Anal Bioanal Chem (2002) 372 : 66–73
DOI 10.1007/s00216-001-1195-5

REVIEW

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Developments in ion mobility spectrometry–mass spectrometry

Received: 19 July 2001 / Revised: 11 October 2001 / Accepted: 16 October 2001 / Published online: 12 December 2001

Abstract Ion mobility spectrometry (IMS) has been used for over 30 years as a sensitive detector of organic compounds. The following is a brief review of IMS and its principles with an emphasis on its usage when coupled to mass spectrometry. Since its inception, IMS has been interfaced with quadrupole, time-of-flight, and Fourier-transform ion cyclotron resonance mass spectrometry. These hybrid instruments have been employed for the analysis of a variety of target analytes, including biomolecules, explosives, chemical warfare degradation products, and illicit drugs.

Keywords Ion mobility spectrometry · Mass spectrometry · Gas-phase electrophoresis · Plasma chromatography

Introduction

Ion-mobility spectrometry (IMS) was first introduced in 1970 under the name plasma chromatography. Initially considered as an ion-separation technique with ion drift times analogous to chromatographic retention times [1, 2], it later became more commonly viewed as a technique for the selective detection of organic compounds [3, 4]. In IMS, radioactive ^{63}Ni (typically) is used to ionize vapors of organic compounds through a series of ion–molecule reactions. The ions are then carried under an electric potential through a drift region to an ion collector (i.e. Faraday plate or mass spectrometer). Ions are selectively detected on the basis of their unique drift times traveling through the drift region.

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Interest in IMS blossomed in the early 1970s because of its analytical versatility, excellent detection limits, suitability for real-time monitoring, and low cost. Despite these attractive features, however, interest declined after 1976 [3]. Loss of interest was associated with universal disappointment by unmet expectations and possible misunderstandings. IMS was mistakenly compared with mass spectrometry (MS), despite its much lower peak resolution and lack of mass information. In addition, chemical aspects of ion formation at atmospheric pressure were not fully appreciated or understood. This caused many to conclude that IMS was an interesting but not practical or usable technology [3, 4, 5, 6].

Between 1980 and the early 1990s, an interest in IMS was renewed as a variety of modifications were made to instrument design, resulting in its suitability for use for a wide range of applications. During this time, IMS was further employed as a detector for gas chromatography [7, 8] and supercritical-fluid chromatography [9, 10]. It was also used for the detection of bacteria [11] and military monitoring in hostile environments [3]. Many attempts were also made to incorporate unconventional ionization sources, such as laser ionization [12] and a form of electrospray ionization (i.e., "coronaspray") into its design [13, 14].

Principles of IMS

The ability to distinguish ions occurs within the drift region. In IMS, ions are separated on the basis of their different velocities attained when accelerated through a drift tube, by a constant electric field, against a counter-flow of neutral gas. The average velocity of an ion, v_d (cm s^{-1}), is determined by the number of collisions it experiences within the drift tube with the neutral drift-gas molecules, which is directly proportional to the applied electric field strength, E (V cm^{-1})

$$v_d = KE \quad (1)$$

where K is the ion mobility constant in units of cm^2 V^{-1} s^{-1} and is a combined property of both the nature of the ion of

interest and the drift gas. Equation 1 is valid only at low field strengths (e.g. <1000 V cm^{-1}). At increasing field strengths, K is no longer directly proportional to E [15]. K can also be calculated at low electric field strengths by use of the Mason–Schamp equation:

$$K = 3/16\left[ze/N_o\,(2\pi/\mu kT)^{1/2}\,(1/\Omega_D)\right] \quad (2)$$

where z is the integer charge of the ion, e is the charge of an electron in Coulombs (i.e., 1.602×10^{-19} C), N_o is the number density of the drift gas (molecules cm^{-1}), μ is the reduced mass of a colliding ion–drift-gas pair [μ=mM/(m+M)], m is the mass of the ion, M is the mass of a neutral drift molecule, k is Boltzmann's constant, T is the operating temperature in Kelvin, and Ω_D is the ion–neutral average cross-sectional area; Ω_D is derived through a series of integrations that average the ion–neutral collisions over all possible scattering angles and energies. For rigid-sphere collisions, integrating analytically yields $\Omega_D=\pi d^2$, where d is the sum of the ion and drift-gas radii. As can be seen, assuming pressure and temperature are constant, $ze/\mu^{1/2}\Omega_D$ is what is actually measured in IMS experiments. For small atomic ions relative to the drift gas molecules (e.g. N_2, He, or air) mobility is largely controlled by reduced mass whereas for heavy ions μ is essentially equal to M. The distinguishing property upon which relatively large ions (the majority of ions analyzed) are separated is, therefore, ionic size or Ω_D. Thus, ions of identical mass, but different shapes (i.e., isomers), can be separated [3, 4, 5, 6].

