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Addressing arsenic and fluoride in drinking water

WHO Collaborating Center for Sanitation and Water in Developing Countries

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Cover Photo:

Women collecting fluoride-treated water at the community filter in Wayo Gabriel, Ethiopia, implemented by Eawag, Oromia Self-Help Organization (OSHO) and Swiss Interchurch Aid (HEKS)

3 Nutritional intake and health risks of arsenic and fluoride

Linda C. Roberts and C. Annette Johnson

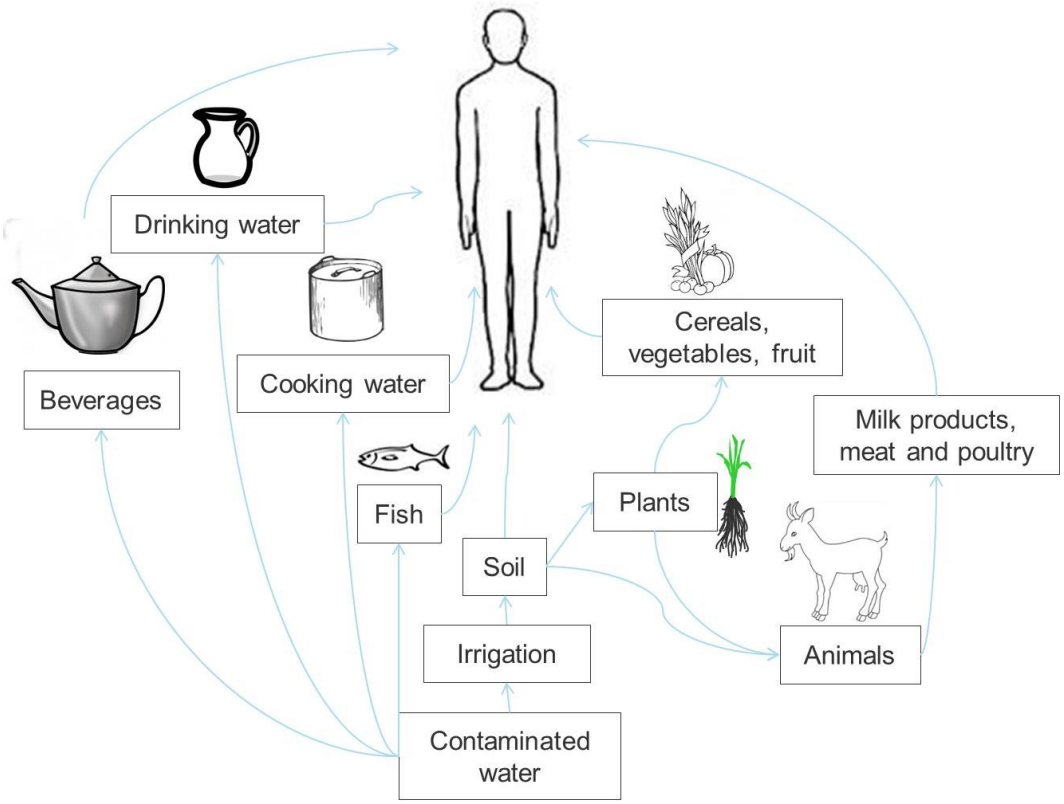

Fig. 3.1 *Different food and water pathways by which contaminants may enter the body*

Uptake via drinking water is only one of the potential pathways by which contaminants enter the human body. Elevated contaminant concentrations may also be found in foodstuffs and beverages or in water used for food preparation (Fig. 3.1). Locally produced cereals and vegetables using contaminated irrigation waters may contain elevated contaminant levels. Medical products or industrial production can also be sources of contamination. Though not an alternative to the provision of safe drinking water where water contamination is high, an understanding of the uptake pathways widens the scope of the mitigation possibilities to include changes in food production and consumption behaviour.

