

Arsenic in food and water – a brief history

S Sambu and R Wilson

Department of Physics, Harvard University, Cambridge, MA, 02138, USA

Arsenic has been used for millenia. Although it has been known for many years that arsenic is soon fatal when ingested at high doses, the effects of low dosages became apparent in the 1980s. The full societal implications are only now becoming clear. It is now known to pose the highest calculated risk of any substance regulated by the US Environmental Protection Agency (EPA); high concentrations have been found in drinking water in many countries. In Bangladesh, in particular, the number of people suffering from over exposure vastly exceeds the number affected by the catastrophic accident at Chernobyl. This article shows the development of the human understanding about chronic arsenic poisoning with Bangladesh as a particular example. *Toxicology and Industrial Health* 2008; 24: 217–226.

Key words: arsenic; Bangladesh; cancer; chronic poisoning; well; fowler

Introduction

A review of the history of arsenic usage in human societies should include the way arsenic appears in mines as a by-product of mining activities. Human societies have used arsenic since 3000 BC (Partington, 1935). For example, in the United Kingdom, the mining industry used arsenicals to extract iron from iron ore. Furthermore, iron deposits may occur as iron-arsenic composites – arsenopyrite (Welch, *et al.*, 2000). The occurrence of arsenic and iron is important in our understanding of the liberation of arsenic into water in a reducing environment.

Tales of death by arsenic poisoning have abounded in political circles. In renaissance Italy, the Borgias used arsenic to kill political opponents. Many have alleged that the white powder often

referred to as *La Cantarella* contained arsenic and an unidentified sweetener (Bentley and Chasteen, 2002). A curious feature of acute arsenic poisoning is that people can become less sensitive by preconditioning themselves with sublethal doses of arsenic. This fascination has motivated novelists such as Dorothy Sayers (1978) to construct narratives with arsenic as an agent of homicide.

Initially, public health authorities thought that the presence of arsenic in surface and subsurface waters was primarily a result of geographically localized activities such as mining. However, toxic levels of arsenic in ground waters can be a natural consequence of local geochemistry. For instance, although there were cases of chronic arsenic poisoning in Hungary in the 1940s, it was not until 1982 that a survey by the Hungarian Public Health Institute concluded that the high levels of arsenic in drinking water was a result of natural biogeochemical processes and not by anthropogenic activities (Csalagovits, 1994).

Correspondence to: Richard Wilson, Jefferson Physical Laboratory 257A, Harvard University, Cambridge, MA 02138, USA.
Email: wilson5@fas.harvard.edu

In spite of the long history of arsenic usage, the major problems of widespread chronic arsenic poisoning are recent and are the subject of this article.

Effects of arsenic on health

Beneficial uses

Physicians prescribed arsenic at intermediate doses of 0.05 to 0.5 mg/kg/day (ATSDR, 2007), taken for a few months only, to cure syphilis before other antibiotics, such as penicillin, were available. It was used as a cure for leukemia even recently (Kwong and Todd, 1997; Novick, 2000). However, until the mid 19th century, many had not realized that arsenic is dangerous at chronic (low repeated) doses. Even then, the realization was slow – so slow in fact that in many parts of the world the ignorance led to catastrophe. Following Paracelsus' legendary maxim that "All things are poison and nothing is without poison, only the dose permits something not to be poisonous," Dr Fowler in 1785 recommended a 1% solution of potassium arsenite for a variety of ailments, including malaria, cholera, and syphilis (Alain, 1993). Fowler's solution was not an outlandish medicine—it is part of the British Pharmacopoeia. The fact that arsenic has beneficial uses has not changed. Nevertheless, the adverse effects, particularly of repeated doses, have become more important.

Chronic Arsenic Poisoning

Arsenic has been present in a few water supplies for many centuries, but the most contaminated supplies were avoided. The public health concern was that high levels of arsenic taken even for a short time might cause acute poisoning. An anecdotal procedure in the desert was to avoid those water sources from which no animals drank. Nonetheless, warnings of ailments caused by prolonged use of arsenic began to appear, but these warnings were widely ignored. Hutchinson (1888) reported that dyspigmentation, keratoses, and cancers had arisen from continuous (a year or more) doses of Fowler's solution. The famous epidemiologist Doll (1992) noted that many years ago, his father got cancer from continued use of Fowler's solution. In 1895, lung cancers were reported from the spraying of

arsenic-based aerosols in French vineyards (Mabuchi, *et al.*, 1980).

