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Determination of pentachlorophenol by negative ion chemical ionization with membrane introduction mass spectrometry

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Pentachlorophenol (PCP) was used as a model compound to explore the potential of desorption chemical ionization (DCI) in the determination of polychlorinated pesticides using membrane introduction mass spectrometry (MIMS). A direct insertion membrane probe was modified so that a chemical ionization plasma could be established at the membrane surface. Using selected ion monitoring (SIM) in a tandem triple quadrupole mass spectrometer with isobutane chemical ionization (CI), the PCP detection limit under positive chemical ionization is 20 ppb whereas negative CI gives detection limits in the low ppb range. This performance is achieved without any pre-treatment or derivatization of the sample. Negative ion CI gives a signal that is linear over a concentration range of 2–1000 ppb. Comparison of data obtained with low ppb samples of 2,4,6-trichlorophenol, 2,3,4,6-tetrachlorophenol and pentachlorophenol suggests that the sensitivity of this analytical procedure increases with increase in the number of electronegative substituents in the molecule.

Introduction

Membrane introduction mass spectrometry (MIMS) is an established method that utilizes a semi-permeable polymer membrane to introduce analytes selectively into a mass spectrometer where they are ionized and mass analyzed. Transport through the membrane involves adsorption on the membrane surface, diffusion through the membrane and evaporation from the inner membrane surface into the vacuum.[1–3] Owing to its simplicity and selectivity for organic compounds in water and air and its high sensitivity, MIMS has been widely used as an on-line technique for the *in situ* determination of volatile organic compounds (VOCs) in air and water samples without pre-treatment.[3–5] Although not as readily accomplished, there are also a growing number of reports on the application of the technique to the analysis of semi-volatile organic compounds (SVOCs).[6,7] Several variations on this technique exist and much work has been done in applying it to environmental[8,9] and industrial monitoring.[10,11]

In addition to standard membrane inlet mass spectrometry, with or without sample control by flow injection analysis (FIA),[12] a number of MIMS variants have been reported.[1] These include analyte preconcentration through cryotrapping (CT-MIMS)[13] or trapping in the membrane[14] (trap-and-release MIMS). In affinity MIMS,[15] a chemically modified membrane makes it possible to perform selective sampling for specific types of analytes. Recent developments include MIMS systems that utilize assisted desorption from the membrane in order to determine non-volatile organic compounds. For example, in desorption chemical ionization MIMS,[16] the trap-and-release technique is combined with chemical ionization in order to evaporate large biomolecules, polyaromatic hydrocarbons and even pesticides from the membrane, using a combination of heat radiation from the filament and charge transfer from the chemical ionization plasma. A low powered laser (laser desorption MIMS)[17] has also been used to stimulate the evaporation of polyaromatic hydrocarbons from the vacuum side of the membrane and deliver them into the mass spectrometer.

Negative ion chemical ionization (NCI) has distinct advantages for the detection of electronegative compounds[18] and many studies have established its value in the determination of halogenated pesticides and similar compounds.[19,20] NCI can also be used in conjunction with MIMS.[21]Along with its unique selectivity, NCI experiments that use electron capture have been shown to provide an increase in sensitivity of two to three orders of magnitude relative to the sensitivity available under positive ion CI conditions.[22]

Chlorinated hydrocarbons, including chlorinated phenolic compounds, have been listed in the US Environmental Protection Agency (EPA) Contaminant Candidate List (CCL) and as possible endocrine disrupting chemicals (EDCs).[23] Pentachlorophenol (PCP), a widely used pesticide and wood preservative, has been listed as a priority pollutant in drinking water by the US EPA owing to the damage it does to the central nervous system and its persistence in the environment. A recent study provided evidence that increased blood levels of PCP have a significant impact on cellular immunodeficiencies.[24] The US EPA regulations set the maximum contaminant level (MCL) for PCP in drinking water at 1 ppb. This limit is based on present technology. The US EPA Method 515.3, the method for detecting pentachlorophenol and other chlorinated acids in drinking water, utilizes gas chromatography with electron capture detection for analysis after liquid–liquid extraction of the sample followed by derivatization. The method detection limit (MDL) using US EPA Method 515.3 for PCP in drinking water is 0.085 ppb.[25] There is clearly a need to develop new methods, especially on-site methods for detecting PCP in the parts-per-trillion (ppt) range.