3.1 Arsenic

Overview of arsenic in soils, plants and foodstuffs

Arsenic is ubiquitous in the environment. Whilst uncontaminated soils typically contain less than 10 mg As/kg, concentrations of up to 80 mg As/kg have been reported from areas irrigated with arsenic-contaminated groundwater (Hossain, 2006). The mobility of arsenic in soils and its availability for plant uptake depend strongly on soil redox conditions. In aerated soils, arsenic is present mainly as arsenate (As(V)), which binds strongly to iron oxides. Arsenic concentrations in soil porewater solutions are therefore generally low. By contrast, much higher concentrations of dissolved arsenic are found in flooded soils, where reducing conditions prevail and arsenite (As(III)) is the dominating species. This is related to As(III) binding more weakly to the solid phase, and to iron oxides, its main host phase, being dissolved under reducing conditions. Plants growing in oxic environments, such as most cereal crops and vegetables, are therefore exposed to relatively low concentrations of As(V) in the soil porewater solution. Plants growing in flooded soils, most importantly rice, are by contrast exposed to higher concentrations of dissolved As(III) (Zhao et al., 2010).

Arsenic is a non-essential and toxic element which plants take up via the channels for essential nutrients. Because of its chemical similarity to phosphate, As(V) is taken up via phosphate transporters. As(III) has recently been shown to share the silicate uptake system in rice plants (Zhao et al., 2009). Since arsenic uptake occurs via the root system, plant roots often accumulate more arsenic than shoots, leaves and fruit. In rice plants, the arsenic content decreases in the order roots > stems and leaves > grain, with arsenic content being generally ~10 times lower in grains than in shoots and leaves (Heikens et al., 2007). Irrigation with arsenic-contaminated groundwater has been shown to lead to increased arsenic levels in rice and vegetables (Williams et al., 2006; Ahsan and del Valls, 2011; Table 3.1). Whilst arsenic speciation in terrestrial plants is dominated by inorganic arsenic, fish and other seafood contain mainly arsenobetaine, an organic arsenic species considered to be of no toxicological concern (Zhao et al., 2010). The overall contribution of seafood to inorganic arsenic exposure is therefore very limited (Table 3.1). The inorganic forms of arsenic are orders of magnitude more toxic than organic species (NRC, 1999, 2001).

Human exposure to arsenic via food

Owing to its traditional cultivation in flooded fields, rice contains significantly higher amounts of arsenic than other cereals (Table 3.1). Rice is the staple food of half the world's population. This includes those living in the large river deltas most affected by the geogenic arsenic contamination of South Asia. In rural Bangladesh, for example, adults consume around 0.5 kg dry weight of rice per day, which accounts for ~70% of their calorific intake ((Khan et al., 2009; FAO/WFP, 2008). Assuming a total As content of 0.13 mg As/kg dry weight in the rice, corresponding to the average As content in rice from urban Bangladeshi markets (Table 3.1), the daily consumption of 0.5 kg dry weight of rice leads to the ingestion of 65 µg As per day. The arsenic intake via the consumption of fresh vegetables,

130 g fresh weight for a typical rural Bangladeshi diet, is less than 5 µg As per day (Williams et al. 2006; Table 3.1). If we assume a body weight of 60 kg, the calculated daily ingestion of arsenic via rice translates to a daily intake of 1.08 µg As per kg body weight. This corresponds to around 50% of the provisional tolerable daily intake (PTDI) for inorganic arsenic recommended by the joint WHO/FAO Food commission (WHO, 1989). In As-affected areas in Bangladesh, where the arsenic content in rice can be up to 0.3 mg As/kg, the daily arsenic ingestion via rice can increase to over 100% of PTDI. As ~80% of arsenic in rice from Bangladesh is inorganic, the contribution of rice consumption to the PTDI in the two examples above is critical (Meharg et al., 2009).

The above estimates illustrate two points: a) among food items, rice contributes most strongly to inorganic arsenic exposure in Bangladesh and b) the amount of inorganic arsenic ingested via rice consumption is of the same order of magnitude as the provisional tolerable daily intake (PTDI) of 2.1 mg As/kg body weight recommended by the joint food commission of WHO/FAO in 1989. The recommended limit was recently withdrawn because of new epidemiological data, but a revised, stricter tolerable daily intake value for arsenic has yet to be established (WHO, 2011). This strongly suggests that exposure to arsenic via rice consumption is likely to lead to negative health impacts in the Bangladeshi population. However, as illustrated in the following, exposure via rice consumption is of secondary importance compared to exposure to arsenic via geogenically contaminated drinking water.