In 1900, the Manchester beer epidemic brought the chronic toxicity of arsenic to the public eye. Although it was originally thought that beer had been made from arsenic contaminated water near Manchester, it became clear that the sulfuric acid used in making beer was supplied by a single firm and was contaminated with arsenic. In summary, there were 6000 reported cases of poisoning and a death toll of 70 (Phillips and French, 1998). Notably, a Royal Commission set up in 1901 reported on the beer epidemic (Thomson, *et al.*, 1901, 1903). This committee recommended a standard, not to be exceeded, of the maximum amounts of arsenic to be ingested. This translates to an amount of arsenic in water of 300 ppb (Gowers, 1901). Although this is higher than the present 10 ppb, it was not anticipated that anyone would drink arsenic-contaminated water continuously. This committee was chaired by Lord Kelvin (William Thomson), one of the brightest men in the 19th century. This committee was more prestigious than the more recent ones in the 20th century. In the 1920s, the discovery of arsenic as an air pollutant from smelters and subsequent demonstration of its ability to cause lung cancer strengthened the argument against the use of arsenic (Hector and Wagner, 1976). Also in the 1960s, there were reported incidents of a rare liver tumor, angiosarcoma, in farmers (Bencko and Slamova, 2007). There were also reports of an incident in Japan where incidences of cancer were above the background level, but the number was small. Nevertheless, there was still no strong action or warning from the world public health or water resource community. This myopia began to change when Tseng, *et al.* (1968) showed that in an area of Taiwan, northeast of Tainan, there were many skin cancers, accompanied by "black foot disease," identifiable by black feet – a terminal gangrene. The affected persons had been drinking from wells, some dug as early as 1913. These wells had large amounts of arsenic therein. This is perhaps the first public mention that arsenic in water supplies caused these ailments. About this time, there were problems noticed in Chile, where arsenic-laden waters from the mountains contributed to the presence of arsenic in water supplies (Borgono and Greiber, 1971). In 1982, Dr Saha

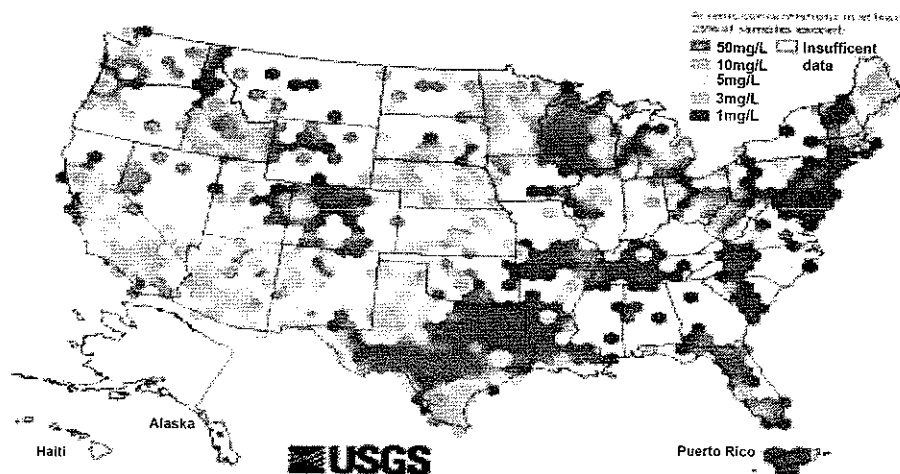


Figure 1 An equal-area map showing arsenic concentrations found in at least 25% of groundwater samples within a moving 50 km radius. (Photo courtesy of the US Geological Survey).

rampant in the 1970s, largely because of using contaminated surface waters. A simple, almost magical, solution seemed to be to install simple, cheap, tube wells to extract ground water, which was free of bacteria. The World Bank, UNICEF, and the British Geological Survey encouraged this switch to ground water but failed to insist on measurement of pollutants. Bangladesh sunk 10 million tube wells before there were serious tests for arsenic. As a result, by the year 2000, there were 60 million people in Bangladesh alone who were drinking water at levels higher than the US EPA standard and that in a tropical country where water intake is large. Many people developed dyspigmentation, keratoses, and skin cancers. If villagers walk on feet with keratoses, they develop gangrene and an amputation follows. Internal cancers, bladder, kidney, and lung are likely to develop in due course. Estimates vary, but over a million people will have adverse health symptoms before the problem is solved and between 100,000 and 1,000,000 will die (Chen and Habibul, 2004). This exceeds by over tenfold the numbers of casualties from the Chernobyl catastrophe where less than 100 died outright, and 1200 children developed thyroid cancer of which only 20 have proven fatal (Mangano, 1998). Calculations, using a linear dose-response relationship, predict that there will be 5000 fatal cancers from Chernobyl in Belarus, Ukraine and Russia and perhaps 20,000 worldwide (Bennett, *et al.*, 2006). When we add in numbers from other regions, including West Bengal, Bihar, and Nepal

to the Bangladesh totals, the comparison of catastrophes is more dramatic.