MIMS has been examined as a method for on-line monitoring of PCP. For instance, using a trap-and-release MIMS system, a limit of detection (LOD) of 10 ppb for PCP was reported.[14] Improvement of the detection limit to 5 ppb was later achieved by derivatizing the PCP with acetic anhydride.[26] However,

quantitative analysis of semi-volatile or non-volatile organic compounds, such as PCP, on a standard MIMS system has been extremely difficult and the results reported thus far are not satisfactory. If the difficulties associated with less volatile organics could be overcome, MIMS could have the advantage of continuous direct sample introduction without the need for extraction or derivatization. Owing to the minimal sample preparation required and its inherent *in situ* capabilities, analysis times with such a system should be short.

These considerations, plus the fact that PCP can serve as a model compound for the determination of polychlorinated pesticides, motivated this study, which explored PCP detection under both positive and negative chemical ionization of isobutane using standard membrane introduction mass spectrometry. Detection in the NCI mode yields an LOD in the low ppb range. These direct analysis results are encouraging and they suggest that with some form of preconcentration, MIMS will yield the desirable ultra-low (ppt) levels of analysis.

Experimental

A Finnigan MAT (San Jose, CA, USA) TSQ 70 triple quadrupole mass spectrometer was employed in all experiments. Samples were introduced using a direct insertion membrane probe (DIMP) with a tubular polydimethylsiloxane (PDMS) membrane (Technical Products, Decatur, GA, USA) of 0.025 in id and 0.047 in od. Sample flow was controlled by a Gilson (Middleton, WI, USA) Minipuls 3 peristaltic pump (Model M313) with a fixed flow rate of 0.8 mL min^{-1}. The solution temperature was maintained at 83 °C, as monitored using a direct insertion probe temperature controller (Finnigan MAT). Both positive and negative CI were performed using isobutane as the reagent gas with a typical manifold pressure of 1.2×10^{-6} Torr. The manifold temperature was maintained at 70 °C and the source temperature was set at 200 °C. The mass spectrometer was run both in the full scan and in the selected ion monitoring (SIM) modes. Data were averaged for 5 s to improve the signal-to-noise ratio (S/N). The source block was modified by doubling the hole size in front of the filament to allow more electrons to enter the ionization volume surrounding the membrane (Fig. 1). The CI ion volume was also modified in the same way. The electron aperture size was increased from 1.4 to 2 mm in diameter. Mass/charge ratios (*m*/*z*) are reported using the Thomson unit (1 Th = 1 atomic mass per unit positive charge).[27]

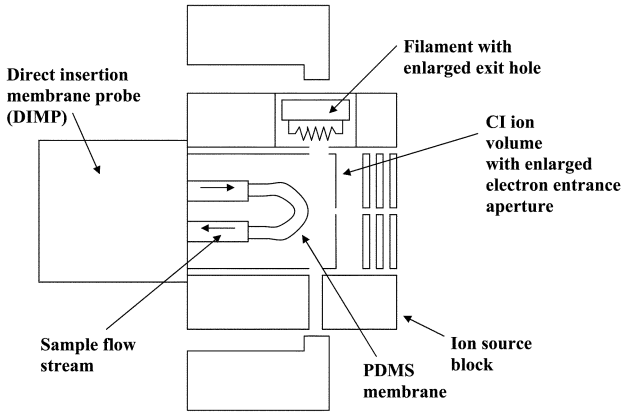

Fig. 1 Tip of the direct insertion membrane probe (DIMP) inside the source of the mass spectrometer showing the alignment with respect to filament, the enlarged exit hole and enlarged electron entrance aperture of the CI ion volume. The tip of the membrane is located slightly displaced from the electron entrance aperture to allow the CI plasma to be established at this point.