Because K, as shown in Eq. (2), is found to be dependent on both temperature and pressure (N_o is a function of pressure), the value calculated by use of Eq. (1) is often converted to a reduced mobility value, K_o

$$K_o = K(P/760)(273/T) \quad (3)$$

where P is the operating pressure in Torr and T is the operating temperature in Kelvin. This normalizes mobility values calculated at different temperatures and pressures for the purpose of comparison.

During its early years IMS was periodically compared with time-of-flight mass spectrometry (TOFMS), which was unfortunate because of its low resolving power and only approximate correlation with ion mass. Its unique advantage over mass spectrometry is its ability to operate at atmospheric pressure or near atmospheric pressure. In addition, data acquired can be used to calculate structural information (e.g. average cross-sectional area) [16, 17, 18]. By interfacing IMS with MS, a somewhat orthogonal comprehensive separation (i.e., structural information) and detection (i.e., mass information) device can be constructed.

IMS–MS developments and applications

Most commercial IMS instruments use Faraday plate detection; that is, ions are detected as they strike a metal plate and induce a current. Faraday plate detection is simple, inexpensive, and can be used for both positive and negative ions. Unfortunately, such detection does not afford additional qualitative information associated with the separation of ions. Because of this, some have chosen to use MS as a means of ion detection and identification.

The advantages of interfacing IMS with MS were understood early in the development of IMS, and the coupling of the two techniques is virtually as old as IMS itself. In early 1971, when IMS was referred to as plasma chromatography (PC), the Franklin GNO Corporation developed the first commercial ion mobility spectrometer–mass spectrometer (IMS–MS) and demonstrated its use as a detector for the identification and analysis of trace amounts of oxygenated compounds (i.e., 1-octanol and 1-nonanol) [19]. The instrument was called the Alpha II PC/MS. It was a two-gated IMS instrument made from stacked rings that had been joined to a modified Finnigan quadrupole mass spectrometer. The IMS section operated at atmospheric pressure and the quadrupole at approximately 10^{-5} Torr (1 Torr=133.322 Pa). The interface between the two included an ion lens for focusing of ions exiting the aperture of the IMS into the quadrupole mass spectrometer. The ions were then detected with an electron multiplier placed at the end of the quadrupole, as in Fig. 1 [20].

The instrument was soon used for comparison of IMS–MS data obtained by ^{63}Ni ionization in nitrogen or pure air, with mass spectral data obtained by chemical ioniza-

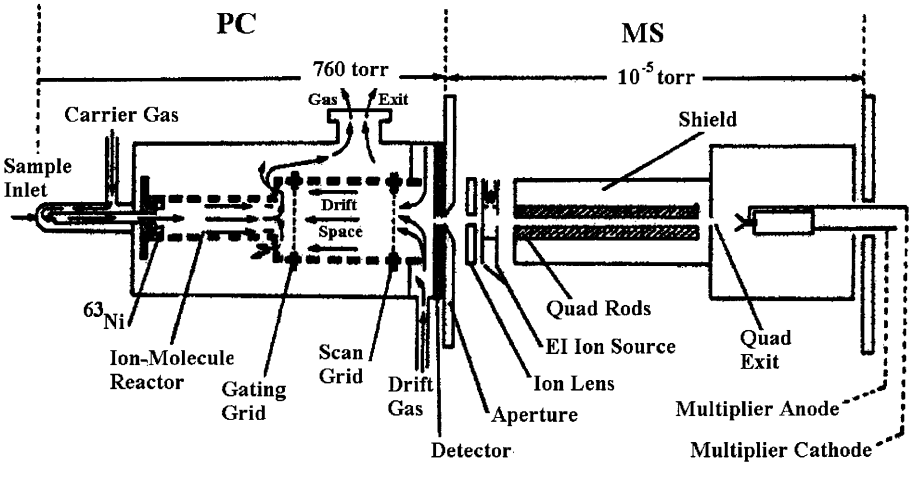

Fig. 1 Schematic diagram of the Alpha II PC/MS combined system (Reproduced with permission from Ref. [17])

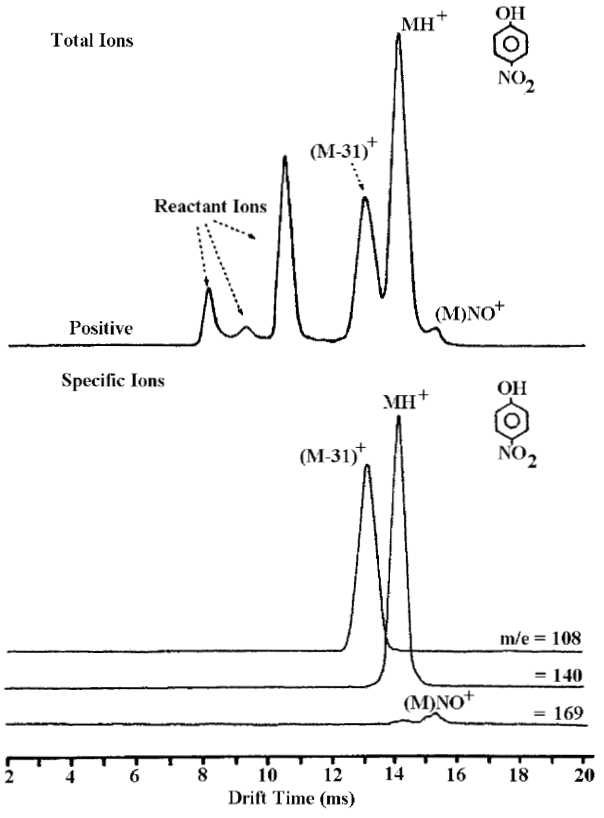

Fig. 2 Total and specific IMS spectra observed for *p*-nitrophenol using the Alpha II PC/MS system (Reproduced with permission from Ref. [17])