The Bangladesh catastrophe, and by extension the problem in all SE Asia and northern India, was not an example of health problems caused by mankind's historical behavior but of health problems caused by mankind's deliberate changes in behavior. It need not have happened, and one can, therefore, call it a man-made disaster as much as Chernobyl was a man-made disaster. The World Bank and UNICEF are immune to lawsuits, but some Bangladeshis sued the UK National Environment Research Council, parent of British Geological Survey, but lost on jurisdictional issues in the UK House of Lords (Sutradhar, appellant, 2006). If blame is indeed appropriate, it should be assigned wider than the above three organizations. The world toxicological community was silent, while Bangladesh dug these wells. One of us (RW) includes himself in that category. In a scientific paper, Crouch and Wilson (1979) compared cancer in various species and noticed that arsenic was an anomaly but only alerted the few readers of the paper. To their credit, the World Bank, UNICEF, and the British Government have since reacted positively to requests for help.

The world response to the Bangladesh catastrophe

Although the first arsenic-caused skin problems in Bangladesh were diagnosed in 1995 (Das, *et al.*, 1995), it is convenient to consider the first of three

International Conferences and subsequent smaller ones, on arsenic, held jointly by the Dhaka Community Hospital (DCH) and School of Environmental Sciences (SOES), Jadavpur University, Kolkata, in February 1998, as a turning point in public attention to the arsenic problem. The 200 participants saw over 165 victims of chronic arsenic poisoning (examples in Figure 2). This number is more than most US dermatologists seen in a lifetime. Most of the participants added an emotional, "we must do something," to their intellectual curiosity.

Work began on three fronts simultaneously. Finding the reasons why arsenic gets into the water with the hope of helping searches for arsenic-free water, finding exactly what chronic arsenic poisoning does to humans, and immediate help to the 50–80 million people drinking arsenic-laden water. This report follows these three lines. Nine years later, progress has been discouragingly slow, particularly in the last of these – immediate help to the villagers. In other places, one of us (RW) and others have discussed the progress, the obstacles, and suggestions for the future (Wilson, 2007).

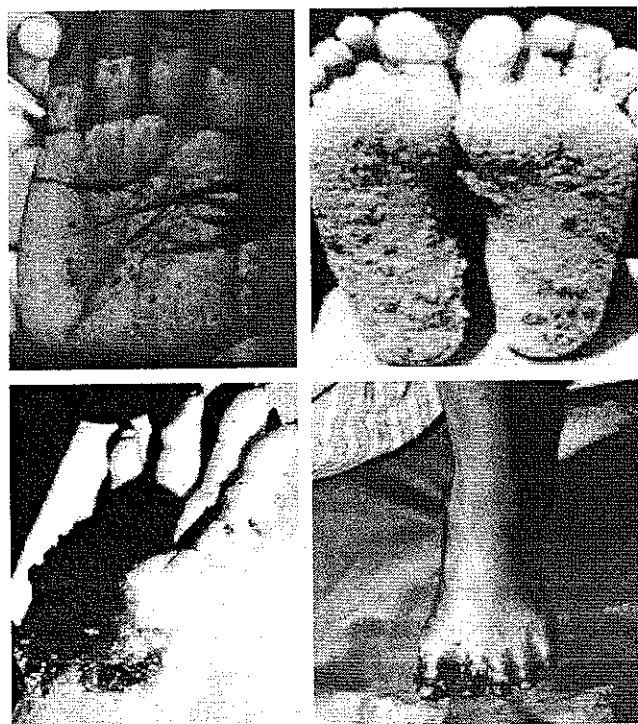


Figure 2 Examples of four dramatically visible problems caused by arsenic pollution: dyspigmentation, keratosis, gangrene, and skin cancer.

