JOURNAL OF ENVIRONMENTAL SCIENCES 58 (2017) 183–190

Available online at www.sciencedirect.com

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JES JOURNAL OF ENVIRONMENTAL SCIENCES

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Case study approach to modeling historical disinfection by-product exposure in Iowa drinking waters

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ARTICLE INFO

Article history:
Received 9 November 2016
Revised 7 March 2017
Accepted 8 March 2017
Available online 18 March 2017

Keywords:
Disinfection by-products
Trihalomethanes
Haloacetic acids
Exposure assessment
Epidemiology
Bladder cancer

ABSTRACT

In the 1980s, a case–control epidemiologic study was conducted in Iowa (USA) to analyze the association between exposure to disinfection by-products (DBPs) and bladder cancer risk. Trihalomethanes (THMs), the most commonly measured and dominant class of DBPs in drinking water, served as a primary metric and surrogate for the full DBP mixture. Average THM exposure was calculated, based on rough estimates of past levels in Iowa. To reduce misclassification, a follow-up study was undertaken to improve estimates of past THM levels and to re-evaluate their association with cancer risk. In addition, the risk associated with haloacetic acids, another class of DBPs, was examined. In the original analysis, surface water treatment plants were assigned one of two possible THM levels depending on the point of chlorination. The re-assessment considered each utility treating surface or groundwater on a case-by-case basis. Multiple treatment/disinfection scenarios and water quality parameters were considered with actual DBP measurements to develop estimates of past levels. The highest annual average THM level in the re-analysis was 156 μg/L compared to 74 μg/L for the original analysis. This allowed the analysis of subjects exposed at higher levels (>96 μg/L). The re-analysis established a new approach, based on case studies and an understanding of the water quality and operational parameters that impact DBP formation, for determining historical exposure.

Introduction

Disinfection of drinking water with chlorine or other disinfectants forms a number of disinfection by-products (DBPs) from reactions with natural organic matter (NOM) and certain inorganic substances (*e.g.*, bromide) in the source water (Krasner et al., 2006). Toxicological studies show that certain DBPs produce cancer in the liver, kidney, and/or large intestine of laboratory animals and that particular DBPs cause adverse reproductive or developmental effects (Boorman et al., 1999). Among these DBPs, the bromine-containing species are more geno- and cytotoxic than their chlorinated analogs (Richardson et al., 2007). Recent research suggests that brominated trihalomethanes (THMs) are one group of DBPs of concern (Cantor et al., 2010). Epidemiologic studies consistently report a modestly

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http://dx.doi.org/10.1016/j.jes.2017.03.007
1001-0742/

increased risk of bladder cancer among men with long-term exposure to drinking water with THMs >50 μg/L (Costet et al., 2011). The evidence linking other cancer sites, such as colorectal, brain, and other cancers, to DBP exposures is suggestive, but less consistent (Villanueva et al., 2015; Rahman et al., 2010).

Data from epidemiologic studies of cancer provide important information that contributes to the weight-of-evidence on the potential health risks from exposure to chlorinated drinking water. The strength of inferences from these studies depends on the precision of estimated exposures to study subjects. However, exposure assessment has been identified as a weakness in many epidemiologic studies on DBPs (Reif et al., 1996). Epidemiologic studies can be affected by either differential or non-differential exposure misclassification. Identifying major differences in DBP exposure among areas and estimating the magnitude of historical DBP exposures are vital in bladder cancer studies, as the latency period for bladder cancer may be up to several decades. Historical databases typically contain very limited DBP data. There were no data for DBPs prior to the 1970s, when they were first discovered.

DBP formation has been predicted in some studies using empirical models, which include various parameters that impact DBP formation (Amy et al., 1987): *e.g.*, total organic carbon (TOC) and ultraviolet absorbance (UVA) at 254 nm, which are measures of the quantity and character of the NOM and are surrogates for the organic DBP precursors; bromide, which is an inorganic DBP precursor. However, historical data for most of these parameters are not available. For example, TOC data may be available since the 1980s, whereas UVA_{254} and bromide data may not be available until the 1990s. Thus, empirical DBP models can be developed and used for recent time periods, but not for the historical database of concern. In addition, empirical models are "central tendency" models, which are better at predicting the central tendency occurrence than that of the outliers; *i.e.*, groups with the highest and lowest exposure, which may represent the cases with highest risk and the control group, respectively, may be the least well predicted with a central tendency model.

The objective of this study (Amy et al., 2005) was to develop improved exposure assessments for two well-conducted, peer-reviewed epidemiologic studies, one in Iowa (U.S.) (Cantor et al., 1998) and the other in Ontario (Canada) (King and Marrett, 1996), which reported an increased risk of bladder cancer associated with chlorinated drinking water and THMs. The development of improved exposure assessment in Iowa is presented in this paper (this paper summarizes the exposure assessment developed in Amy et al., 2005, with some new insights provided in the current paper). In the initial study, Cantor et al. (1998) looked at the incidence of bladder cancer associated with drinking water in Iowa; cases were residents between the ages of 40 and 85 years diagnosed with bladder cancer between 1986 and 1989.

In the Cantor study, investigators developed a semi-quantitative model for estimating past DBP exposure. Mean concentrations of 1987 total THM (TTHM) levels were used to estimate past levels for communities using a similar source water and treatment process. For the calculation of means, communities were grouped according to the water source (surface water, shallow or non-alluvial groundwater)—based on the premise of higher NOM levels in surface water and the lowest levels in deep groundwater—and point of chlorination (pre- and/or post-) used by the community's water treatment plant. Groundwater systems were further segmented by those with relatively high or low amounts of brominated THMs.

Because this method assigned the same THM level to communities with similar water sources and treatment practices, it may not have accurately represented the variations between communities, especially for those that used surface water sources, which have varying amounts of NOM (*i.e.*, DBP precursors). Many U.S. drinking water treatment plants changed their treatment and/or disinfection practices in the 1980s to comply with the 1979 THM Rule, which established a maximum contaminant level (MCL) of 100 μg/L, where compliance was based on a running annual average of quarterly (seasonal) samples. A U.S. survey conducted in the mid 1980s, based on THM data from 1984 to 1986, estimated that the 1979 THM Rule reduced, on average, the concentrations of THMs in large systems by 40%–50% (McGuire and Meadow, 1988). Thus, an alternative modeling approach that addressed these issues was developed to predict historical DBP exposure in Iowa for a re-analysis.

1. Materials and methods

1.1. Overview

A case study approach was developed that examined utility-specific data on chronological changes in treatment and disinfection practices, and changes in source water. A secondary effort focused on plants that treated water from the same or similar watersheds and whose current treatment and disinfection scheme was the same as another plant's historical treatment and disinfection scheme, thus permitting predictions of historical DBP exposure for the latter plant. The objective was to predict TTHMs, haloacetic acids (HAAs) (another class of regulated DBPs), and individual THM and HAA species for the Iowa communities back to the early 1900s in order to predict lifetime exposures. Throughout this timeline, a revised set of predictions was made whenever a plant made a significant change in treatment or disinfection practices or source water supply that could substantially impact DBP formation.

1.2. Databases and sources of information

Since the 1970s, various surveys were conducted and databases established to address DBP occurrence. Details on the information obtained for this study are provided in the Appendix A. This included some THM occurrence data prior to the promulgation of the 1979 THM Rule. In addition, there were some subsequent THM and HAA data from small utilities not regulated under the 1979 THM Rule; the data provided crucial information on possible DBP levels in large systems prior to the THM Rule, as they represented DBP formation at plants in the absence of regulatory requirements to control DBPs.