tion [21]. Also, work was performed to enable better understanding of the formation of ions in the reaction region of the IMS [20, 22]. In addition, many used the Alpha II PC/MS to help clarify the validity of IMS mass-mobility relationships [23, 24]. Several papers, before the above-mentioned studies, attempted to create mass-mobility correlation curves by speculative assignment of masses to the identified IMS peaks without the use of a mass spectrometer [25, 26, 27]. The use of the Alpha II PC/MS enabled this former work to be refined and corrected.

The Alpha II PC/MS was equipped with three distinct modes of operation. Each mode was dependent on the operation of the entrance and exit gates of the IMS drift tube. The entrance gate enabled ions to enter the IMS instrument for analysis, and the exit gate enabled them to leave the drift tube and enter the mass spectrometer. Mass spectral data were acquired by holding both of the gates open, thus enabling all ions formed within the reaction region of the IMS instrument to continually drift down the tube into the quadrupole mass spectrometer. The mass spectrometer was then scanned to produce a total mass spectrum of ions present in the sample. Total IMS spectra could be obtained by operating the entrance gate of the instrument in its normal gating fashion (enabling periodic pulses of ions to enter the drift tube) with the exit gate continuously open. The mass spectrometer was then operated in the total-ion-monitoring mode, enabling all ions leaving the drift tube to be detected, but not mass analyzed. Finally, mass identification of individual IMS peaks could be achieved by operating the instrument with both gates

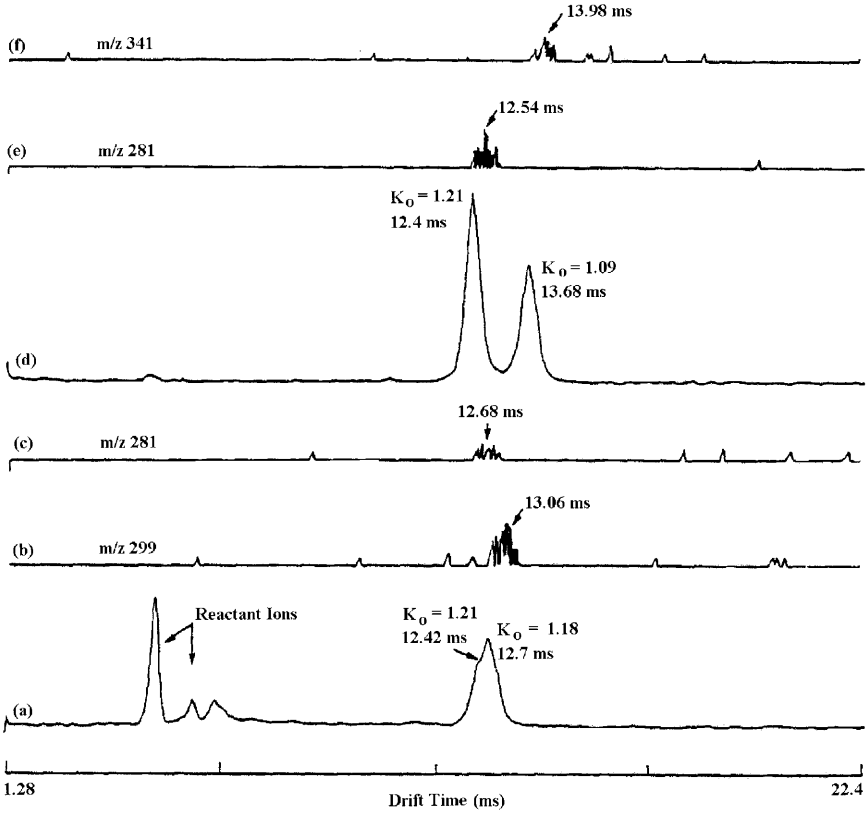

Fig. 3 Positive IMS spectra and mass-identified IMS spectral data for codeine (traces **a**–**c**) and acetylcodeine (traces **d**–**f**) at 220 °C (Reproduced with permission from Ref. [26])

opening and closing in such a fashion that only ions of a desired drift time could pass into the mass spectrometer. The mass spectrometer would then be tuned to a previously assumed mass-to-charge ratio (m/z) for the purpose of identification. In this manner, direct correlation could be made between a given IMS peak and its corresponding mass (or masses, for more than one compound of distinct m/z defining a given IMS peak). Figure 2 shows data collected using both the total- and selected-ion-monitoring modes of the mass spectrometer [20].