How does the arsenic get into the water? The reduction hypothesis

Before 1998, few people, in any country, discussed how arsenic appeared in the water. In 1998, two alternate hypotheses were being suggested for Bangladesh: the oxidation hypothesis and the reduction hypothesis. In the oxidation hypothesis, lowering of the water in the relevant aquifer by continuous pumping was presumed to lay bare iron arsenide and allow the oxidation of iron and subsequent release of arsenic. A modified proposal that the lowering was caused by the barrage across the Ganges River has particular difficulty because the relevant aquifer is fed by rainfall not by the river level (Harvey, *et al.*, 2005). The reduction hypothesis is now considered the correct one for Bangladesh. McArthur (2007) stated "It becomes increasingly clear that severe arsenic pollution of ground water in most alluvial aquifers worldwide is driven by the microbiologically-mediated metabolism of organic matter, with FeOOH acting as the source of oxygen: the oxide is reduced during the process and its sorbed arsenic is released to ground water. Despite the widespread acceptance of this mechanism, much about it remains obscure." See also Muller *et al.* (2007).

How does the arsenic get into the water? The oxidation procedure

All down the spine of western America, from Canada to Chile, lie many volcanos and volcanic lakes that are sources of arsenic. Indeed, one of the major epidemiological studies that show that arsenic ingestion causes cancer is from such an area in Chile. These volcanic lakes are only now being properly investigated. Here an oxidation process occurs. Ravenscroft (2007) and Amini, *et al.* (2008) have presented world maps showing which explanation is applicable to which region. See also the maps on our website Arsenic Project Maps (2007).

Getting pure water to the people

When the governments of Chile and Taiwan realized that arsenic in ground water was a major health problem, they promptly assured alternative water supplies. However, the problem in south-east

Asia and Indian continent is so massive, and the countries concerned sufficiently poor, that progress has been slow, and assistance from the rest of the world is necessary. The DCH and others began a "Rapid Action" survey of selected villages in Bangladesh in 1998. However, a complete survey took a few years. The wells were painted either green (for safe) or red (for not to use). Nevertheless, the villagers have not always heeded these warnings. Some estimates are that only 30% of villagers have switched wells. Although this fraction is not high enough, 20 million villagers now have pure water instead of the impure water they drank before. In the Ariahazar Upazilla, Columbia University researchers report the fraction rose to 60%. Therefore, the most important remediation effort that authorities could undertake immediately is a massive education programme: particularly among the women in the villages.

In 1998, it was already known that many communities in southern Bangladesh and Dhaka itself obtained their water from deep tube wells, which tap an aquifer below a clay layer where the water chemistry was such that the arsenic in the solid phase was not made available in the water. However, this has been slow. The Bangladesh Department of Public Health Engineering produced an excellent detailed report (Ahmed, *et al.*, 2006), discussing 80,000 new deep tube wells that goes a long way toward addressing concerns of the doubtful. Filtration and removal of arsenic at a household level was expected to be a temporary help. Initially, many inadequate units were installed and abandoned, but in January 2007, the US National Academy of Engineering awarded Dr Abul Hasam of George Mason University in the United States the Grainger prize for the development of the successful SONO filter (Khan, *et al.*, 2000), manufactured in Kushtia by his brother Abul Munir. A second silver prize of \$200,000 went to Sengupta (Sarkar, *et al.*, 2006) of Lehigh University in the United States whose filters are being made by a relative in West Bengal. This suggests to us that help from overseas is most effective when accompanied by a local backup group.

The Bangladesh national policy, promulgated in 2004, set a preference for a return to surface waters. Alas, most Bangladeshis ignored the success of the rest of the world in chlorination of water to prevent

disease (Okun, 1996). Moreover, the guidelines for chlorination were not clear (WHO, 2004). However, starting in early 2006, detailed measurements were made by DCH (Yousef, *et al.*, 2007). High levels of bacteria were found in wells, particularly in the monsoon period when the filtering effect of the soil is reduced. In 2006, chlorination using US EPA recommended amounts brings the coliform bacteria levels down to reasonable levels, but they rise again rapidly after 20 days. In 2007, the monsoon flooding was worse, and bacteria levels rose after a week. They recommend adding chlorine at least every 2 weeks and more if flooding is severe.

Long-term future

There are several long-term issues that must be faced. In the developed world, information about arsenic is rapidly becoming available, and the issues are likely to be faced immediately. But more issues arise in the developing world, which must not be ignored.

Agriculture and long-term fate

All countries should be concerned about the use of arsenic-laden irrigation water for agriculture. In the United States, arsenic was used as a herbicide until about 1970 when it was replaced by the more effective chlorinated hydrocarbons. In 1970, the United States imported 10,000 tons of arsenic a year, added perhaps as much from domestic sources, sprayed it on American crops, and forgot about it. Not only did the arsenic get into the food, some inevitably ended up in water supplies, although the extent to which it flowed out to sea or bound to the soil is still not clear. Currently, American chicken farmers use arsenic as a growth enhancer in chicken feed with little or no regard for inevitable waste problems (Burros, 2006).