Comparison of exposure to arsenic via food and drinking water

The drinking-water limit for arsenic in Bangladesh is 50 µg/L. An adult weighing 60 kg and consuming 3 L of drinking water complying with this limit ingests 2.5 µg As/kg body weight. This alone corresponds to around 120% of the PDTI (Watanabe et al., 2004). In many rural areas of Bangladesh, however, people continue to rely on water with arsenic concentrations well above the national limit. Arsenic exposure via drinking water can thus easily be 2–6 times higher than the exposure calculated here. Wherever people do not have access to drinking water complying with the Bangladeshi guideline value, exposure to inorganic arsenic via drinking water therefore clearly exceeds exposure via food. The most urgent and effective mitigation measure in geogenically contaminated areas is therefore the provision of safe drinking water.

Mitigating exposure to arsenic in food

Various measures can be taken to reduce the arsenic content of food crops, including breeding low-arsenic cultivars, diversifying agriculture towards crops requiring less irrigation input and modifying the growing conditions of water-intensive crops. In particular, growing rice in fields flooded only intermittently or in raised beds with furrow irrigation represents a promising strategy for reducing the arsenic content of rice grain and straw (Duxbury and Panuallah, 2007; Roberts et al., 2011). Since straw is used as cattle feed in Bangladesh

and West Bengal, avoiding high arsenic concentrations in rice straw represents an important additional measure limiting the introduction of arsenic into the food chain (Ahsan and del Vals, 2011). A more comprehensive review of mitigation options in crop production can be found in Brammer (2009) and Zhao et al. (2010).

Table 3.1 *Arsenic content of different foodstuffs, expressed as mg As/kg of dry weight (rice) and fresh weight (vegetables and other food items)*

Foodstuff	**Mean** (mg/kg)	n*	**Range** (mg/kg)
Global [1]			
Rice grain	0.15	901	0.01 – 0.82
Europe [2]			
Rice grain	0.14	1122	0 – 1.18
Cereal products (excluding rice)	0.02	1004	0 – 0.89
Vegetables	0.012	2604	0 – 1
Fish and seafood **	2.38	5083	0 – 195
Milk and dairy products	0.0089	3896	0 – 0.66
Meat and meat products	0.0098	9890	0 – 0.98
Eggs	0.0080	1404	0 – 0.182
Bangladesh [3,4]			
Rice grain, urban markets	0.13	144	0.02 – 0.33
Rice grain, farmers' fields	0.192	326	0.04 – 0.27
Rice grain, farmers' fields, As-affected areas	0.347	397	0 – 1.08
Vegetables, farmers' fields	0.0293	144	0.004 – 0.23

n = number of samples analysed.
*The percentage of inorganic arsenic in rice falls in the 30%-90% range (EFSA, 2009). Rice grown in Bangladesh contains an average of 80% of inorganic arsenic (Meharg et al., 2009).
**Fish and other seafood contain the non-toxic organic As compound, arsenobetaine. Inorganic As ranges between 0.03 mg and 0.1 mg As/kg fresh weight (EFSA, 2009).

[1] Meharg et al., 2009

[2] EFSA, 2009

[3] Williams et al., 2006

[4] Zavala and Duxbury, 2008

In terms of food processing/preparation, two simple measures can be taken to reduce As ingestion via rice: a) rice milling and b) boiling rice in excess As-free water and discarding

the water after cooking. Both rice milling and cooking rice with excess water are common practices in Bangladesh and West Bengal. Rice milling removes the outer bran layer of the grain where arsenic concentration is particularly high. A drawback of rice milling is that it also leads to the removal of beneficial trace nutrients such as zinc (Zhao et al., 2010) and vitamin B1 (thiamine) (WHO, 1999). Boiling rice in water with low As concentrations lowers grain As content. By contrast, cooking rice with As-contaminated water leads to an increase in grain arsenic and should therefore be avoided (Mondal et al., 2010). Using excess arsenic-free pond water for cooking therefore represents an option for reducing arsenic ingestion via rice consumption.