PCP was obtained from Aldrich (Milwaukee, WI, USA) and used without further purification. A stock standard solution of 1 g L^{-1} of PCP was prepared by dissolving 10 mg of PCP in 10 mL of methanol. All samples were diluted in distilled water from the stock standard solution. Similar techniques were used for the preparation of other compounds detected in this study.

Results and discussion

Optimization of MIMS system

Experimental conditions were investigated in detail to optimize the performance of the membrane introduction triple quadrupole mass spectrometer system. For instance, the sensitivity is affected by the rate of sample transfer from the membrane to the vacuum system and is thus related to the temperature of the sample flow. To maximize sample transport into the mass spectrometer, the temperature should be as high as possible. However, when the temperature approaches the boiling point of water, gas bubbles are produced. As a result, continuous flow is interrupted and permeation efficiency drops. In this study, the sample temperature was maintained at 83 °C to avoid this problem. Variations in sample temperature were found to increase the background noise so the temperature was carefully maintained within ±2 °C.

The membrane length is critical for the low level detection of PCP using the current system. Fig. 1 depicts the tip of the DIMP inside the source block of the mass spectrometer. If the membrane is too long or too short, it will not be directly under the aperture to the filament and the CI plasma will not be established at the membrane surface. The result will be a less efficient pervaporation and ionization, especially for low volatility analytes. However, at the same time the plasma might cause a serious surface charging problem due to the insulating nature of the PDMS membrane. Surface charging decreases the sensitivity and makes quantitative analysis difficult. If the membrane is pushed forward in the ion volume, then a significant drop in sensitivity is observed as a result of shielding of the exit aperture. The final selection was a slightly shortened membrane such that the tip of the membrane is aligned with the filament aperture. In this fashion surface charging effects were avoided, although with some sacrifice in terms of the sensitivity.

Detection of PCP in positive and negative ion CI

Fig. 2(a) shows a full scan mass spectrum of 200 ppb of pentachlorophenol recorded using positive ion chemical ionization with isobutane (i-C_4H_{10}) as the CI reagent. Under the chosen experimental conditions, the most abundant ion is the phthalate fragment ion, *m*/*z* 149, generated from the membrane itself. Ions at *m*/*z* 167 and 279 are also present and are characteristic of dibutyl phthalate that is most likely present in the membrane. The PCP molecular ion ($M^{+\cdot}$) shows the expected chlorine isotopic pattern at *m*/*z* 264, 266, 268 and 270 and is much more abundant than protonated PCP [$(M + 1)^+$] or its HCl elimination product (peaks centered at *m*/*z* 230). Although the production of a radical cation as the principal form of molecular ion is not commonly encountered in proton-transfer chemical ionization, some halogenated aromatics including chlorobenzene undergo addition of a proton followed by loss of a neutral radical (in this case H·) to give the thermodynamically stable radical cation.[18] This behavior is expected to be enhanced by the *ortho*-chloro substituents in PCP. The major sample-derived ions observed in the 200 ppb PCP experiment are listed in Table 1. The spectrum recorded under positive ion CI conditions is noisier than that under negative ion conditions. The NCI mass spectrum of 100 ppb

PCP [Fig. 2(b)] recorded under otherwise identical conditions shows much better S/N and the ions are at least 100 times more abundant. The most abundant ion is the fragment due to HCl loss (leading to the chlorine isotopic quartet at *m*/*z* 228, 230, 232 and 234) while elimination of Cl_2 (*m*/*z* 196) is also observed, in addition to a possible phthalate radical anion (*m*/*z* 148).