In 1975 Franklin GNO Corporation halted its manufacturing operation. Shortly after, however, two former founders, M. J. Cohen and R. F. Wernlund, formed a new company, PCP (West Palm Beach, FL, USA) to continue the technology under the patent license of Franklin GNO. Unfortunately, as mentioned previously, interest in ion mobility spectrometry began to wane in the late 1970s and through the mid-1980s. The 1980s brought a better understanding of IMS, however, and this, in turn, sparked a renewal of interest. At this time, many felt IMS was more a spectrometric than chromatographic process. This new consensus fostered a name change of the process from plasma chromatography to ion mobility spectrometry. PCP began manufacturing an early version of the Alpha II PC/MS as the Phemto-Chem MMS-160 ion mobility spectrometer–mass spectrometer. Several models were ultimately produced; in all of these the basic operation of the new instrument remained the same as that of its predecessor. To acquire both IMS and MS data the instrument was gated for a certain drift time and the mass spectrometer was tuned to a specific m/z value for the analyte of interest. The IMS–MS instrument was primarily regarded (and used) as a selective detector.

Most of the limited IMS–MS work in the 1980s was, as in the 1970s, performed using the commercially available instrument supplied through PCP. Work with this instrument in the 1980s included the identification and characterization of illicit and prescription drugs. It was thought that an IMS–MS system could be used to aid rapid identi-

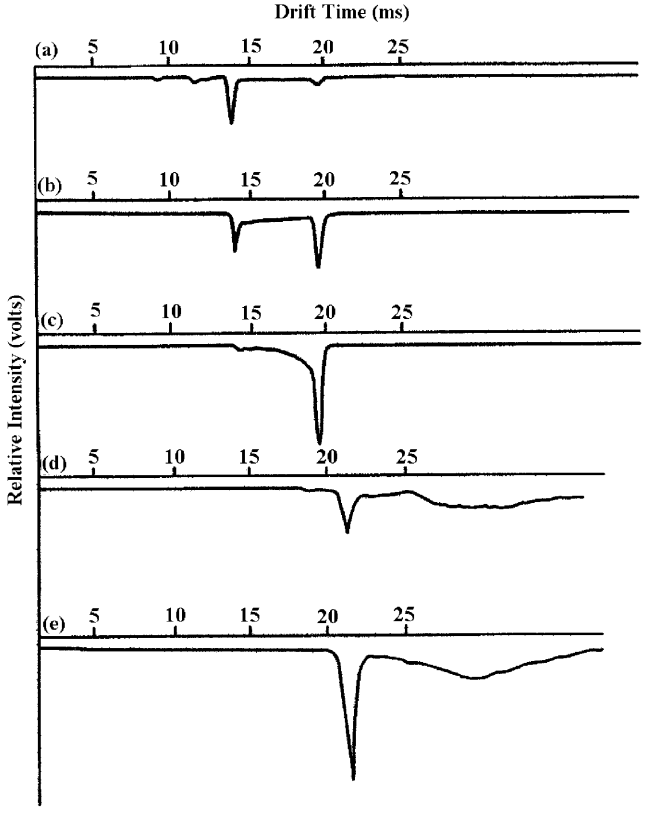

Fig. 4 IMS spectra for DMMP at 220 °C in N_2 at a concentration of (**a**) 15 μg m^{-3}, (**b**) 50 μg m^{-3}, and (**c**) 100 μg m^{-3} for ions produced by the ^{63}Ni β source and (**d**) 15 μg m^{-3} and (**e**) 100 μg m^{-3} for ions produced by laser radiation at 266 nm (Reproduced with permission from Ref. [28])

