over the dive; D, oral intake (mL) per 1 h diving

An example can be seen in Table 2. A recreational diver is exposed to benzene contaminated sediment at the SRC of

Table 2 Hours of diving permitted in an area with serious risk concentrations (SRC) for humans in sediment and water

Calculation	Dermal-water	Dermal-sediment	Oral intake
Standard (ppm)	0.024	113	1
Measured concentration	0.251	5	0.251
Measured/standard	10.5	0.044	0.251
Correction factor	None	15%/50% = 0.3	None
Final for equation	10.5	0.013	0.251
Total = 10.763[a]			

[a] Hours per day = 1/10.764 = 0.0929 h per day, or 2.8 h per month

5 mg/Kg (15% of his body). The recreational divers entire surface area is also exposed to a benzene SRC in surface water of 0.251 mg/L. The diver drinks 10 mL of this contaminated water on each dive. We calculate the hours per month that will lead to absorption of benzene that is equal to that absorbed from drinking water at the MCL also over a 1-month period. Each concentration is corrected by the standard so that for dermal water absorption, the factor is 0.251 mg divided by 0.024 = 10.5. The sediment value is 5/113 but corrected for the fact that only 15% rather than 50% of his body was covered with sediment (used to calculate the threshold value) (5/113) * 0.3 = 0.013. The gastrointestinal value is 0.251. The total is 10.5 + 0.013 + 0.251 = 10.764, and 1 divided by 10.764 equals 0.0929 h allowable per day or 2.8 h per month (0.0929 * 30). The sediment exposure is relatively unimportant in this calculation (0.012/10.763, around 0.1% of the total value). The increased lifetime risk to the diver diving 12 h per month for a lifetime would be 4.3 fold (12/2.8 = 4.3 times the recommended limit) or 4.3 per 100,000 divers. Since the lifetime risk in the white male population in the United States for all types of leukemia, (U.S. NIH and NCI 2007)) is 9 per 1,000, a diver with leukemia exposed to the SRC levels of benzene for a lifetime of diving would have around a 0.04% chance that his leukemia was due to the exposure to benzene while diving (personal attributable risk = 0.004/9.004). If the concentrations were known, then it would be acceptable to dive 2.8 h per month with an acceptable theoretical lifetime increased risk for leukemia of 1 per 100,000 divers.

A major finding of our study is that exposure to benzene is not a serious health hazard for divers and that any potential risk comes from the water and not from exposure to sediment. Usually benzene surface water concentrations in lakes are less than the MCL for drinking water (U.S. ATSDR 2007) with maximal concentrations of 100 μg/L (surface waters tested in 571 sites during the years 2003–2005 (U.S. ATSDR 2007)). Even at this level of exposure allowable monthly diving time would be 7.2 h (calculations not shown).

At concentrations of benzene in water and sediment defined as presenting a serious risk for humans, the potential personal attributable risk in a diver with leukemia is extremely low. Furthermore at the SRC, exposure to the water is much more important than the exposure to the sediment. We assumed that 15% of the divers body surface area was exposed to sediment as was used for adults during recreational activities in a polluted lake (Albering et al. 1999). Although the proportion of the skin exposure to polluted sediment in divers is unclear, it can be calculated that even in a rare case with extremely polluted sediment (benzene concentrations of 100 mg/kg, 20 times higher than the SRC) and 50% of the body smeared with mud, allowable diving time would still be 30 h a month (calculations not shown).

There are few human data regarding oral or dermal exposure to benzene. Our method of basing the diving standard on absorption from inhalation might be questionned. The simple absorption ratio approach taken to route-to-route extrapolation here cannot account for differences in disposition of benzene after it crosses the pulmonary, skin or gastrointestinal barrier. First-pass metabolism of ingested benzene may result in a more efficient production of leukemogenic metabolites. On the other hand, rapid clearance of benzene and metabolites after ingestion may be a mitigating factor (U.S. EPA 1999). Nevertheless the U.S. EPA has recommended extrapolating from the benzene inhalation unit risk extimate to the oral route of exposure (U.S. EPA 1999) in determining water standards. This is based on the finding that inhaled or ingested benzene results in similar toxic effects and metabolites of benzene in animals.

This method is appropriate for other pollutants such as arsenic, known to cause cancer by oral absorption. However, calculated allowable diving times for exposures to chromium and other chemicals not shown to cause cancer in humans or in animals by the oral or dermal routes of absorption, might be overly conservative (U.S. EPA 2005b).

We conclude that by limiting diving time, risks that are acceptable for the general population for benzene induced acute leukemia can be achieved. It appears that nearly all recreational divers will not be exposed to extreme benzene concentrations requiring limiting diving time. We recommend that limiting human exposure to “severe risk concentrations” of benzene should take into consideration the findings of our study.

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