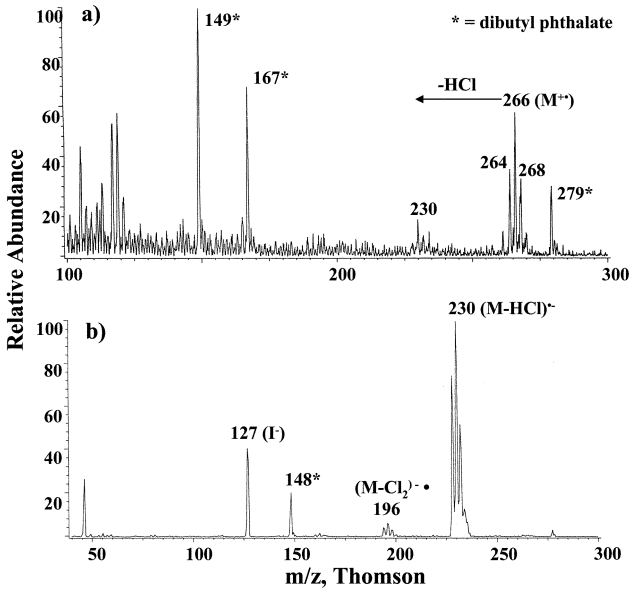

Fig. 2 Full scan mode mass spectra of (a) 200 ppb PCP in water, positive ion CI and (b) 100 ppb of PCP in water, negative ion CI, both using MIMS.

Table 1 Comparison between major ions of PCP, experimental conditions and detection limit under both positive and negative ion CI conditions

Major ionic products (*m*/*z*)[a]	Positive CI 230, 266[b]	Negative CI 196, 230[c]
Ion monitored in SIM mode (*m*/*z*)	266	230
Sample time (min)	3	3
Sample flow rate (mL min^{-1})	0.8	0.8
MIMS detection limit (S/N^d = 3) (ppb)	20	2[e]

[a] In the selected ion monitoring region from *m*/*z* 250 to 290 for PCI and from *m*/*z* 220 to 250 for NCI excluding contaminant ions. [b] At a concentration of 200 ppb PCP. [c] At a concentration of 100 ppb PCP. [d] Signal-to-noise ratio. [e] Estimate.

In order to increase the sensitivity further, experiments were performed using SIM; *m*/*z* 266 and 230 were selected in the positive and negative ion modes, respectively. Fig. 3(a) depicts a typical SIM spectrum showing the ion current due to *m*/*z* 230 for a 10 ppb PCP sample under negative ion CI conditions. The SIM spectrum shows a small spike at the point of initial sample introduction and a large spike when changing the sample stream from the PCP solution to water background; both are ascribed to gas bubbles introduced at those points which allow rapid heating of the membrane, and therefore an increase in the amount of sample evaporating from the membrane is observed. The sensitivity under NCI was significantly better than that observed under PCI, and these data suggest that LODs at least one order of magnitude better are possible in the negative ion mode.

To explore this point further, Fig. 3(b) shows a direct comparison between the sensitivity for PCP under positive and negative ion conditions. The fragment ion at *m*/*z* 230, generated from a solution of 20 ppb PCP, was first monitored under NCI conditions. After a complete sample introduction cycle, the source polarity was changed to the positive CI mode and the molecular radical cation at *m*/*z* 266 was monitored under identical conditions. An intense peak was observed in the NCI mode, but in the PCI mode only a very low abundance ion (S/N ≈ 3:1) was observed. The contrast between the intensity over the detection of 20 ppb PCP in the NCI and PCI modes directly demonstrates the higher sensitivity of NCI than PCI for PCP detection.

To evaluate the analytical performance of this system, SIM experiments involving different concentrations of PCP were studied under identical conditions. Plots of the ion abundance *versus* concentration (Fig. 4) are linear over almost four orders of magnitude (from 2 to 1000 ppb) with a correlation coefficient (R^2) of 0.998. The relative uncertainty for each data point was less than 2%. The linearity is lost when the concentration is raised above 10 ppm. It is important to note that a significant drop in ion intensity is observed for long-term, continuous monitoring and this is mainly attributed to the surface charging issue addressed earlier. 2,4,6-Trichlorophenol and 2,3,4,6-tetrachlorophenol were also monitored using this system. Comparison of the SIM spectra for PCP and these two compounds showed that the sensitivity of the detection method improved as the number of chlorine atoms on the analyte molecule increased.