Already there are indications that the uptake by rice and subsequent ingestion by people in Bangladesh is equivalent to about 15 $\mu\text{g/L}$ (15 ppb) in the water (Williams, *et al.*, 2006). Here also the long-term fate of arsenic is unknown. Does arsenic bind itself to the surface? Do rivers wash it out to sea (to concentrate in shellfish)? Much of the environmental movement in the world has been concerned about the long-term fate of high-level nuclear waste because it remains carcinogenic for thousands of years. However, arsenic lasts forever (Wilson, 2003).

Measurement

Measurement is crucially important and is taken for granted in developed countries. For centuries, countries have emphasized the importance of weights and measures. In 2002, measurement problems became evident in Bangladesh. Even a comparison of laboratory equipment for measuring arsenic showed appalling reliability. This had improved by 2004, but the field test equipment, while adequate on average, may still leave a lot to be desired. WHO (2007) noted "Accurate measurement of arsenic in drinking-water at levels relevant to health requires laboratory analysis using sophisticated and expensive technique, facilities as well as trained staff not easily available or affordable in many parts of the world. Analytical quality control and external validation remain problematic. Field test kits can detect high levels of arsenic but are typically unreliable at lower concentrations of concern for human health. Reliability of field methods is yet to be fully evaluated." Kosmos (1998) developed a digital device, the "Arsenator" to reduce the subjectivity in observing the color changes, but for reasons unclear to us has not achieved wide acceptance.

Measurement of *arsenic concentrations* is only one of the widespread measurement problems. A failure to measure *bacteria levels* reliably is equally troubling and tends to inhibit a return to use of surface waters.

Communication

In the developed world, good communication about successes and, even more important, about failures is taken for granted. For example in the United States, there are excellent websites by US EPA and the US Geological Survey. However, in developing countries, good communication is rare. On January 7, 1998, the "Arsenic Crisis Information Centre" (Bennett, 1998) site appeared but has not been updated since 2003. It was followed by an informal discussion group (Arsenic Crisis, 2003). Our site, the arsenic project website (Wilson and Sambu, 2007), appeared in summer 1998, others from the School of Environmental Sciences (SOES, 2007) in Kolkata, India, Columbia University, Sanbre and SOES (Columbia, 2007), London Arsenic Group (2007), Japan (SOS, 2007), and

other overseas NGOs. The Bangladeshi government websites have been more confusing. The Bangladesh Water Supply Program Project (BWSPP, 2006) has taken over the functions of the Arsenic Policy Support Unit and the National Arsenic Mitigation Information Centre (NAMIC). Important files have been picked up by Buet (2008). It is indicative of the inattention of the world that a simple Google of NAMIC in 2008 comes up with three organizations but not the one in Bangladesh.

Future arsenic concentrations

Once arsenic has been measured in a developed country, action is simple and affordable. For the most part, surface water will continue to be used with chlorination. In the central valley of California, many town wells had been used with arsenic levels of well over 50 ppb. Now that arsenic as a pollutant is understood and measured, it is only a small expense to measure the new arsenic at different levels and to pump only from these arsenic free levels to a tank to supply the city's water supply (Guilbert, 2007). As Guilbert described this at the American Geological Society (AGS) Denver meeting, he used a throw away phrase that should be noted by third world countries, *after chlorination*.

In developing countries, action is slower. But in 50 years, we speculate that most of Bangladesh will have water from a central facility. Probably, in most cases, from a deep aquifer. But in parts of the world, there is no safe deep aquifer (Sracek, 2007), and the use of surface wells have to continue. The DCH (Bangladesh) and West Bengal experience with chlorination will be an important path to follow. However, even those who are most optimistic about the ability of a deep aquifer to supply drinking water to all the people argue that the use of the deep aquifer for agriculture, for which less bacteriologically pure surface waters may suffice, should be discouraged and probably forbidden. As in many other countries, agriculture can use 100 times as much as water as is used domestically.

Running water to the kitchens

The fact that most of Bangladesh villages have electricity leads to another suggestion. Affected communities could pump water into an overhead tank whence it can gravitationally flow to water taps

throughout the village by simple PVC piping. This has been implemented by DCH, using improved dug wells as the source of water, and has proved very popular, particularly among village women whose historical role has been to carry water. The popularity of this system among the villagers is evident, especially, among the women of the villages who are the traditional carriers of water. Ahmad and Misra (2005) have shown that villagers are prepared to pay more for running water than they are for arsenic-free water. The Bangladesh Water Supply Program Project, using deep tube wells as the water source, is installing piped water for 300 villages.