Since there is no effective medical treatment of arsenicosis, avoiding arsenic intake represents the only way to improve the health status of affected populations. Nevertheless, there is evidence that symptoms of arsenicosis are less pronounced in people with varied diets rich in proteins and vitamins (Milton et al., 2004; Mitra et al., 2004). Selenium deficiency, which is common in Bangladesh, on the other hand, appears to exacerbate arsenicosis (Zwolak and Zaporowska, 2012). Diversifying people's diet to include more vegetables and proteins or the provision of selenium supplements (Sah and Smits, 2012) may thus also contribute to reducing the incidence of As-related symptoms.

3.2 Fluoride

Overview of fluoride in soils, plants and foodstuffs

Fluorine is an abundant element in the Earth's crust, and soil concentrations can range from approximately 100 to over 1000 mg/kg. With its high affinity for electrons fluorine exists as the negatively charged ion, fluoride. Geochemical factors control fluoride solubility, and the resulting reduction in availability, coupled with only a passive plant uptake mechanism, limits food concentrations to at most a few mg/kg (Table 3.2). However, plants grown in fluoride-contaminated soils may accumulate considerable amounts of fluoride, although the amount of fluoride accumulated appears to be very dependent on the species. In general, roots accumulate more fluoride than shoots, leaves and fruit, and it is also thought that in some cases, fluoride accumulation is related to the calcium content of the plant. The high fluoride content in Ethiopian cereal products, in particular teff, could possibly be related to the fluoride-rich soils of the Rift Valley (Table 3.2).

In addition to standard food items, such as those listed in Table 3.2, other products such as toothpaste can make a significant contribution to fluoride intake. Trona, a salt used in the Rift Valley of East Africa for cooking, contains significant amounts of fluoride (100 to 17,900 mg/kg, Nielsen and Dahi, 1995), as does the condiment "black salt" (rock salt), used extensively in Indian cuisine (~ 20,000 mg F/kg, single measurement, Eawag). Another potential source of fluoride intake for young children, soil ingestion, can be excluded in most cases (NRC, 2006).

Table 3.2 *Fluoride content of different foodstuffs*

Foodstuff	Content mg F/kg	Reference
Milk and milk products	0.01 – 0.8	Hungary, Germany, USA, China Fawell et al., 2006
Meat and poultry	0.01 – 1.7	
Fish	0.06 – 4 6	
Baked goods and cereals	0.04 – 1.9	
Vegetables	0.01 – 1.3	
Beverages	0.003 – 1.3	
Brewed tea	0.05 – 5.0	
Cereals from the Rift Valley, Ethiopia		
Teff, white, Ethiopia	6.0	Malde et al., 1997
Wheat flour, Ethiopia	4.9	
Maize flour, Ethiopia	1.1	

Fluoride intake standards

Fluoride has both beneficial and adverse effects on human health. In low concentrations, it is known to contribute to the prevention of dental caries; however, in excess amounts, it is toxic (Gazzano et al., 2010; see Section 2.2 for more details). The range between adequate and excess fluoride intake is quite narrow. Standards for fluoride intake have been established for the USA and other industrialised countries (Table 3.3). They stipulate an adequate intake of 0.05 mg F/kg/day, based on the amount necessary to prevent dental caries. Tolerable upper daily intake levels are around 0.1 mg F/kg/day for infants and 0.1–0.14 mg F/kg/day for adults.

Estimates of total daily fluoride intake in selected industrialised countries around the world with fluoride water concentrations up to 1.0 mg/L range from 0.2 to 1.3 mg F/day for children and up to 3 mg F/day for adults. Young children are thought to be particularly at risk of excess fluoride intake. The study estimates that for children aged between 7 and 10, beverages, including water, account for only one third of fluoride uptake, while for adults, beverages, primarily tea, account for two thirds of fluoride intake (Cressey et al., 2009).

Mitigating exposure to fluoride via food

Fluoride metabolism (absorption into and excretion from the body) is influenced by a number of factors, including respiratory and metabolic disorders, altitude of residence,

physical activity, nutritional status, composition of diet and genetic predisposition (Buzala and Whitford, 2011). These factors can lead to an acid-base imbalance in the body.