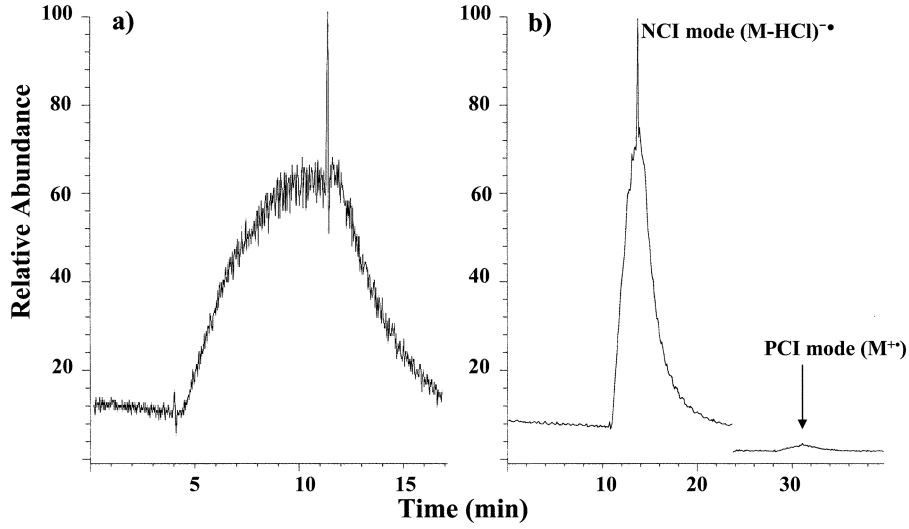

Fig. 3 SIM experiments showing (a) detection of 10 ppb PCP under negative ion CI with *m*/*z* 230 being monitored and (b) direct comparison of SIM data for 20 ppb PCP under both negative and positive ion CI. The ion monitored was *m*/*z* 230 and 266, respectively.

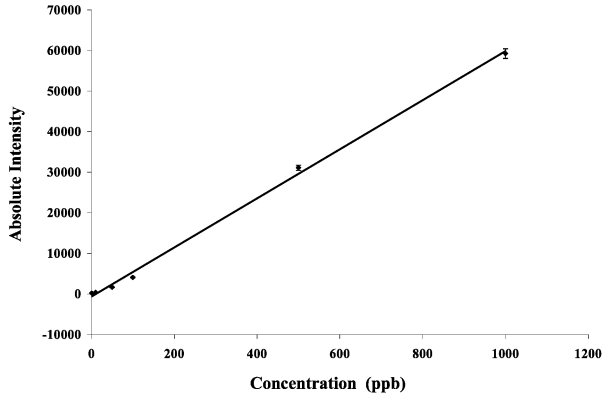

Fig. 4 Ion abundance (*m*/*z* 230) *versus* concentration in SIM spectra recorded using negative ion CI showing the response of PCP from 2 to 1000 ppb with *m*/*z* 230 being monitored. Values shown are the average of triplicate measurements ± standard deviation. Correlation coefficient (R^2) = 0.998.

Conclusion

A low level detection method for detecting PCP under chemical ionization using isobutane with a standard operated MIMS system without derivatization of the sample is reported. While the detection limit using PCI is 20 ppb, detection under NCI conditions without sample pre-treatment is in the low ppb range. This suggests that the sensitivity can be further improved by using trap-and-release methods. With an optimized version of this system, continuous monitoring of low volatility compounds might also be possible. It is by virtue of the seamless combination of sampling and analysis functions that MIMS is competitive with chromatography-mass spectrometry methods, even when the response times are relatively long, as here. Fieldability is just one additional advantage of the method. Future research may include seeking a solution for the surface charging issue and applying negative ion CI to the determination of other halogenated SVOCs and also polychlorinated pesticides and chemical warfare agents using a DCI-MIMS system.

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