Potential other catastrophes

We must always wonder whether another public health catastrophe is waiting "in the wings." It is, therefore, important to reexamine the history of how we got to where we are to ensure that the world does not make the mistakes again. This is hardest of all the steps to take, and the authors hope that this brief history will stimulate a little thought in that direction.

Acknowledgments

The authors in preparing the arsenic website have had submissions from dozens of scientists throughout the world. They have had discussions in numerous meetings with scientists and others. To these dozens of people, too numerous to name individually, we give our thanks.

References

- Ahmad, BG, Misra, S (2005) Value of arsenic-free drinking water to rural households in Bangladesh. *J Environ Manage* 74: 173–178.
- Ahmed, KM, *et al.* (2006) Final report of Deep Aquifer Data Base and Preliminary Deep Aquifer Map Bangladesh Department of Environmental Health Engineering. Available at: http://physics.harvard.edu/~wilson/arsenic/remediation/GoB_Deep_aquifer_Report2006.pdf.
- Amini, M, Abbaspour, KC, Berg, M, Winkel, L, Hug, SJ, Hoehn, E, *et al.* (2008) Statistical modeling of global geogenic arsenic contamination in groundwater. *ASAP Environ Sci Technol* 42: 3669–3675. ASAP Article, 10.1021/es702859e.
- Arsenic Project Maps (2007) Available at: http://physics.harvard.edu/~wilson/arsenic/countries/bangladesh/arsenic_project_maps.html (accessed 27.09.2007).
- Arsenic crisis (2003) <http://tech.groups.yahoo.com/group/arsenic-crisis/>
- ATSDR (2007) Agency for Toxic Substances and Disease Registry.
- Bangladesh Water Supply Project, BAWSP (2006) <http://www.bwspp.org>, last visited 05/05/2008.
- Bencko, V, Slámová, A (2007) Best practices for promoting farmers' health: the case of arsenic history. *J Public Health (Bangkok)* 15: 279–288.
- Bennett, B, Carr, Z, Raapacholi, M (eds) (2006) Health Effects of the Chernobyl Accident and special Health Programs, report of the UN Chernobyl Forum, Expert Group "Health". Geneva: World Health Organization.
- Bennett, S (1998) Arsenic Crisis Information Center. <http://www.bicn.com/acis>, last visited 06/11/2006.
- Bentley, RR, Chasteen, TG (2002) Arsenic curiosa and humanity. *Chem Educator* 7: 51–60.
- Borgono, JM, Greiber, R (1971) Epidemiological study of arsenicism in the city of Antofagasta. *Rev Med Chil* 99: 702–707.
- Buet (2008) Bangladesh University for Engineering Technology: <http://www.buet.ac.bd/itm/> Accessed 10/17/2008.
- Burros, M (2006) Chicken with Arsenic? Is that OK? The New York Times, April 5 2006.
- Chakraborti, AK, Saha, KC (1987) Arsenic dermatoses from tube well water in West Bengal. *Indian J Med Res* 85: 326–334.
- Chen, CJ, Chuang, YC, You, SL, Lin, TM, Wu, HY (1986) A retrospective study on malignant neoplasms of bladder, lung and liver in black foot disease endemic area in Taiwan. *Br J Cancer* 53: 399–405.
- Chen, Y, Habibur, A (2004) Cancer burden from arsenic in drinking water in Bangladesh. *Am J Public Health* 94: 741–744.
- Columbia (2007) <http://superfund.ciesin.columbia.edu/home.html>.
- Crouch, E, Wilson, R (1979) Interspecies comparison of carcinogenic potency. *J Toxicol Environ Health* 5: 1095–1118.
- Crump, KS, Hoel, DG, Langley, CH, Peto, R (1976) Fundamental carcinogenic processes and their implications for low-dose risk assessment. *Cancer Res* 36: 2973–2979.
- Csalagovits, I (1994) Arsenic-Bearing Artesian Waters Of Hungary. Budapest: Geological Institute of Hungary.
- Das, D, Chatterjee, A, Mandal, B, Samanta, G, Chanda, B, Chakraborti, D DCH (1999) Conferences, report submitted to *Environmental Safety and Health* 2007.
- Das, D, Samanta, G, Mandal, BK, Chowdhury, TR, Chanda, CR, Chowdhury, PP, Basu, GK, Chakraborti, D (1995) Arsenic in ground water in six districts of West Bengal, India: the biggest arsenic calamity in the world in Part 2 Arsenic concentration in drinking water, hair, nails, urine, skin-scale and liver tissue (biopsy) of the affected people. *Analyst* 120: 917–924.
- Doll, Sir Richard (1992) Private communication to Richard Wilson.

