NEW WATER DISINFECTION BYPRODUCTS:
TOXICITY, OCCURRENCE AND HEALTH RISKS

DR. XING-FANG LI, UNIVERSITY OF ALBERTA

CANADIAN WATER NETWORK
RÉSEAU CANADIEN DE L'EAU

NEW WATER DISINFECTION BYPRODUCTS:
TOXICITY, OCCURRENCE AND HEALTH RISKS

DR. XING-FANG LI, UNIVERSITY OF ALBERTA

WHY DID WE DO THIS RESEARCH?

Over the past 30 years, the water sector has invested heavily in resources to meet the increasingly stringent regulations for drinking water quality. One major area of growing attention for assuring drinking water safety has been disinfection byproducts (DBPs). DBPs are formed when disinfectants used in water treatment (e.g., chlorine, chloramine) react with naturally occurring organic matter present in surface waters to create new compounds (e.g., trihalomethanes). The first DBPs were discovered in 1974 - so-called trihalomethanes (THMs). Chloroform was by far the most prevalent of these DBPs, being detected at some level in any surface water disinfected with chlorine.

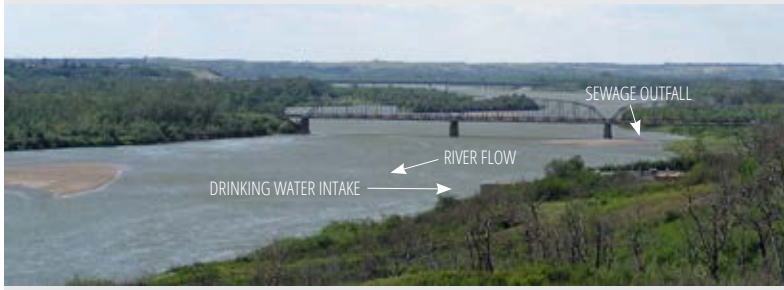
The issue of DBPs in drinking water has posed a risk tradeoff challenge.

Chloroform was widely used in consumer products (toothpaste, mouthwash, etc.) at that time but based on a rodent cancer bioassay published in 1976, it was declared a carcinogen. That evidence led to a chloroform ban on commonly ingested consumer products as well as the development of THM drinking water guidelines in Canada by 1978. The issue of DBPs in drinking water has posed a risk tradeoff challenge. We have known for more than a century that a failure to disinfect microbial pathogens in drinking water will allow them to cause waterborne diseases. More recently, waterborne disease outbreaks in Walkerton and North Battleford have demonstrated the critical importance of achieving adequate drinking water disinfection.

The discovery of DBPs has raised concerns about a wide range of proposed adverse health effects ranging from cancer to adverse reproductive outcomes. These proposed health risks, although not proven, have made reduction of DBPs in drinking water a priority for suppliers. By the mid 1990s, research demonstrated that chloroform only caused rodent tumors at massive doses, like those used in the original 1976 rodent bioassay. (Otherwise, chloroform exhibits a threshold level of exposure, below which it poses no cancer risk to consumers. The concentrations of chloroform that could be found in drinking water were well below this threshold). Informal surveys among several audiences have shown that most drinking water professionals are not aware that chloroform does not cause cancer by drinking water exposure. The precautionary drinking water guideline levels for THMs provide a very wide margin of safety. Accumulated research results have indicated that even the brominated THMs at the levels present in drinking water are not likely to cause cancer (Bull 2012).

Since 1974, more than 600 DBPs have been identified in drinking water. Any effective, comprehensive disinfection process will yield some level of DBPs. Chlorination is the most prevalent, cost effective disinfection process, particularly for small systems that pose the greatest risk for pathogen contamination. More than half of the total quantity of chlorinated DBPs in water remains unidentified. A wide variety of technological responses to reduce the formation of DBPs has been developed, including alternative disinfection processes such as ozonation and chloramination. These alternative disinfection processes can generate non-chlorinated DBPs, such as bromate (from ozonation) and nitrosamines (from chloramination), which are far more toxic than THMs on a per molecule basis. Therefore, changes in disinfection processes for regulatory compliance must be based on full knowledge of possible DBP health risks. To better understand which DBPs may be of health concern, there is a need to have reliable data for risk assessment. This requires analytical methodologies that can detect and identify as many DBPs as possible, in addition to techniques for judging their relative toxicity compared with THMs.

(above) Walkerton, Ontario, May 2000. Microbial pathogens in cattle manure from a barnyard contaminated a nearby municipal well, caused 7 deaths and over 2000 cases of illness among consumers because disinfection was not adequate to cope with the manure contamination that reached the well.



(above) Pathogenic *Cryptosporidium* from the sewage outfall (in front of the bridge) passed through the drinking water treatment plant at North Battleford, Saskatchewan causing an outbreak of illness affecting an estimated 6000 consumers in March / April 2001.

