



Scientific Facts on Water Disinfectants & disinfectant by-products

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Level 2 - Details on Water Disinfectants

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This Digest is a faithful summary of the leading scientific consensus report produced in 2000 by the International Programme on Chemical Safety (IPCS):
"Executive Summary of the Environmental Health Criteria (EHC) 216: disinfectants and disinfectant by-products"

The full Digest is available at: <https://www.greenfacts.org/en/water-disinfectants/>



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- Each question is answered in Level 1 with a short summary.
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- Level 3 consists of the Source document, the internationally recognised scientific consensus report which is faithfully summarised in Level 2 and further in Level 1.

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1. What disinfectants and by-products are we talking about?

1.1 Why is there concern about water disinfectants?

Chlorine has been used very widely to kill germs in drinking water and fight waterborne disease. However chlorine reacts with natural material in the water to form a range of disinfectant by-products (DBPs) of public health concern. Therefore, alternative chemical disinfectants are increasingly being used, either alone, in addition to chlorine, or in combination with one another. They include ozone (O₃), chlorine dioxide (ClO₂) and chloramines (NH₂Cl). However, each has been shown to form its own set of disinfectant by-products (DBPs).

There is thus a need to better understand the health risks associated with each mode of disinfection and to decrease the chemical risk without compromising the microbiological safety of drinking water.

1.2 How are disinfectant by-products formed?

Disinfectant by-products (DBPs) are formed when chemical disinfectants react in the water either with natural organic matter (NOM) or with bromide ions (Br⁻). Natural organic matter (NOM) comes mainly from the breakdown of plants and organic matter in soil and Br⁻ comes from natural sources and from wastewater discharges. The reactions of disinfectants are influenced by the physical characteristics of the water, such as pH and temperature, and by treatment conditions, such as disinfectant dose. When inorganic bromide is present, it can also take part in the reaction to produce brominated by-products.

When the disinfectant is chlorine, the reaction gives rise to halogenated (addition of chlorine or bromine) by-products such as trihalomethanes, haloacetic acids, chloral hydrate, haloketones, haloacetonitriles and halogenated hydroxyfuranone derivatives. When bromide is also present in the water, a mixture of different by-products containing varying amounts of chlorine and bromine will be formed.

When the disinfectant is ozone, it oxidizes natural organic matter to form a number of by-products, with aldehydes being dominant. If bromide is present ozone can form brominated compounds similar to some of those produced by chlorine, and also inorganic bromate.

When the disinfectant is chlorine dioxide, it does not appear to form many by-products, but it does break down to form chlorite and chlorate.

When the disinfectant is chloramine, it generally leads to the formation of cyanogen chloride and significantly reduced levels of chlorine disinfectant by-products, but it can also form nitrite in the distribution system if it is not properly controlled.

1.3 What are the most relevant disinfectant by-products?

When the disinfectant is chlorine, the predominant by-products are the trihalomethanes (THMs), followed by the haloacetic acids (HAAs). The THM usually present in highest concentration is chloroform, followed by dibromochloromethane. The HAAs present in the greatest concentrations are dichloroacetic acid and trichloroacetic acid.

When the disinfectant is ozone, the most important by-product is bromate, which is present at very variable concentrations.

When the disinfectant is chlorine dioxide, predictable quantities of chlorite and chlorate are formed, depending on the amount of chlorine dioxide used.

Disinfectant by-products are usually present in complex mixtures that can vary greatly as conditions vary. The most widely studied process is chlorination and there are comparatively few studies on other disinfectants.

1.4 How can the amount of disinfectant by-products be reduced?

The amounts of disinfectant by-products (DBPs) formed can be reduced by:

- reducing DBP precursors (e.g. NOM, Br⁻ ions) which react with disinfectants to form disinfectant by-products (DBPs):
 - limiting the amount of natural organic matter (NOM) in the water, using coagulation, granular activated carbon, membrane filtration or ozone biofiltration;
 - protecting the quality of the water at the source.
- optimizing the use of disinfectant by combining different disinfectants at different stages, i.e. at the treatment plant (primary disinfection) and in the distribution system (secondary disinfection). Ozone can be used exclusively as a primary disinfectant, chloramines exclusively as a secondary disinfectant, and both chlorine and to a lesser extent, chlorine dioxide, in either role. It is less usual for chloramines to be used as a primary disinfectant because it acts much more slowly.

