

Arsenic trioxide versus tetraarsenic oxide in biomedical research: misunderstandings and misinterpretations

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Abstract This work presents an analytical chemist's view on the sometimes unconscious use of arsenic trioxide in (bio)medical research. Arsenic trioxide is a frequently used chemical in cancer treatment research and its action to various malignant cells has been extensively studied and published. Unfortunately some research articles show trivial errors with regards to background knowledge of the chemical, handling the chemical, experimental design and interpretation of results like e.g. in a range of articles comparing advantages of tetraarsenic oxide over arsenic trioxide (dimeric/monomeric) although the dissolution of both yields the same active compound (HAsO_2). To fully understand the implications of these errors we will highlight some of them with the intent to harmonize future work in this field.

Keywords As_2O_3 · As_4O_6 · Tetras · Concentration units · Redox conversion · Cell cultures

Background

Mineral arsenicals have been used in traditional medicine for thousands of years and in some cases they are also the best choice available in modern days (Liu et al. 2008). After the first description and explanation of the effect of arsenic trioxide on the treatment of acute promyelocytic leukemia (APL) by Chen et al. (1996), the number of research articles on the subject increased exponentially (1,700 in total to date). The American Food and Drug Administration approved in September 2000 the use of TRISENOX[®] (Cell Therapeutics, USA), a sterile injectable solution of arsenic trioxide, for treatment of APL (Trisenox 2000). The molecular formula of the drug substance in the solid state is As_2O_3 (molecular weight of $197.84 \text{ g mol}^{-1}$) and at present contains a concentration of 1.0 mg ml^{-1} in 10 ml ampoules for single use. Inactive ingredients are sodium hydroxide (1.2 mg ml^{-1}), which is added to increase the solubility of As_2O_3 (poorly soluble in pure water) and hydrochloric acid, which is used to adjust the pH to 7.5–8.5.

Arsenic trioxide is a white solid compound existing in two forms, arsenolite (cubic crystal structure) and claudetite (monoclinic crystal structure) (Wiberg et al. 2001; Henke and Hutchison 2009). Under normal conditions (room temperature and atmospheric pressure) solid arsenic trioxide is present in the form of As_4O_6 (dimeric As_2O_3 , sometimes named tetraarsenic oxide) and only above

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800°C dissociates into monomeric As_2O_3 . Upon dissolution of arsenic trioxide in aqueous media (like e.g. in the case of TRISENOX[®]) both As_2O_3 and As_4O_6 are converted into the same arsenic species, HAsO_2 and/or AsO_2^- , depending on the pH.

Besides use of arsenic trioxide in medical treatment it is also used in metabolic studies (determination of arsenic metabolites in body fluids and tissues of patients treated with arsenic trioxide) and biomedical/genetic studies (unravelling of mechanisms related to arsenic in target cells/organs, mostly conducted on cell cultures). Although valuable research data have been obtained we feel that a more insightful approach might even further advance the (bio)medical research field, especially with regards to setting up and evaluating experiments from an analytical chemistry perspective. Below some commonly made misunderstanding and misinterpretation mistakes are given to illustrate the need to refine the way of working.

Misunderstandings and misinterpretations

Definition of concentrations

In many papers concentration units are poorly defined and often various units are used in one and the same paper with more interpretations possible. An example is given to illustrate this problem: Shen et al. (1997) dissolved arsenic trioxide to prepare a solution containing $1 \text{ mg ml}^{-1} \text{As}_2\text{O}_3$ (supposedly containing $0.758 \text{ mg ml}^{-1} \text{As}$) and presented the same experimental data in graph and table form, with concentration units in $\mu\text{mol l}^{-1} \text{As}$ and $\mu\text{mol l}^{-1} \text{As}_2\text{O}_3$, respectively, implying an arsenic concentration difference of a factor two. Although the research yielded very interesting results, the unfortunate mishmash of units frustrates the reader and potentially leads to mistakes in follow-up research by other research groups. To make the relationships between the various units unambiguous, in Fig. 1 the $\mu\text{mol l}^{-1} \leftrightarrow \mu\text{g l}^{-1}$ conversions for As_2O_3 and As_4O_6 are given.