WHAT DID OUR RESEARCH INVOLVE?

This program engaged research teams at the Universities of Alberta, Waterloo, Toronto and Laval. Three main aspects were evaluated:

1. ***Developing new analytical methods with improved ability to analyze trace levels of unregulated and new DBPs.***
2. ***Identifying and evaluating the occurrence of newly discovered DBPs.***
3. ***Developing novel toxicity-testing techniques to screen new DBPs and evaluate the toxicity of DBPs.***

1. *Development of DBP analytical techniques*

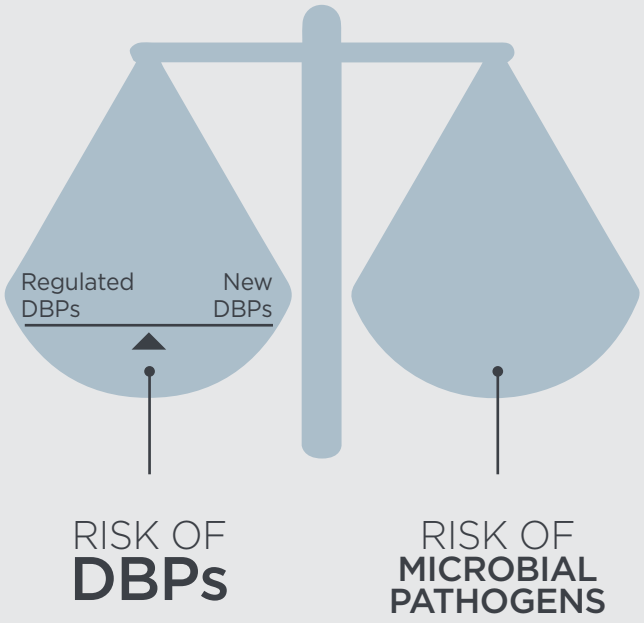
Because DBPs occur at very low concentrations, from fractions of a ng/L (1 part in a trillion) to a few µg/L (1 part in a billion), analytical methods must be very sensitive (able to detect ultra-trace amounts) as well as very specific (able to distinguish accurately the target DBP from countless other ultra-trace substances in water).

Nitrosamines are small molecules, including some recognized carcinogens, which are very challenging to analyze. Novel techniques for sampling and extraction of these DBPs were developed along with a variety of analytical methods that provide excellent sensitivity and specificity. These allowed analysis of some DBPs that degrade during analysis by other common techniques.

"Disinfection by-product research is extremely valuable to drinking water utilities across the country. Currently, the Canadian Drinking Water Quality Guidelines only include two groups of disinfection by-products (THMs and HAAs), plus the disinfection by-product nitrosodimethylamine (NDMA); however, there may be other by-products formed during the treatment process that while not regulated, pose a significant chemical health risk. Knowing which by-products are present and at what concentrations, enables a utility to plan for future process improvements, as well as plan for future regulations."

Andy Campbell, City of Ottawa Drinking Water Services.

THE COMPLEX, COMPETING RISKS INVOLVED IN DBP REGULATION



2. *Identification of new DBPs*

The newly developed analytical techniques identified DBPs in drinking water not previously found. One entirely new class of DBPs (halobenzoquinones, HBQs) was discovered after being predicted to be found in chlorinated drinking water and judged likely to be carcinogenic. The research assessed a selection of Canadian water treatment plants including several combinations of treatment processes applied to different surface waters. These were assessed for occurrence of nitrosamines and for the newly discovered HBQs.

3. *New toxicity testing tools*

This research developed and evaluated a novel approach allowing the evaluation of large numbers of samples and contaminant combinations with real time measurement of toxicity to a variety of human cell lines. Also, a novel method was developed to assess the ability of various DBPs to bind to DNA, a potential marker of a chemical with the ability to damage DNA.

WHAT DID WE FIND?

1. ***Analytical method development***

Several advances were achieved for the sampling and extraction of eight simple nitrosamines, including nitrosodimethylamine (NDMA), the most commonly found nitrosamine. This was combined with development of automated sample preparation with separation and detection methods for high throughput analysis including validation of thin-film micro-extraction for DBPs. A new thin-film active sampler was also developed and field-tested for rapid on-site water sampling that is user-friendly and easier to commercialize than previous samplers.

New mass spectrometry methods were developed and used to identify the precursors of N-nitrosodiphenylamine (NDPhA), a nitrosamine not found with previous analytical methods.

2. ***Identification of new DBPs***

The analytical advances were successfully applied to both identify DBPs not previously identified in drinking water, and to characterize occurrence of several unregulated DBPs in a wide variety of circumstances. This was necessary to judge any potential public health risks for Canadians.