2. What happens to disinfectants and their by-products when ingested or inhaled?

2.1 Kinetics and metabolism of disinfectants

Some of the chlorine disinfectant can still be present in drinking water and react with saliva and stomach content, resulting in the formation of disinfectant by-products similar to those they produce in water.

2.2 Kinetics and metabolism of chlorine by-products

The way chlorine by-products are metabolised depends on several factors:

- Trihalomethanes (THMs) can be taken in by drinking the water and breathing its vapours (for example when showering). They are then metabolised and eliminated rapidly. Most THMs are metabolised into a less-toxic form, but some are transformed into more reactive substances, especially at high concentrations.
- Different haloacetic acids are eliminated differently. Dichloroacetic acid (DCA) is metabolised by forming both monochloroacetic acid and substances naturally found in human metabolism, the rate of conversion being dependent on the dose. trichloroacetic acid is partly metabolised to DCA, which then undergoes further conversion.

- Chloral hydrate undergoes several transformations in the body, leading to the formation of trichloroacetic and dichloroacetic acids (see above).
- Little is known about the elimination of haloacetonitriles.
- The most studied halogenated hydroxyfuranone derivative is called MX. Research indicates that MX is rapidly absorbed and excreted, mainly in urine but also in feces. MX itself cannot directly be measured in blood.

2.3 Kinetics and metabolism of chlorine dioxide by-products

The main by-products of chlorine dioxide, chlorite and chlorate, are probably absorbed and largely broken down to chloride in the body.

2.4 Kinetics and metabolism of ozonation by-products

Bromate formed during ozonation of the water is rapidly broken down to inorganic bromide and eliminated in urine.

3. How can disinfectants and their by-products affect health?

3.1 Disinfectants toxicology

Disinfectants themselves, at the concentrations used, do not appear to contribute to toxicity but it is the by-products and breakdown products that have received attention. Chlorine gas, chloramine and chlorine dioxide are strong respiratory irritants, but only at much higher exposure than would result from the release of vapors through from drinking-water.

3.2 Chlorine by-products toxicology

The different groups of chlorine by-products have different toxicity. They can particularly affect the liver and kidney of laboratory rats and mice:

- The toxicity of the trihalomethanes (THMs) in laboratory animals is higher when administered with corn oil than with water. Chloroform is not considered to be genotoxic and induces cancers only at high doses after tissues have been damaged. The other THMs appear to be weakly genotoxic. At high doses, some induce tumours of the liver and kidney and others of the large intestine, when administered in corn oil.
- The haloacetic acids (HAAs) produce a range of effects in rodents including tumours of the liver and reproductive and neurological effects, but only at very high doses. They are only weakly genotoxic but this does not appear to be how they cause tumours.
- Chloral hydrate has been shown to potentially induce liver tumours and other health effects in laboratory rodents but only at very high doses. Some of the other halogenated aldehydes and ketones are highly genotoxic possibly carcinogenic and one, chloroacetaldehyde has induced liver tumours in laboratory animals.
- The haloacetonitriles have not been well studied. Some are mutagenic, but may not induce tumours.
- MX is a very potent mutagen in bacteria and also appears to cause some tumours in laboratory rats.

3.3 Chlorine dioxide by-products toxicology

The by-products of chlorine dioxide, chlorite and chlorate, can damage red blood cells. Chlorite may cause mild neurobehavioural effects in rat pups at relatively high doses but does not increase tumours in laboratory animals. Chlorate shows lower toxicity than chlorite.

3.4 Ozonation by-products toxicology

Bromate, the main by-product of ozonation, has been shown to induce tumours of the kidney, peritoneum and thyroid in rodents at high doses.

4. Have disinfectants and their by-products affected human health?

4.1 Has water disinfection caused cardiovascular disease or cancer?

There are no indications that chlorinated or chloraminated drinking-water are a cause of cardiovascular disease in humans. Studies on other disinfectants have not been performed.

Many epidemiological studies have been carried out on the possibility that chlorinated drinking water, and to a lesser extent chloramination, could contribute to cancer in human populations. There have been weak indications that the consumption of chlorinated drinking water may have increased the number of cancers of the bladder, rectum and colon in some studies. However, because the exposure to water contaminants was generally not adequately evaluated, there is no sufficient evidence to say that chlorinated drinking water was or was not the cause of these cancers. It is possible that the associations observed might be due to some other factors.