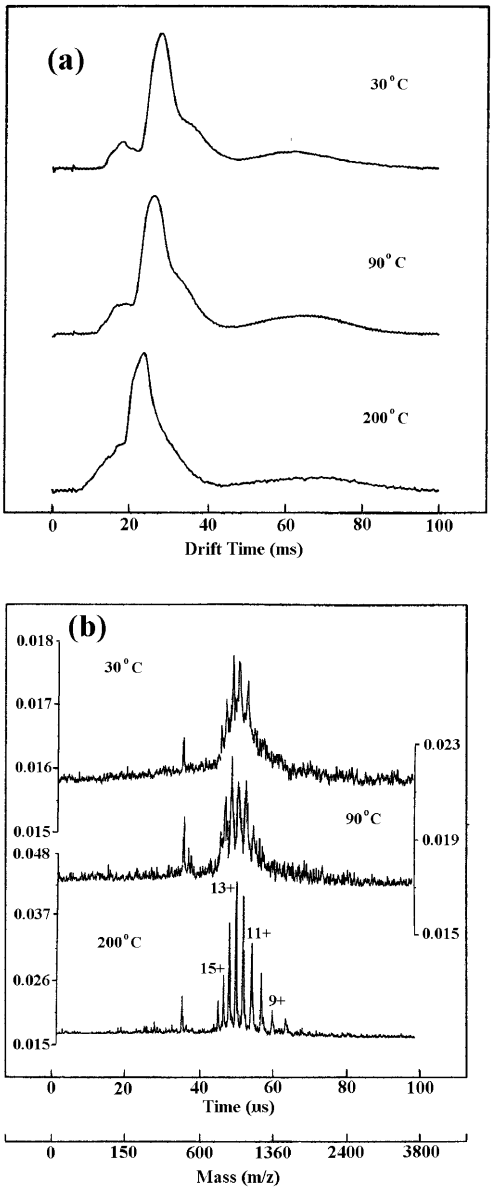

Fig. 5 (**a**) IMS spectra of cytochrome c at 30, 90, and 200 °C. (**b**) Corresponding time-of-flight mass spectra at 30, 90, and 200 °C (Reproduced with permission from Ref. [30])

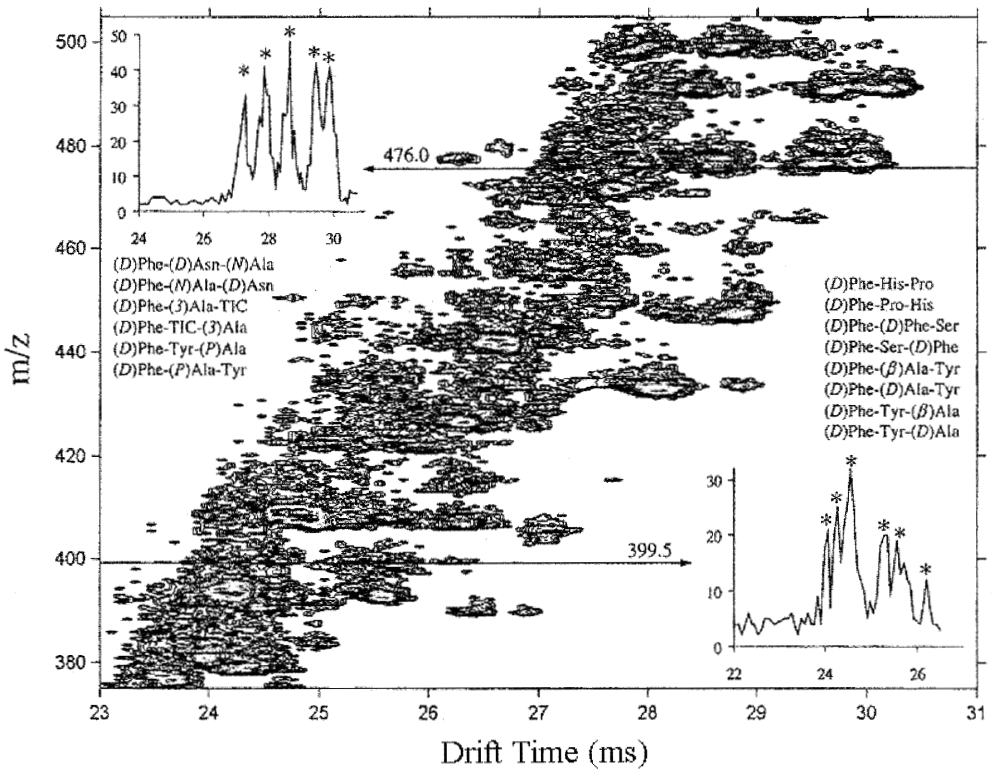

Fig. 6 Contour plot of the nested data recorded for the (D)Phe-Xxx-Xxx-$CONH_2$ peptide library over an m/z range of 375–505. The insets show IMS slices (and peak intensities) taken at m/z=399.5 and 476.0. Reproducible features are indicated with an asterisk. Sequences that are expected at these m/z ratios are indicated (Reproduced with permission from Ref. [37])

fication of drug residues on the hands of patients admitted to the hospital with a drug overdose [28, 29] (Fig. 3). The instrument was also used to identify structurally different ions with the same m/z values [30]. A modified version of the instrument was used by Lubman and coworkers, after laser desorption of solid samples, including ^{63}Ni ionization in the normal fashion. They used this method to detect explosives (i.e., trinitrotoluene, cyclotetramethylene-tetranitramine, and cyclotrimethylene-trinitramine). In addition, throughout their studies, ^{63}Ni ionization was compared with laser ionization (Fig. 4) [12, 31].

In the 1990s, work continued in the field of IMS–MS, but with more of a departure from the use of the commercially available design offered through PCP. Guevremont and coworkers purchased an IMS–MS instrument from PCP and modified it to accommodate a time-of-flight mass spectrometer to study ions formed during the initial stages of electrospray ionization (Fig. 5). A LeCroy digital oscilloscope (Model 9350, Chestnut Ridge, NY, USA) was used for data collection and processing [32]. TOFMS enabled complete mass spectra of individual peaks separated in the IMS instrument to be obtained. This eliminated the tedious task of having to tune the mass spectrometer to the assumed m/z value of an IMS peak.