Two nitrosamines, NDPhA and nitrosopiperidine and two related nitrogenous DBPs, phenazine and N-chlorophenazine were discovered in drinking water for the first time by using the new analytical methods developed. These DBPs were investigated in 38 drinking water systems (DWSs) in Canada and the USA. NDMA was the most frequently detected, followed by NDPhA which was detected as a DBP in both treated surface water and ground water. The main factor driving nitrosamine occurrence was chloramination, a disinfection process alternative commonly adopted to meet current regulatory limits for THMs.

The predicted occurrence of a previously undetected class of DBPs, the HBQs was verified in drinking water systems, providing a major discovery in this field. The HBQs are important because they appear to be many times (up to 1000 to 10,000 times) more toxic than the THMs. Fortunately, the analytical capability to study these compounds has revealed that the HBQs occur in DWSs at low ng/L concentrations rather than the thousand fold higher concentrations of the THMs. The investigation of HBQs in nine DWSs using chlorination, chlorination / chloramination, chloramination, and ozonation / chloramination treatments found that 2,6-dichlorobenzoquinone is present in all DWSs studied and 2,6-dibromorobenzoquinone (DBBQ) in 72% of DWSs. Ozonation, another disinfection process alternative to reduce THMs was found to increase DBBQ levels in the finished water.

3. ***Development of novel toxicity testing technology***

This research demonstrated application of a cell culture technique using real time – cell electronic screening. The ability of this technology to use human cell lines vs. single cell organisms like bacteria provides a very useful addition to the tools for rapidly assessing the toxic potential of individual DBPs. This technique was used to demonstrate the severe cytotoxicity of NDPhA by finding it to be 24 times more toxic than the more common NDMA, which is itself regarded as a strong carcinogen in rodents. The toxicity results provide important input into the assessment of potential health risks of DBPs. Evaluation of the reliability and robust behaviour of this technique for environmental surveillance applications was performed.

In addition a DNA-damage testing approach for DBPs was developed. The combination of measuring cell toxicity and DNA damage is very useful for characterizing the nature of toxic effects and an indication of potential for causing cancer. Toxicity testing of four HBQs showed them to be highly toxic to the cells and HBQs also damaged DNA and proteins. Furthermore, a novel mass spectrometry technique was developed that was able to determine binding of certain DBPs to DNA.

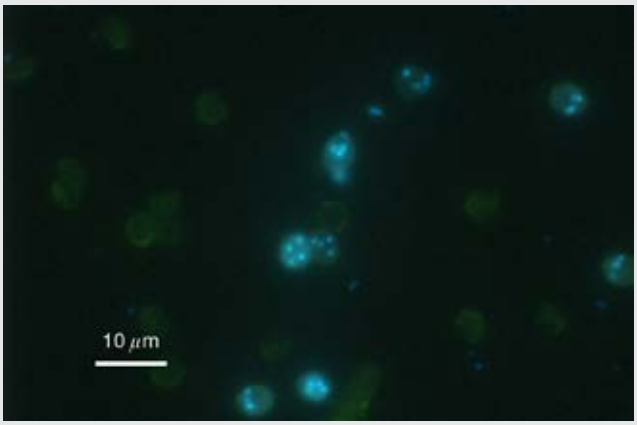
"The available toxicological evidence indicates that the THMs represent a risk that is two orders of magnitude less (i.e. 100 fold less) than has been associated with chlorinated drinking water in epidemiological studies... As data become available to assess the risks associated with other DBPs, the importance of the THMs as cancer risks should recede completely into the background."

Bull (2012).

WHAT DO THESE FINDINGS MEAN FOR DRINKING WATER PROFESSIONALS?

Public health risk issues associated with DBPs in drinking water are extremely complex, despite 40 years of investigation since THMs were first discovered. Initial regulations were precautionary based on evidence that chloroform was a rodent carcinogen. Drinking water providers have been responding with precautionary remedial actions to minimize DBP formation while recognizing that disinfection is essential to ensuring safe drinking water.

A fundamental inconsistency regarding DBP public health risks is that human epidemiology studies have shown some consistent evidence for a relationship between drinking water chlorination and bladder cancer risk, but there is no toxicological explanation for these risk estimates in terms of any one or a combination of known DBPs.



Cryptosporidium oocyst stained by fluorescent stain that binds to four nucleii in each oocyst.
Photo credit - H.D.A Lindquist, U.S. EPA

This research program has advanced, in several tangible ways, the analytical tools available for characterizing DBPs in public drinking water supplies. Furthermore, new DBPs have been identified in Canadian drinking water supplies and new rapid toxicological assessment technologies have been applied to gain insight into the possible health risks these new and known DBPs may pose. These tools have been and continue to be applied for identification of new DBPs to provide better understanding of DBP health risks. The collaborations from this research program made possible a user-friendly book addressing the subject of DBPs and human health risk. This book (Hrudey and Charrois 2012), with contributions from several research team members, provides important perspectives for drinking water professionals about the comparative human health risk from DBPs – primarily that DBPs need to be managed as an uncertain, precautionary issue. As yet, causation of any human illness via drinking water exposure has not been proven for any DBP.