A special case of this concentration unit confusion can be found in some articles on the advantage of tetras (tetraarsenic oxide, As_4O_6) over arsenic trioxide (As_2O_3) (e.g. Park et al. 2003, 2009; Woo et al. 2005). Not surprisingly, tetraarsenic oxide was found to be more effective than arsenic trioxide when the

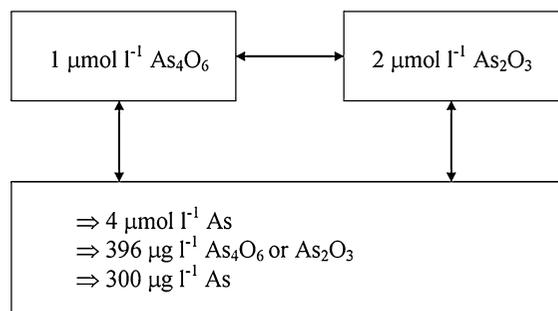


Fig. 1 Conversion of concentration units ($\mu\text{mol l}^{-1} \leftrightarrow \mu\text{g l}^{-1}$) for As_2O_3 and As_4O_6

same concentrations, expressed in $\mu\text{mol l}^{-1}$, were used (again implying a factor of 2 difference concentration of arsenic). However, this “novel” arsenic compound for anticancer intervention must be regarded as a misunderstanding as in dissolved form tetras and arsenic trioxide are one and the same arsenic species. Unfortunately, some reviews (e.g. Wondrak 2009) have proclaimed tetraarsenic oxide to be an alternative for arsenic trioxide and a patent appeared on the subject as well (Bae et al. 2003). Speculation on the different behaviour of the “two compounds” (Kim et al. 2005; Chang et al. 2007) must be taken with a grain of salt and are probably associated with concentration unit confusion as described above or other imperfections in experimental design. Such problems are not limited to the arsenic field only as Filella and Williams (2010) identified similar issues for studies on antimony in cell culture media.

Redox conversion

Another topic which is almost never touched in medical research (especially in cell cultures studies) is the possibility of redox conversion between arsenic species (Bertolero et al. 1987; Zelenik et al. 2010). Besides the occurrence of HAsO_2 and AsO_2^- (commonly named arsenite or trivalent arsenic) unwanted pentavalent arsenic species (H_3AsO_4 , H_2AsO_4^- , HAsO_4^{2-} and AsO_4^{3-} , commonly named arsenate or pentavalent arsenic) might be generated as a result of redox conversion (see Fig. 2). The possibility of this redox conversion occurring depends on the pH and the so-called reduction potential Eh of the solution, as defined by the composition of the solution and its redox chemistry. Whether or not this

actually happens in practice depends also on the kinetics of the processes involved and thus the timescale of the experiment.

Different cell culture growth media should have rather uniform pH (optimally 7.4) and Eh (optimally