In 1997, Clemmer et al. designed an IMS–MS instrument with a quadrupole mass spectrometer for characterization of oligosaccharides and proteins [33, 34, 35, 36]. Later, they constructed an IMS–MS instrument with a time-of-flight mass spectrometer to study biomolecules, incorporating a unique time-to-digital converter data system linked to, and operated by, a Pentium computer [37, 38, 39, 40, 41, 42, 43, 44, 45]. Data were presented as drift times associated with a "nested" flight time. Sample ionization was achieved by electrospray ionization. With the information acquired, a contour plot of flight time against drift time could be generated (Fig. 6). Clemmer also performed high-resolution IMS studies. An ion trap and octapole collision cell were incorporated into the design to increase the duty cycle and obtain fragment information, respectively.

Recently, Hill et al. designed and constructed an in-house electrospray IMS instrument, and interfaced it with a C50-Q (ABB Extrel, Pittsburgh, PA, USA) quadrupole mass spectrometer. The instrument was used successfully for the study of isomeric peptides, illicit drugs, chemical warfare degradation products, explosives, and IMS selectivity [46, 47, 48, 49, 50, 51] (Fig. 7). High IMS resolution values were also reported and associated with the very small diameter (i.e., 40 μm) entrance orifice into the mass spectrometer, which enabled the sampling of ions from the most homogenous region of the electric field within the drift tube [52]. Modes of operation were equivalent to those offered by the commercial IMS–MS instrument available through PCP.

Russell et al. and Ionwerks (Houston, TX, USA) recently collaborated in the development of an IMS–TOFMS instrument with a high-pressure matrix-assisted laser desorption ionization source for sample ionization. The instrument was used for the analysis of peptide mixtures (Fig. 8) [53]. Data were collected and processed in an ion-counting mode by means of an Ionwerks time-to-digital converter (Model TDCX4). They also designed a Fourier-transform ion cyclotron resonance mass spectrometer–ion mobility spectrometer with TOFMS detection [54].

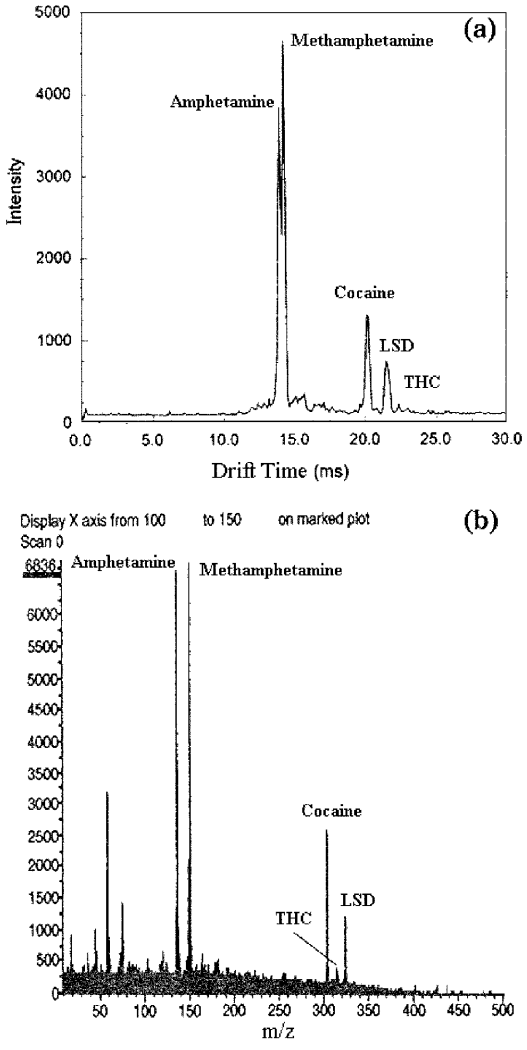

Fig. 7 (**a**) IMS spectrum obtained from a drug mixture of amphetamine, methamphetamine, cocaine, LSD, and THC. (**b**) Mass spectrum of the drug mixture (Reproduced with permission from Ref. [45])

Also recently, Lee et al. [55] developed an IMS–TOFMS instrument with an Ionwerks data system (Model TDCX4) and a Jaguar TOFMS (LECO, St. Joseph, MI, USA). The instrument incorporated a recently developed ambient pressure and temperature electrospray ionization interface [56]. This instrument was used for the analysis of selected benzodiazepines, triazine herbicides, and combinatorial chemistry samples. Their work emphasized the use of IMS as a rapid separation technique capable of performing high-throughput analysis of potential drug candidates synthesized through combinatorial chemistry techniques. The ability of the IMS to separate compounds was characterized in terms of separation figures of merit (i.e., separation efficiency and peak capacity) [52, 56]. Efficiencies of 35,000–50,000 theoretical plates were achieved in less than 50 ms. Figure 9 shows reconstructed selected-ion IMS separations of selected benzodiazepines and triazine herbicides using TOFMS detection.