There are no epidemiological studies on the carcinogenic effects of other disinfectants.

4.2 Has water disinfection harmed pregnancies?

Some studies of populations having consumed chlorinated water, have found small to moderate increased risks for some adverse birth outcomes such as miscarriage and neural tube defects. However, these studies are difficult to interpret because of methodological limitations or suspected bias and they need to be confirmed by other studies.

The experts concluded that the results of currently published studies do not provide convincing evidence that chlorinated water or THMs cause adverse pregnancy outcomes.

5. What are the risks posed by disinfectants and their by-products?

5.1 What tolerable daily intakes and guideline values has the WHO set?

For disinfectants and disinfectant by-products (DBPs) with sufficient data, the World Health Organisation (WHO) has set safe acceptable intake levels. These levels are called Tolerable Daily Intakes (TDIs). TDIs are determined by taking the level at which no harmful health effect has been observed (No Observed Adverse Effect Level or NOAEL) in a particular animal species (e.g. mice, rats, hamsters) and applying an uncertainty factor (in this case, between 100 and 1000 depending on studies available and confidence in the results).

These TDIs are used as a basis for developing the WHO drinking water guidelines that are, in turn, used by many countries, including the European Union (EU), as a basis for their drinking water standards. The guideline values are typically derived from the TDI assuming the average adult weighs 60 kg and drinks 2 litres of water per day.

The following tables present TDIs for disinfectants and disinfectant by-products and the NOAELs from which they were derived. In addition to the data from the IPCS report, presented in the first two columns, a third column is added, which is based on the "Third edition of the WHO Guidelines for Drinking-Water Quality" 2004, providing the most up-to-date guideline values in terms of concentrations in drinking water.

5.1.1 Disinfectants

Table 1. Intake reference values for disinfectants

	<i>NOAEL</i> (µg/kg body weight)	<i>Tolerable Daily Intake (TDI)</i> (µg/kg body weight)	<i>WHO drinking water guideline value</i> (µg/litre)*
Chlorine	15 000	150	5 000
Monochloramine	9 400	94	3 000
Chlorine dioxide (based on chlorite) <small>(1 [see Annex 1, p. 12])</small>	2 900 (chlorite)	30	700 (chlorite)

Source & ©: * Source: "Third edition of the WHO Guidelines for Drinking-Water Quality" 2004 [see http://www.who.int/water_sanitation_health/dwq/gdwq3/en/index.html]

5.1.2 Chlorine by-products

Table 2. Intake reference values for chlorine by-products

	NOAEL (µg/kg body weight)	Tolerable Daily Intake (TDI) (µg/kg body weight)	WHO drinking water guideline value (µg/litre)*
Trihalomethanes			(1 [see Annex 1, p. 12])
-BDCM	-	-	60 (2 [see Annex 1, p. 12])
-DBCM	30 000	30	100
-Bromoform	25 000	25	100
-Chloroform	10 000	10	200
Haloacetic acids			(3 [see Annex 1, p. 12])
-DCA	40 000	40	50
-TCA	40 000	40	200
Chloral hydrate	160 000	16	10 (4 [see Annex 1, p. 12])
Haloacetonitriles			(5 [see Annex 1, p. 12])
-DCAN	15 000	15	20
-DBAN	23 000	23	70
MX			Not established (6 [see Annex 1, p. 12])

Source & ©: *: "Third edition of the WHO Guidelines for Drinking-Water Quality" 2004 [see http://www.who.int/water_sanitation_health/dwq/gdwq3/en/index.html]

5.1.3 Chlorine dioxide by-products

Table 3. Intake reference values for chlorine dioxide by-products

	NOAEL (µg/kg body weight)	Tolerable Daily Intake (TDI) (µg/kg body weight)	WHO drinking water guideline value (µg/litre)*
Chlorite	2 900	30	700 (1 [see Annex 1, p. 12])
Chlorate	30 000	30	700 (1 [see Annex 1, p. 12])

Source & ©: *: "Third edition of the WHO Guidelines for Drinking-Water Quality" 2004 [see http://www.who.int/water_sanitation_health/dwq/gdwq3/en/index.html]

Notes referring to the above table

1: The Tolerable Daily Intake (TDI) for chlorite and for chlorate has translated into a WHO provisional drinking water guideline value. The TDI reflects current lack of a specific long-term study which is in progress.