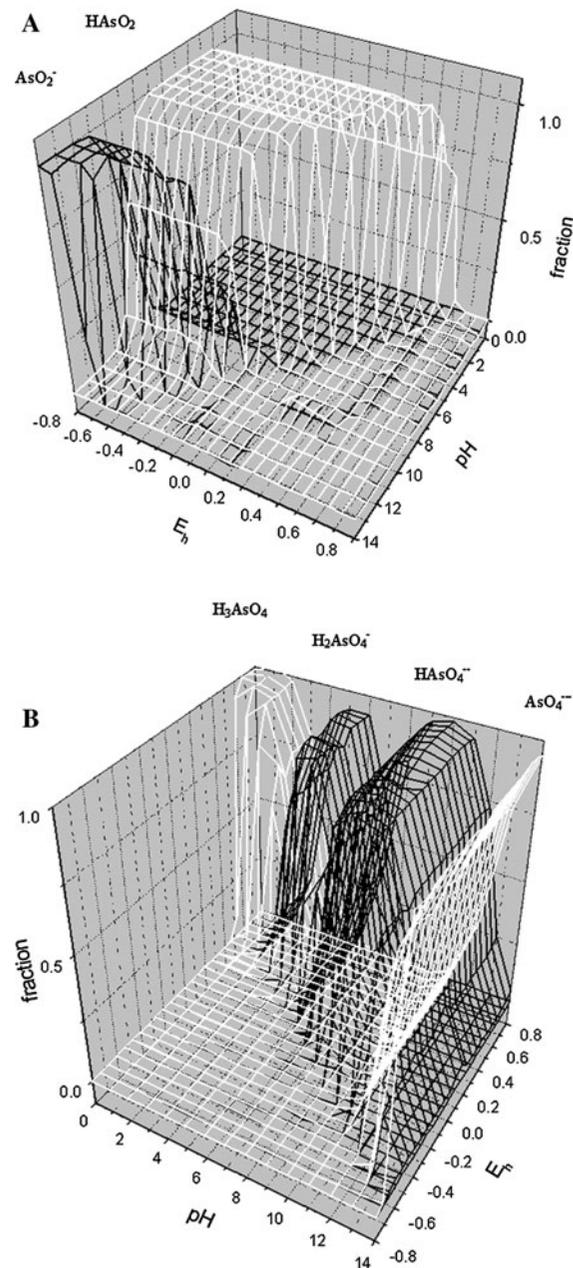


Fig. 2 Equilibrium arsenite species (a) and arsenate species (b) species distribution according to the thermodynamic equilibria given in the text. It should be noted that for better visualization the orientation of Figures a and b is different; the pH-Eh planes are rotated for 90°

ca. +75 mV for many cell lines) values (Griffiths 2000), although Eh values can vary considerably even when tried to be kept constant (Meneses et al. 2000). Redox potential is not only affected by oxygen, pH and medium composition, but to a significant extent also by the rate of generation of reductants by cells (Pluschkell and Flickinger 1995–96). Under the optimal conditions for cell culture growth mentioned above it can be calculated (Van Elteren et al. 2002) that upon spiking the culture with arsenite the thermodynamic equilibrium distribution of arsenic species is as follows: 0.3% HAsO_2 , 41.9% H_2AsO_4^- and 57.8% HAsO_4^{2-} (i.e., 0.3% trivalent As and 99.7% pentavalent As). However, this is a distribution pattern at equilibrium; since the kinetic parameters are unknown the actual rate towards equilibrium is unpredictable. Small deviations from ideal growth conditions might result in prevailing trivalent arsenic species at lower Eh and pentavalent arsenic species at higher Eh. Cells on their own have a broad range of Eh values from ≈ -240 mV (in proliferation) to ≈ -170 mV (in apoptosis) (Schafer and Buettner 2001) and as such provide more chances for arsenic to stay in trivalent form. Toxicities of tri- and pentavalent arsenic species are notably different, as are their mechanisms of uptake and action in human cells.

The integrity of arsenite in stock and working solutions has to be controlled regularly since redox conversion is possible in these solutions as well. Oxidation of arsenite to arsenate in stock solution (mg ml^{-1} range) is neither very common nor very fast although it can happen, but oxidation of arsenite in working solutions ($\mu\text{g ml}^{-1}$ range) and final diluted solutions (ng ml^{-1} range) might be (very) fast (in the order of days).

Precision in conducting of experiments

Laboratory work requires a high level of awareness and accuracy, especially when preparing stock solutions and standards, in this case of arsenic trioxide. Real-life experiences from working with students showed us that preparation of a defined concentration of arsenite in solution was sometimes off more than 20% when compared to an arsenite reference standard. Since weighing is a very precise operation reasons might be found in the use of damp hygroscopic As_2O_3 as a starting compound or incomplete

dissolution of arsenic trioxide. It should be highlighted that dissolution in a simple buffer might not yield the expected dissolved concentration as arsenic trioxide is sparingly and extremely slowly soluble in cold water (O'Neil 2006). Much larger errors in arsenic concentrations were found in final cell culture media with deviations up to 50% from the nominal value. Imprecise micropipetting of tiny amounts of arsenic stock solution was found as a reason for this error. Micropipettes can be extremely accurate but need to be checked and calibrated on a regular basis.

Conclusions

Misunderstandings and misinterpretations on the use of arsenic trioxide in (bio)medical research have been highlighted from an analytical chemist's point of view with the intention to come to a more conscious use of this chemical and interpretation of the experimental data obtained.

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