IMS–MS has also found its way into industrial applications. Probably the most successful application has been in the semiconductor industry by Carr et al., while working at IBM. They showed, through a series of papers presented almost exclusively at conferences, that IMS–MS technology could be used to detect and identify surface contaminants on semi-conductors and in headspace vapors in sealed electronic packages [57, 58, 59, 60].

High-field asymmetric waveform ion mobility spectrometry, similar to ion mobility spectrometry, acquires data as a function of ion mobility constant values. Developed in the late 1990s, it exploits the change in an ion's mobility constant at increasing electric field strengths, and operates as an atmospheric pressure ion filter. Guevremont et al. coupled this instrument to both a quadrupole and a triple quadrupole mass spectrometer [61, 62, 63, 64, 65, 66]. The hybrid instruments, employing primarily electrospray ionization, were successfully used to analyze chlorinated and brominated byproducts of drinking water disinfection and a variety of biomolecules.

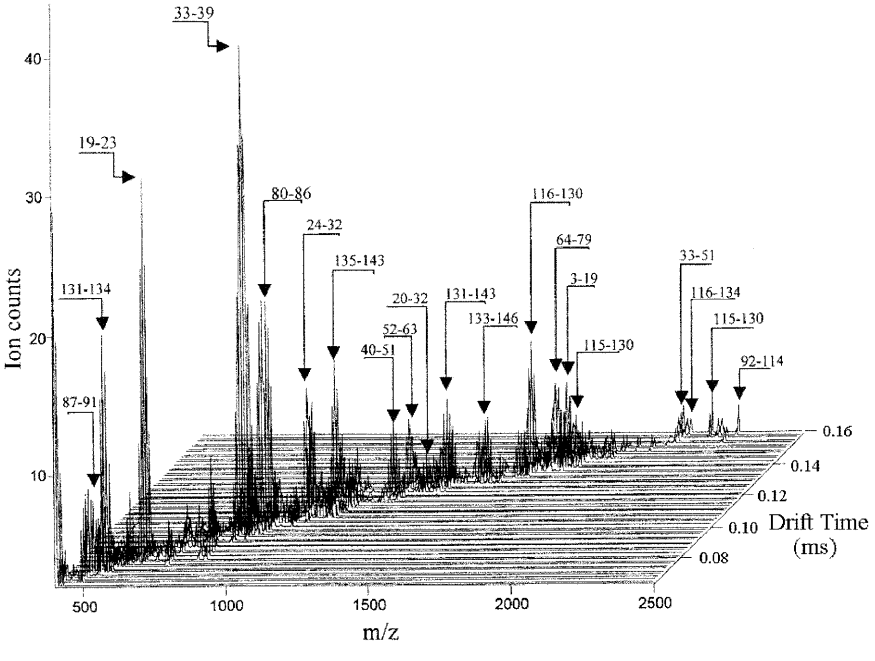

Fig. 8 3D plot of m/z against IMS drift time of a tryptic digest of thermally denatured chicken egg white lysozyme (Reproduced with permission from Ref. [50])

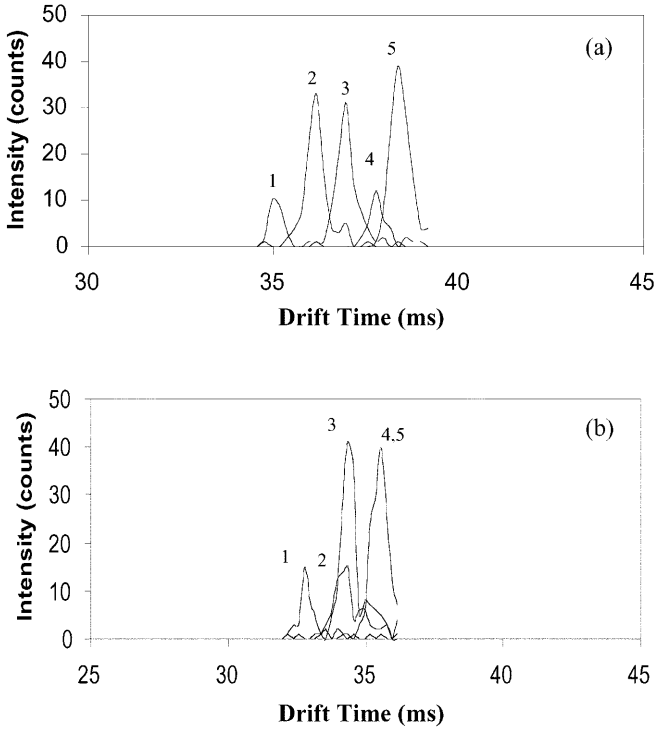

Fig. 9 Reconstructed selected-ion IMS separations of (**a**) five benzodiazepines and (**b**) five triazine herbicides using TOFMS detection. Conditions: 27 cm drift tube, 15 kV drift voltage, 20 kV electrospray, 25 °C, ~650 Torr (1 Torr=133.322 Pa), 0.5 μL min^{-1} sample, 0.2 ms gate pulse width, 35 Hz (IMS), 5 kHz (TOFMS), 30 s data collection, N_2 1500 mL min^{-1}. Peak identifications (in order as above): (**a**) oxazepam, diazepam, nitrazepam, clonazepam, and prazepam; (**b**) simetryn, ametryn, prometon, terbutryn, and prometryn