5.1.4 Ozonation by-products

Table 4. Intake reference values for ozonation by-products

	NOAEL (µg/kg body weight)	Tolerable Daily Intake (TDI) (µg/kg body weight)	WHO drinking water guideline value (µg/litre)*
Bromate	1 300	1	10 (1 [see Annex 1, p. 12])

Source & ©: *: "Third edition of the WHO Guidelines for Drinking-Water Quality" 2004

Notes referring to the above table

1: At present there are conflicting data regarding the exact mechanism by which bromate causes cancer in laboratory animals and how that would impact on risk assessment. The WHO has developed a drinking water guideline value of 10 µg/litre based on two approaches and taking into account the practicality of using ozone. Where bromide is present in the

raw water, the guideline value can only be achieved by appropriate control of disinfection conditions.

5.2 How much disinfectants and by-products are we exposed to?

Typically, several milligrams of disinfectant per litre (mg/l) of water are employed in the system, corresponding to the dose necessary to kill the microorganisms in the treatment plant (primary disinfection) and the dose necessary to maintain a residual disinfection in the distribution system (secondary disinfection). The concentration at the tap is considerably less than initially injected.

The concentrations of disinfection by-products will vary according to the raw water quality and its physical and chemical properties such as pH and temperature, and the level of drink-water treatment.

Chlorine by-products:

- Trihalomethanes (THMs) are normally dominated by chloroform but the levels of brominated THMs will depend on the bromide present in the water.
- The concentration of total haloacetic acids (HAA) is generally about half of the total THMs but it is quite difficult to generalize. Dichloroacetic acid (DCA) and trichloroacetic acid (TCA) are the first and second most dominant species.
- If a hypochlorite solution is used instead of chlorine gas, chlorate may also occur during chlorination.

When the disinfectant is chloramine, the by-products depend on the mode of chloramination, application of ammonia followed by chlorine leading to lower levels of chlorine by-products.

Bromate is primarily formed by ozonation of water containing bromide: about 50% of the bromide is converted to bromate. In European water treatment plants, the concentration of bromate was found to be a maximum of 16 mg per litre.

When the disinfectant is chlorine dioxide, about 50 to 70% of the applied dose forms chlorite.

5.3 Are there uncertainties in assessing exposure?

Toxicological studies attempt to extrapolate the results of laboratory animal studies to humans. This may lead to an estimation of risk factors for some health effects. Epidemiological studies attempt to link human health effects (e.g. cancer) to a cause (e.g. exposure to a disinfectant by-product, DBP) and require exposure assessments.

Humans can be exposed to chemical risks from disinfected drinking-water through several routes:

- ingestion of disinfectant by-products (DBPs) in drinking-water;
- ingestion of drinking-water that has a residual of free chlorine at the tap and the resulting formation of DBPs in the mouth and stomach (ozone cannot be present at the tap and chloramines and chlorine dioxide do not react to form by-products);
- inhalation of volatile DBPs during showering.

However, it is generally assumed that the most significant route is the ingestion of DBPs.

Human health effects depend on both DBP concentration and duration of exposure. They are difficult to assess because DBP mixtures:

- are complex, e.g. trihalomethanes (THMs) versus haloacetic acids (HAAs), chlorinated versus brominated species ;
- change with time, as a function of temperature, nature and concentration of natural organic matters (NOM) in the source water ;
- change with location, i.e. throughout a distribution system.

For epidemiological studies, some historical databases exist for disinfectant doses (e.g. chlorine) and possibly for DBP precursors (e.g. total organic carbon, TOC) and THM concentrations. In contrast, data for HAAs, bromate and chlorite are much more recent and hence sparse. When DBP data is not available, exposure can be estimated indirectly from the chlorine dose and other data.

5.4 Have epidemiological studies been able to evaluate the risks?

5.4.1 Epidemiological studies are a very valuable tool in determining the possible risks from exposure to environmental chemicals. However, there are limitations to the use of Epidemiological studies because it is generally difficult to measure individual exposure to the chemical accurately and because there are usually other causes of the effect of interest, such as smoking or diet. This is also true for epidemiological studies of disinfectant by-products (DBPs). There is often no information on individual water consumption and generally very little information on the concentrations of DBPs other than trihalomethanes (THMs).