- Ferreccio, C, Gonzalez, C, Milosavljevic, V, Marshall, G, Sancha, AM, Smith, AH (1998) Lung cancer and arsenic exposure in drinking water: a case-control study in northern Chile. *Cad Saude Publica* 14(Suppl. 3): 193-198.
- Gowers, WR (1901) Epidemic of arsenical poisoning in beer-drinkers in the north of England during the year 1900. *Roy Med Chir Lancet* i: 98-100.
- Guylaine Alain, MD, Jacqueline Tousignant, MD, FRCPC, Eva Rozenfarb, MD, FRCPC (1993) Chronic Arsenic Toxicity International Journal of Dermatology 32(12): 899-901.
- Guilbert, ME (2007) Well design criteria providing reduced concentrations of geogenic arsenic and uranium. Geological society of America, Annual meeting, paper abstract 222-13. (http://gsa.confex.com/gsa/2007AM/finalprogram/abstract_122447.htm).
- Harvey, CF, Swartz, CH, Badruzzman, B, Keon, NE, Yu, W, Ali, A, et al. (2005) Groundwater arsenic contamination on the Ganges delta: biogeochemistry, hydrology, human perturbations, and human suffering on a large scale. *Comptes-Rendus. Geoscience* 337: 285-296.
- Héctor, PB, Wagner, W (1976) Case study 4: inorganic arsenic—ambient level approach to the control of occupational carcinogenic exposures. *Ann N Y Acad Sci* 271: 179-186.
- Hutchinson, J (1888) On some examples of arsenic-keratosis of the skin and of arsenic-cancer. *Trans Pathol Soc London* 39: 352-363.
- Kosmos, W (1998) The evaluation of the arsenator, Report by Department of Analytical Chemistry, the Arsenic Crisis Information Center. Austria: Graz University.
- Kwong, ML, Todd, D (1997) Delicious Poison: arsenic trioxide for the treatment of leukemia. *Blood* 89: 3487-3488.
- Khan, AH, Rasul, SB, Munir, AKM, Habibuddowla, M, Alauddin, M, Newaz, SS, et al. (2000) Appraisal of a simple arsenic removal method for groundwater of Bangladesh. *J Environ Sci Health* 35: 1021-1041.
- Lamm, SH, Engel, A, Kruse, MB, Feinleib, M, Byrd, DM, Lai, S, et al. (2004) Arsenic in drinking water and bladder cancer mortality in the USA. An analysis based on 133 US counties and thirty years of experience. *J Occup Environ Med* 46: 298-306.
- London Arsenic Group (2007) <http://www.es.ucl.ac.uk/research/lag/as/index.htm>, last visited 05/05/2008.
- Mabuchi, K, Lilienfeld, AM, Snell, LM (1980) Cancer and occupational exposure to arsenic: a study of pesticide workers. *Prev Med* 9: 51-77.
- Mangano, JJ (1998) Low-Level Radiation and Immune System Damage: An Atomic Era Legacy. CRC Press/Lewis.
- Meharg, A (2005) Venomous Earth: How Arsenic Caused the World's Worst Mass Poisoning. New York, NY: Macmillan.
- Muller, D, Médigue, C, Koechler, S, Barbe, V, Barakat, M, Talla, E, et al. (2007) A tale of two oxidation states: Bacterial colonization of arsenic-rich environments. *PLoS Genet* 3: e53 10.1371/journal.pgen.0030053.
- Novick, SC, Warrell Jr, RP (2000) Arsenicals in hematologic cancers. *Semin Oncol* 27: 495-501.
- Okun, DA (1996) From cholera to cancer to cryptosporidiosis. *J Environ Eng* 122: 453-458.
- Partington, JR (1935) Origins and Development of Applied Chemistry. London: Longmans, Green & Co.
- Phillips, J, French, M (1998) The pure beer campaign and arsenic poisoning, 1896-1903. *Rural Hist* 9: 195-209.
- Ravenscroft, P (2007) Predicting the Global Distribution of Arsenic Pollution in Groundwater, Royal Geographical Society Annual International Conference, Department of Geography, Cambridge University, http://phys4.harvard.edu/~wilson/arsenic/conferences/2007_RGS/S1.2_P_Ravenscroft.pdf
- Saha, KC (2007) Bitter experience in the discovery of arsenicosis in West Bengal, India. Accepted for arsenic special Issue Environmental Science and Health but not published for reasons not stated. Available at: <http://physics.harvard.edu/~wilson/arsenic/references/Commentary.rtf> accessed 05/05/2008
- Sarkar, S, Gupta, A, Biswas, RK, Deb, AK, Greenleaf, JE, SenGupta, AK (2006) Well-head arsenic removal units in remote villages of Indian subcontinent: field results and performance evaluation. *Water Res* 39: 2196-2206.
- Sayers, D (1978) Strong Poison. Harper (reprint of 1933 book) New York: Grand Pub.
- Shrivastava, R, Delomenie, C, Chevalier, A, John, G, Ekwall, B, Walum, E, Massingham, R (1992) Comparison of in vivo acute lethal potency and in vitro cytotoxicity of 48 chemicals. *Cell Biol Toxicol* 8: 157-170.
- Smith, AH, Hopenhayn-Rich, C, Bates, MN, Goeden, HM, Hertz-Picciotto, I, Duggan, HM, et al. (1992) Cancer risks from arsenic in drinking water. *Environ Health Perspect* 97: 259-267.
- Smith, AH, Lopipero, PA, Bates, MN, Steinmaus, CM (2002) Arsenic epidemiology and drinking water standards. *Science* 296: 2145-2146.
- SOS Japan (2007) <http://www.sos-arsenic.net>, last visited 05/05/2008.
- Sracek, O (2007) Presented to the Royal Geographical Society Annual Conference. Available at: http://physics.harvard.edu/~wilson/arsenic/conferences/2007_RGS/S3.3%20O%20Sracek.pdf, last visited 05/05/2008.
- Sutradhar (FC) (Appellant) v. Natural Environment Research Council (Respondents) v (2006) Judgement by UK HOUSE OF LORDS, SESSION 2005-06 UKHL 33.
- Thomson, W, et al. (1901) First Report of the Royal Commission to inquire into Arsenical Poisoning from the consumption of beer and other articles of food and drink. London: Her Majesty's Stationary Office.
- Thomson, W, et al. (1903) Royal Commission Appointed to Inquire into Arsenical Poisoning from the consumption of beer and other articles of food or drink, Final report Part I. London, England: Wyman and Sons.
- Tseng, WP, Chou, HM, How, SW, Fong, JM, Lin, CS, Yeh, S (1968) Prevalence of skin cancer in an endemic area of chronic arsenicism in Taiwan. *J Natl Cancer Inst* 40: 453-463.

