Analysis of Haloacetic Acids in Drinking Water using Electrospray Ionization – High Field Asymmetric Waveform Ion Mobility Spectrometry – Mass Spectrometry

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Introduction

We have shown in preliminary experiments that a new analytical technique that combines direct injection electrospray ionization mass spectrometry with ion separation based on gas-phase ion mobility in an electric field (ESI-FAIMS-MS) can provide extremely rapid and sensitive quantitative determination of polar organic compounds, such as haloacetic acids (HAAs), in drinking water. HAAs are one class of compounds that can be formed as disinfection by-products (DBPs) during the drinking water chlorination. New rules for the regulation of DBPs in treated drinking waters have recently been introduced (EPA 1998) in which the MCL for the sum of five HAAs (monobromo-, monochloro-, dibromo-, dichloro-, and trichloroacetic acid) is set at 60μg/L. EPA methods 552.1 (1992) and 552.2 (1995) and Standard Method 6251B (1995) are the primary methods of HAA analysis in drinking water. These methods use solvent extraction, derivatization and GC-ECD or GC-MS detection. The procedure is time consuming and labor intensive, due to the extraction and derivatization steps, and the standard GC analysis run is >45 minutes per sample. Electrospray ionization (ESI) has been shown in recent literature to allow for the direct determination of HAAs in both water and plasma samples (Hashimoto and Otsuki 1998; Brashear et al. 1997), as well as larger polar DBPs (Richardson et al. 1999). While ESI analysis is considered feasible, it is not practical because of the intense background of solvent- and salt-related ions produced by the ionization technique, which interfere with the detection of the compound of interest. Tandem MS has also been used to eliminate the effect of the high background, with Brashear et al.(1997) reporting detection limits at low ppb levels for the chloro-substituted HAAs in plasma.

ESI-FAIMS-MS

High field asymmetric waveform ion mobility spectrometry (FAIMS) is a continuous flow device that separates ions at atmospheric pressure and room temperature [Figure 1] (Purves et al. 1998, Guevremont and Purves 1999). By passing electrospray-generated ions through FAIMS, the mixture of ions that is presented to the entrance of the mass spectrometer can be greatly simplified. The technique can remove the complex continuum of electrospray background ions, which typically limits the lower levels of detection of small ions (below m/z 200), and the detection limit for these ions can be improved by over a factor of 100.

FAIMS is based on the change of ion mobility at high electric fields. At electric fields above 10000 V/cm, the ion drift velocity is no longer directly proportional to the applied field. The ion mobility, K, becomes dependent on the applied electric field (Mason and McDaniel 1988; Eiceman and Karpas 1994) and is better represented by K_h, a non-constant, high field, mobility term. This dependence of K_h on the applied electric field has been the basis for the development of FAIMS (Riegner et al. 1997, 1998; Purves et al. 1998; Carnahan et al. 1996). The high field behavior of K_h is compound-dependent and makes it possible for FAIMS to separate ions. The change in mobility at high electric field appears to reflect the size of the ion, its interaction with the bath gas, and its structural rigidity.

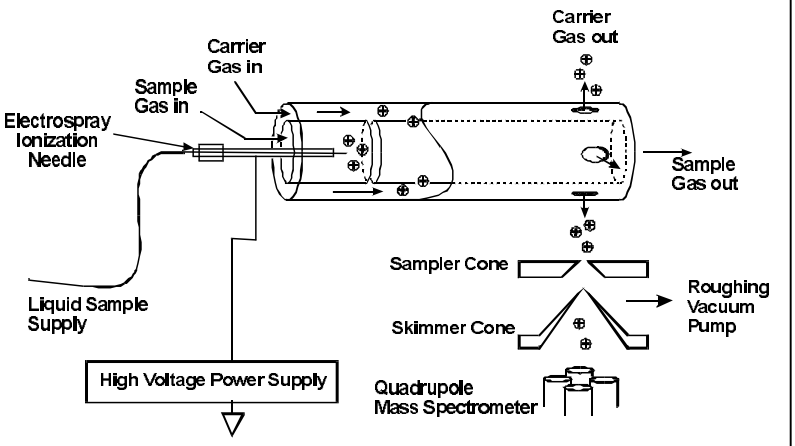

Figure 1. Schematic drawing of ESI-FAIMS-MS.

Briefly, FAIMS works as follows: An ion is carried between parallel plates. One of the plates is maintained at ground potential while the other has an asymmetric waveform, with the peak voltage defined as the dispersion voltage (DV), applied to it. If an ion is migrating away from one plate, a constant negative dc voltage, called the "compensation voltage" (CV), can be applied to this plate to reverse, or "compensate" for the offset drift. Thus, the ion will not travel toward either plate. If the ions derived from two compounds respond differently to the applied high electric field, the ratio of K_h to K is different for each compound. Consequently, the magnitude of the CV necessary to prevent ion drift toward either plate will also be different for each compound. Under conditions in which the CV is appropriate for transmission of one compound, the other will drift towards one of the plates and be lost. Hence, the FAIMS instrument is an ion filter, capable of selective transmission of only those ions with the appropriate ratio of K_h to K. To separate a mixture of ions, the CV can be scanned to yield a compensation voltage spectrum (CV spectrum). If the combination of DV and CV are appropriate, and the ions are not lost to the walls, the ions will pass out of the FAIMS analyzer through an opening and into the orifice of the mass spectrometer.