This research has demonstrated the risk of pursuing alternative disinfection technologies for DBP reduction without full evaluation of what possible new DBPs may be formed or increased by the alternative processes to achieve THM reduction. The challenge of balancing the certain health risk from microbial pathogens against highly complex and uncertain health risks from DBPs creates a difficult tension for drinking water providers. However, with an improved understanding of accurate knowledge about DBP health risks, drinking water providers can more confidently manage DBPs in a sensible precautionary manner.

This research provides clear evidence for continuing with a suitably precautionary approach to minimize DBP formation with reasonable measures.

This research provides clear evidence for continuing with a suitably precautionary approach to minimize DBP formation with reasonable measures. Likewise, there is risk in blindly pursuing any alternate technology to reduce regulated DBPs without clearly understanding the potential of such options for creating alternative DBPs. These alternative DBPs may pose a greater health risk or alternate disinfection processes may compromise disinfection efficiency. The knowledge arising from this research provides reassurance that current levels of DBP regulation offer a reasonable, precautionary balance among the complex, competing risks involved (e.g., DBPs vs. microbial pathogens, regulated DBPs vs. newly discovered DBPs).

Escherichia coli (E. coli) is a species of bacteria that is essential to human digestion in the gut and, as a result, is present in huge numbers, making it an excellent indicator of fecal contamination. Some strains of E. coli, like the O157:H7 strain infamous for causing illness and deaths in Walkerton, are pathogenic to humans.
Photo credit – G. Armstrong, University of Calgary

REPORT AUTHORED BY ELIZABETH J. HRUDEY, UNIVERSITY OF ALBERTA

RESEARCH TEAM

XING-FANG LI, University of Alberta, xingfang.li@ualberta.ca
STEVE E. HRUDEY, University of Alberta, steve.hrudey@ualberta.ca
ROBERT ANDREWS, University of Toronto, andrews@ecf.utoronto.ca
SUSAN ANDREWS, University of Toronto, sandrews@civ.utoronto.ca
PATRICK LEVALLOIS, Université Laval, patrick.levallois@msp.ulaval.ca
JANUSZ PAWLISZYN, University of Waterloo, janusz@sciborg.uwaterloo.ca
JEFFREY CHARROIS, Alberta Research Council (then Curtin University), jeffrey.charrois@gov.ab.ca

PARTNERS

EPCOR WATER SERVICE, EDMONTON
WATER DEPARTMENT, CITY OF CAMROSE, ALBERTA
LABORATORY SERVICE, ENVIRONMENT, CITY OF QUEBEC
WATER MANAGEMENT, CITY OF LEVIS, QUEBEC
METROPOLITAN WATER DISTRICT OF SOUTHERN CALIFORNIA
MASSACHUSETTS WATER RESOURCES AUTHORITY, USA
HEALTH CANADA
ALBERTA HEALTH AND WELLNESS
ALBERTA RESEARCH COUNCIL
LABORATORY SERVICE BRANCH, MINISTRY OF ENVIRONMENT, ONTARIO

REFERENCES

ZHAO, Y., ANICHINA, J.; BULL, R.J.; KRASNER, S.W.; HRUDEY, S.E. AND X.-F. LI. 2012. Occurrence and Formation of Chloro- and Bromo-Benzoquinones during Drinking Water Disinfection. Water Research. 46(14): 4351-4360.

HRUDEY, S.E. AND J.W.A. CHARROIS. EDS. 2012. Disinfection By-Products and Human Health. IWA Publishing, London. May 2012. 324pp.

BULL, R.J. 2012. Toxicological evaluation of experimental data that informs the magnitude of cancer risk from disinfection by-products. 179-212, In: Hrudey, S.E. & J.W.A. Charrois. Eds. 2012. Disinfection By-Products and Human Health. IWA Publishing, London. May 2012. 324pp.

BOYD, J.M.; HRUDEY, S.E. ; RICHARDSON, S.D. AND X.-F. LI. 2011. Solid-phase extraction and high-performance liquid chromatography mass spectrometry analysis of nitrosamines in treated drinking water. Trends in Analytical Chemistry 30(9): 1410-1421.

HRUDEY, S.E. 2009. Chlorination disinfection by-products, public health risk tradeoffs and me. Water Research. 43: 2057-2092.

ZHAO,Y.-Y., BOYD, J.M., WOODBECK, M., ANDREWS, R.C., QIN, F. HRUDEY, S.E., AND X.-F. LI. 2008. Formation of N-nitrosamines from eleven disinfection treatments of seven different surface waters. Environmental Science & Technology. 42(13): 4857-4862.