Fluoride absorption in the stomach is pH-dependent. In acidic gastric fluids, fluoride is protonated (< pH 3.4), and the neutral HF species can pass through the lipid bilayer membrane of the stomach a million times more readily than the charged fluoride ion (F^-). Some fluoride absorption (independent of pH) also occurs in the small intestine (Buzala and Whitford, 2011).

Diet has an important influence on fluoride absorption. For example, a vegetarian diet leads to an increase in urinary pH. Calcium in the diet reduces fluoride absorption in the body by the formation of insoluble fluorite (CaF_2). In China, a study in Jiangzi province showed that children that drank milk had a significantly lower dental fluorosis rate than those who did not (Chen et al., 1997).

Table 3.3 *Standards for fluoride intake*

Standard	Intake		Source
Adequate Intake (AI)	0 – 6 months > 6 months 4 – 8 years Adults (male) Adults (female)	0.01 mg/kg/day 0.05 mg/kg/day 1 mg/day 4 mg/day 3 mg/day	Food and Nutrition Board of the USA (SCSEDRI, 1997) (Based on assessment of requirements for caries prevention)
Tolerable Upper intake Level (UL)	0 – 8 years > 8 years	0.1 mg/kg/day 10 mg/day	SCSEDRI, 1997
Tolerable Upper intake Level (UL)	1 – 3 years 4 – 8 years 9 – 14 years >15 years	1.5 mg/day 2.5 mg/day 5 mg/day 7 mg/day	European Food Safety Authority EFSA, 2011
Dental Fluorosis NOAEL* LOAEL**		0.06 mg/kg/day 0.12 mg/kg/day (8 mg/day for adults)	US Department of Health and Human Services USDHHS, 2003
Skeletal fluorosis NOAEL* LOAEL**		0.15 mg/kg/day 0.25 mg/kg/day (17.5 mg/day for adults)	

* No Observed Adverse Effect Level
**Lowest Observed Adverse Effect Level (5% of test population)

In India, where fluorosis is endemic, dietary change to lower the intake of fluoride and increase the uptake of calcium, iron, vitamins and antioxidants is recommended (Godfrey et al., 2011). Reversal of skeletal disfigurement caused by fluorosis in young children has been achieved by giving them dietary supplements and switching them to low-fluoride drinking water (NEERI, 2007). It should be pointed out, however, that the diagnosis of

skeletal fluorosis requires X-ray analysis, and some bone alterations appear to be permanent (Krishnamachari, 1986). Cortical bone thickening and calcification of muscle insertions and ligaments appear to remain unchanged (Grandjean and Thomsen, 1983).

Fluorosis and dietary assessment and mitigation guides have been developed by the Fluorosis Research and Rural Development Foundation (Susheela, 2000) and the National Environmental Engineering Research Institute (NEERI, 2007). It is recommended that the potential for fluorosis mitigation through dietary changes be explored as an integral part of a fluorosis mitigation strategy.

3.3 Quantitative health risk analysis

Risk assessment is the scientific evaluation of known or potential adverse health effects resulting from human exposure to environmental hazards. One of the more commonly used risk assessment paradigms, the Quantitative Health Risk Analysis (QHRA), is based on the U.S. National Academy of Science in Risk Assessment in the Federal Government: Managing the Process (NAS, 1983), colloquially known as the "Red Book". In the Red Book, the four steps are:

Hazard identification: The identification of known or potential health hazards associated with a particular agent.

For the QHRA, it is important to identify health effects that are characteristic for the contaminant under consideration. For arsenic, skin lesions and cancers are typical health effects (e.g. Lokuge et al., 2004). For fluoride, dental and skeletal fluorosis are clearly visible health effects (Serap and Buchanan, 2005; Fewtrell et al., 2006).