Methods

A concentrated standard haloacetic acid solution was diluted appropriately in 9:1 methanol:tap water containing 0.2 mM ammonium acetate. The separation of HAAs by varying CV , and the effect of DV is shown Figure 2. At each peak in the CV spectrum, mass spectral data can be evaluated to characterize ions that have been transmitted through the FAIMS. For subsequent HAA analysis, data were collected at a DV = -3300 V and the CV set to the optimal voltage for transmission of the desired ion.

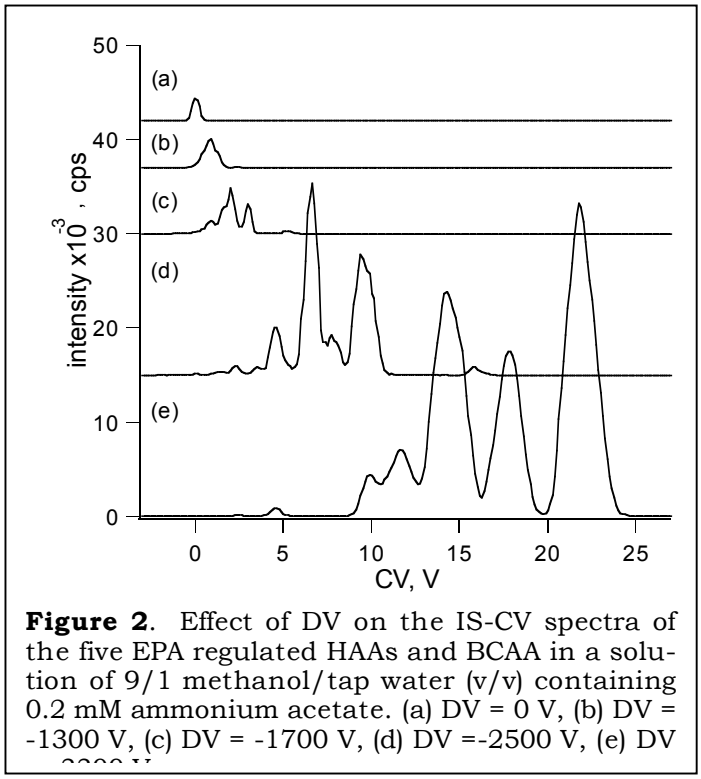

Figure 2. Effect of DV on the IS-CV spectra of the five EPA regulated HAAs and BCAA in a solution of 9/1 methanol/tap water (v/v) containing 0.2 mM ammonium acetate. (a) DV = 0 V, (b) DV = -1300 V, (c) DV = -1700 V, (d) DV =-2500 V, (e) DV

In order to evaluate the improvement in the signal to background ion intensity ratio, it is useful to compare mass spectra collected with conventional ESI-MS with those collected using the new tandem ESI-FAIMS-MS system. In Figure 3 are mass spectra of a solution containing the nine chloro- and bromo-acetic acids in 9:1 methanol:tap water (v/v) containing 0.2 mM ammonium acetate. Monobromoacetic acid (MBAA) and trichloroacetic acid (TCAA) are in the solution at concentrations of 400 ng/mL and 200 ng/mL, respectively. The upper trace, Figure 3 (a), collected using conventional ESI-MS, has been plotted over a m/z range of -60 to -160, and has been expanded vertically such that the MBAA ion (m/z -137) is full scale. The spectrum is observed to be complex, with peaks observed for several of the haloacetic acids present in the solution, as well as for adduct peaks. Fragment ions, such as may result from the loss of CO_2 from the bromo-containing acids (e.g., bromo-chloroacetic acid (m/z -171)), will overlap with other acids (e.g. dichloroacetic acid (m/z -127)) making quantitation difficult in the presence of several of the haloacetic acids in solution. The lower trace, Figure 3 (b), was acquired using ESI-FAIMS-MS at DV=-3300 V and CV = 18.0 V, nearly optimal conditions for the transmission of both TCAA and MBAA. The spectrum is dramatically simplified over that observed from ESI-MS, with only TCAA, MBAA, and Br^- (m/z -79 and -81, resulting from fragmentation of MBAA in the mass spectrometer interface), along with some background ions, transmitted at this CV. The TCAA signal in Figure 3 is not seen to be subject to overlap from acetate dimer ions as is the case with ESI-MS as observed in Figure 3 (a), and the expected isotope distribution for the ion is readily apparent. The overall abundance of the ions has increased with ESI-FAIMS-MS due to ion focusing mechanisms. This focusing, along with the decreased background signal, provides improvement in the lower level of detection of these compounds in solution. Using Figure 3 (a), the lower limit of detection of MBAA would arguably be near the 200 ng/mL concentration shown here, whereas the detection limit of MBAA using FAIMS (Figure 3(b)) is reduced to approximately 2 ng/mL.

Using ESI-FAIMS-MS the detection limits for the regulated HAA's and BCAA tested to date, lie between 0.5 and 4 ppb from a 9:1 methanol:tap water solution (v/v) with no preconcentration of the sample required. Preconcentration methods have been described in the literature, and a further concentration of at least 10 to 200 times appears feasible.

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Figure 3. Conventional ESI-MS (a) and ESI-FAIMS-MS (b) of a solution containing a mixture of halacetic acids, including trichloroacetic acid (200 ng/mL) and monobromoacetic acid (400 ng/mL). Both plots are normalized to the m/z -137 ion CH_2BrCOO^-. It is doubtful that m/z -137 in (a) is only the monobromoacetate ion. The lower trace, with FAIMS, has background ions removed and increased sensitivity.