- USGS (2001) Workshop on Arsenic in the Environment, February 21-22, Denver, CO. Abstracts available at the USGS website at: USGS Workshop on Arsenic in the Environment. February 21-22, 2001, Denver, CO. Extended Abstracts at: http://wwwbrr.cr.usgs.gov/projects/GWC_chemtherm/Arsenic/finalabstracts.htm, last visited 05/05/2008.
- Water News, US (2001) New arsenic study puts pressure on EPA, US Water News, October 2001. <http://www.uswaternews.com/archives/arcquality/1newars10.html>, last visited 09/22/2008.
- Welch, AH, Westjohn, DB, Helsel, DR, Wanty, RB (2000) Arsenic in ground water of the United States- occurrence and geochemistry. *Ground Water* 38: 589-604.
- WHO (2004) Guidelines for Drinking Water Quality. Geneva: World Health Organization. Available at: http://www.who.int/water_sanitation_health/dwq/gdwq3rev/en/index.html, last visited 05/05/2008.
- WHO (2007) Arsenic in Drinking Water, Fact Sheet. Geneva: World Health Organization Available at: <http://www.who.int/mediacentre/factsheets/fs210/en/>, last visited 05/05/2008.
- Williams, PN, Islam, MR, Adomako, EE, Raab, A, Hossain, SA, Zhu, YG, *et al.* (2006) Increase in rice grain arsenic for regions of Bangladesh irrigating paddies with elevated arsenic in ground waters. *Environ Sci Technol* 40: 4903-4908.
- Wilson, R (2003) Underestimating arsenic's risk. *Regulation* 24: 50-53.
- Wilson, R, Sambu, S (2007) Chronic Arsenic Poisoning: History, Study and Remediation, <http://physics.harvard.edu/wilson/arsenicproject/introduction.html> Or <http://arsenic.ws>, last visited 05/05/2008.
- Wilson, R (2007) The Bangladesh Arsenic Catastrophe: One view from Overseas Accepted for arsenic special issue but not published in Journal of Environmental Science and Engineering, for reasons unstated available at <http://physics.harvard.edu/~wilson/arsenic/references/pp890.doc> last visited 05/05/2008.