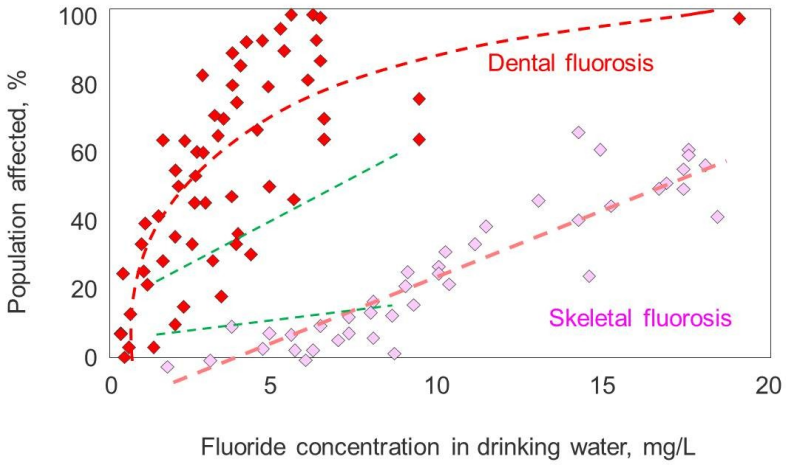

Fig 3.2 *Sketch of dose-response curves for dental and skeletal fluorosis determined by Fewtrell et al. (2006). Superimposed as green dashed lines are the regressions from Bo et al., (2003).*

It should also be noted that though some health effects may not be considered in a QHRA, it does not mean that they are insignificant. For example, there is growing

evidence that excess in the intake of both fluoride and arsenic is linked to impaired cognitive development (e.g. Wang et al, 2007; Seraj et al., 2012; Choi et al., 2012).

Dose-response assessment: In this step, the relationship between the dose of the contaminant and the risk of a subsequent health effect is characterised. For arsenic and fluoride, dose-response assessments are based on the relationships between the contaminant concentration in drinking water (and food) and the incidence of a particular health effect.

This step requires measured data. Health effects need to be identified and characterised by health experts and related to the exposure. An example is given in Figure 3.2. Fewtrell et al. (2006) examined the dose-response relationships from 12 publications on dental fluorosis and 4 publications on skeletal fluorosis. They concluded that more data would be required and that it would be important to include nutritional status and fluoride sources in addition to drinking water.

Also shown in Figure 3.2 are the results of a study in Jilin province in China (Bo et al., 2003). The dose-response curves are encouragingly similar. Nevertheless, the nature of the relationship between dose and response remains contentious, and there are calls for more biologically-based risk assessments (Carlson-Lynch et al., 1994; Kitchin and Conolly, 2010).

Great efforts have been made to evaluate the dose-response of arsenic-related diseases. Fewtrell et al. (2005) estimated the risk of developing skin lesions caused by elevated arsenic concentrations in drinking water using data from Bangladesh, Inner Mongolia (China) and West Bengal (India). The evaluation showed that at a drinking-water arsenic concentration of >350 µg/L, the age-adjusted prevalence of skin lesions is around 33%. The evaluation of cancer rates and mortality linked to arsenic exposure has also been the subject of many studies (for example Fig. 3.3) and evaluations (e.g. NRC 1999, 2001, 2014). Dose-response functions have been developed to predict incidence rates from arsenic exposure (usually in drinking water). The functions include available demographic parameters, such as gender and age (e.g. Yu et al., 2003).

The determination of dose-response functions for both arsenic and fluoride is very much a field of development. As new data sets become available, the models will certainly be refined. One important factor is nutritional status, as malnutrition increases the likelihood of disease (NRC, 2001 and references therein). Differences in water consumption and diet, and the speciation of the contaminant in foodstuffs, have also been noted as factors that affect dose-response functions.