Another important point for epidemiology is the consistency of the results between different studies. There have been more studies looking at bladder cancer than any other cancer but the evidence is not consistent. Some studies show an increased risk while others do not. In those that do show an increased risk, there are differences in the risk reported and between the sexes and smokers and non-smokers.

5.4.2 The epidemiological studies available provide insufficient evidence to establish that water disinfectants and their by-products cause any of the observed effects, mainly because of incomplete information about exposures to specific water contaminants.

Risks may be due to other water contaminants or to other factors not taken into consideration.

6. Conclusions

Water disinfection is, without question, one of the most important barriers to waterborne disease in most parts of the world. As a consequence disinfection should never be compromised in attempting to control disinfection by-products (DBPs). The risks of illness and death from germs in drinking water is very much greater than the risks from disinfectants and disinfection by-products. However, actions have been taken to reduce the levels of DBPs.

Chlorine and alternative chemical disinfectants (ozone, chlorine dioxide and chloramines) all lead to the formation of disinfectant by-products (DBPs). Currently, the DBPs of most concern include trihalomethanes (THMs), haloacetic acids (HAAs), bromate and chlorite. The toxicology of the DBPs suggests that the likelihood of adverse effects is not significantly different between different water disinfection options.

Animal studies indicate that none of the chlorination by-products studied to date is a potent carcinogen at concentrations normally found in drinking water. There is insufficient epidemiological evidence to conclude that drinking chlorinated water causes cancers.

The results of currently published studies do not provide convincing evidence that chlorinated water or THMs cause adverse pregnancy outcomes.

Nevertheless it is prudent to take steps to minimise exposure to DBPs, where this can be achieved without compromising disinfection. Strategies should focus on eliminating organic impurities fostering DBP formation.

Annex

Annex 1: Footnotes

5.1.1 Disinfectants

Table 1. Intake reference values for disinfectants

1: There is no guideline value for chlorine dioxide because it breaks down rapidly and because the provisional guideline value for its major breakdown product, chlorite, is adequately protective.

5.1.2 Chlorine by-products

Table 2. Intake reference values for chlorine by-products

1: The drinking water guidelines for the four trihalomethanes (THMs) are 200 µg/litre for chloroform, 60 µg/litre for bromodichloromethane (BDCM) and 100µg/litre for both dibromochloromethane (DBCM) and for bromoform. However, the WHO advises that trihalomethanes be taken as a group, which is why national standards are normally set as total THMs. The WHO recommends that the sum of the ratio of the concentration of each trihalomethane to its respective guideline value should not exceed 1.

2: For some carcinogens, the guideline value is the concentration in drinking-water associated with an upper-bound excess lifetime cancer risk of 10⁻⁵ (one additional cancer per 100 000 of the population ingesting drinking water containing the substance at the guideline value for 70 years), computed from laboratory animal data by using a theoretical mathematical model.

3: The haloacetic acids are dominated by the chlorinated acids and the WHO has recommended guideline values of 40 µg/litre for dichloroacetic acid (DCA) and 200 µg/litre for trichloroacetic acid (TCA). The calculated guideline value for DCA is below the level that can be achieved through practical treatment methods or source control and disinfection is likely to result in the guideline value being exceeded.

4: Guideline value not reviewed in 3rd edition of guidelines. Under review, new data indicate probable significant increase in guideline value.

5: WHO has recently reviewed the 1993 guideline values for dichloroacetonitrile (DCAN) and dibromoacetonitrile (DBAN). In the case of dichloroacetonitrile (DCAN) there is evidence of a potential hazard, but the available information on health effect is limited. No TDI can be established for trichloroacetonitrile (TCAN), because available data is inadequate.

6: Because MX occurs at concentrations well below those at which toxic effects are observed and because it is difficult to measure at low concentrations, no guideline values have been established.

5.1.3 Chlorine dioxide by-products

Table 3. Intake reference values for chlorine dioxide by-products

1: The Tolerable Daily Intake (TDI) for chlorite and for chlorate has translated into a provisional drinking water guideline value, which is likely to be exceeded by disinfection.

5.1.4 Ozonation by-products

Table 4. Intake reference values for ozonation by-products

1: At present there are conflicting data regarding the exact mechanism by which bromate causes cancer in laboratory animals and how that would impact on risk assessment. The WHO has developed a drinking water guideline value of 10 µg/litre based on two approaches and taking into account the practicality of using ozone. Where bromide is present in the raw water, the guideline value can only be achieved by appropriate control of disinfection conditions.