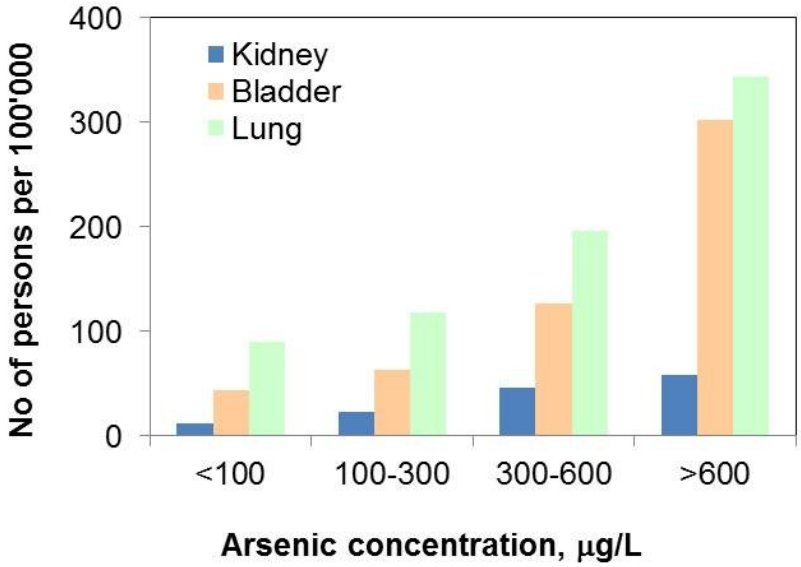

Fig 3.3 *Mortality rates from different cancers as a function of the arsenic concentration in drinking water in the 50–69 age group (men and women) in an endemic area of chronic arsenicosis on the southwest coast of Taiwan from 1973 to 1986 (Chen et al., 1992).*

Exposure assessment: The determination of the size and nature of the population exposed, and the route, amount and duration of the exposure.

The estimated daily intake (EDI) is the sum of all possible inputs, including water and foodstuffs, per unit body weight per unit time. More details can be found, for example, in Phan et al., 2010 or Erdal and Buchanan, 2005. The EDI can be simplified to contaminant intake via water, but ideally it should be demonstrated that other pathways can be excluded. This step is important, because in cases where contaminant concentration in water is not so high, other sources become important. Section 9.4 provides a good example of fluoride intake in Ethiopia.

Risk characterisation: An integration of steps 1–3 to estimate the magnitude of the public health problem, including information uncertainties. The units are the number of people affected, often per 100,000 people.

With a QHRA, it is possible to estimate the number of people that are at risk in a particular population, but how can different health effects (i.e. skin lesions, cancer) be compared? How can death and/or disability be compared? Comparisons of risks on the same scale are a valuable aid in evaluating and planning interventions to improve health. The concept of disease burden is based on the need for such a tool.

Estimation of disease burden

The disease burden can be quantified in terms of Disability Affected Life Years (DALYs), which quantifies the number of years affected or lost due to disease (WHO, 2014).

One DALY can be thought of as one year of healthy life lost, and the overall disease burden can be thought of as a measure of the gap between current health status and ideal health status, where the individual lives to old age free from disease and disability. Fewtrell et al. (2005, 2006) assume a life expectancy of 80 years. The health burden (expressed in DALYs) is the sum of mortality (years of life lost, YLL, and years of life with disability, YLD). Disability levels are weighted (see Table 3.4). The weighting correlates to the degree of disability (WHO, 2014).

DALY = YLL + YLD

where YLL = N x L

N: Number of deaths
L: Standard life expectancy at age of death in years

and YLD = P x DW

P: Number of prevalent cases
DW: Disability weighting

Table 3.4 *Definition of disability weighting (DW) (Murray, 1994)*

Class	Description	Weight
1	Limited ability to perform at least one activity in one of the following areas: Recreation, education, procreation or occupation	0.096
2	Limited ability to perform most activities in one of the areas listed in Class 1	0.220
3	Limited ability to perform activities in two or more of the areas listed in Class 1	0.400
4	Limited ability to perform most activities in all of the areas listed in Class 1	0.600
5	Needs assistance with instrumental activities of daily living such as meal preparation, shopping or housework	0.810
6	Needs assistance with activities of daily living such as eating, personal hygiene or toilet use	0.920

The weighting corresponds to the loss in quality of life. Fewtrell et al. (2006) give dental fluorosis a low weight of 0.0033 that remains constant with age. They base the weight for skeletal fluorosis on that of untreated rheumatoid arthritis with a weight of 0.24 for the age range 40–59 and of 0.5 for those aged 60 or above. A weighting of 0.1–0.2 is given for arsenic-related skin lesions, depending on the length of exposure (Fewtrell et al., 2005).

The DALY can be used to compare different scenarios. For example, DALY estimates have been used to compare the health burden associated with water consumption from different arsenicosis mitigation options in Bangladesh considering both the potential decrease of

arsenic intake and the potential increase in microbial contamination (Howard et al., 2006, 2007),

Due to the complexity of the calculations, no examples are given in this handbook. Seriously interested readers should consult the literature and guidelines and tools provided by the WHO on the estimation of the national burden of disease (WHO, 2001, 2014).

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