Conclusions

IMS is a separation technique that affords qualitative information associated with the average cross-sectional area of ions. When interfaced with a mass spectrometer, data can be collected which gives additional qualitative information (i.e., mass information). IMS has been successfully coupled to quadrupole, time-of-flight, and Fourier-transform ion cyclotron resonance mass spectrometry using radioactive ^{63}Ni, electrospray, laser, and matrix-assisted laser desorption ionization sources. Applications have been reported for the analysis of illicit drugs, explosives, chemical warfare degradation products, biomolecules, and combinatorial chemistry samples. Instrumentation has also been used to study ions formed in an electrospray source and to generate high-resolution IMS separations.

References

1. Karasek FW (1970) Res Dev 21:34–37
2. Karasek FW (1970) Res Dev 30:25–27
3. Eiceman GW (1991) Critical Rev Anal Chem 22:471–489
4. Spangler GE, Campbell DN, Vora KN, Carrico JP (1984) ISA Trans 23:17–28
5. St Louis RH, Hill HH Jr (1990) Anal Chem 21:321–355
6. Hill HH Jr, Siems WF, St Louis RH, McMinn DG (1990) Anal Chem 62:1201–1209A
7. Balm MA, Hill HH Jr (1982) Anal Chem 54:38–43
8. Snyder AP, Harden CS (1993) Anal Chem 65:299–306
9. Morrissey MA, Hill HH Jr (1989) J Chromatogr Sci 27:529–533
10. Huang MX, Markides KE, Lee ML (1991) Chromatographia 31:163–167
11. Snyder AP, Shoff DB (1991) Anal Chem 63:526–529
12. Lubman DM, Kolaitis L (1986) Anal Chem 58:1993–2001
13. Shumate CB, Hill HH Jr (1989) Anal Chem 61:601–606
14. McMinn DG, Kinzer JA, Shumate CB, Siems WF, Hill HH Jr (1990) J Microcol Sep 2:188–192
15. Revercomb HE, Mason EA (1975) Anal Chem 47:970–983
16. Karpas Z (1986) Anal Chem 74:153
17. Karpas Z, Stimac RM, Rappoport R (1988) Int J Mass Spectrom Ion Proc 83:163
18. Karpas Z (1989) Anal Chem 61:684
19. Karasek FW, Cohen MJ, Carroll DI (1971) J Chromatogr Sci 9: 390–392
20. Karasek FW, Kim SH, Hill HH Jr (1976) Anal Chem 48:1133–1137
21. Karasek FW, Denney DW, DeDecker EH (1974) Anal Chem 46:970–973
22. Kim SH, Betty KR, Karasek FW (1978) Anal Chem 50:1784–1788
23. Carr TW (1977) Anal Chem 49:828–831
24. Griffin GW, Dzidic I, Carroll DI, Stillwell RN, Horning EC (1973) Anal Chem 45:1204–1209
25. Karasek FW, Kilpatrick WD, Cohen MJ (1971) Anal Chem 43:1441–1447
26. Kilpatrick WD (1971) Abstracts from the 19th Annual Conference on Mass Spectrometry, Atlanta, GA, p 320
27. Karasek FW, Tatone OS (1972) Anal Chem 44:1758–1763
28. Lawrence AH, Nanji AA (1988) Biomed Environ Mass Spectrom 16:345–347
29. Lawrence AH (1986) Anal Chem 58:1269–1272
30. Kim SH, Spangler GE (1985) Anal Chem 57:567–569
31. Lubman DM, Huang SD, Kolaitis L (1987) Appl Spectrosc 41: 1371–1376
32. Guevremont KW, Siu KWM, Wang J, Ding L (1997) Anal Chem 69:3959–3965
33. Yansheng L, Clemmer DE (1997) Anal Chem 69:2504–2509
34. Hoaglund CH, Valentine SJ, Clemmer DE (1997) Anal Chem 69:4156–4161
35. Shelimov KB, Clemmer DE, Hudgins RR, Jarrold MF (1997) J Am Chem Soc 119:2240–2248
36. Dugourd Ph, Hudgins RR, Clemmer DE, Jarrold MF (1997) Rev Sci Instrum 68:1122–1129
37. Valentine SJ, Counterman AE, Hoaglund CS, Reilly JP, Clemmer DE (1998) J Am Soc Mass Spectrom 9:1213–1216
38. Hoaglund CS, Valentine SJ, Sporleder CR, Reilly JP, Clemmer DE (1998) Anal Chem 70:2236–2242
39. Henderson SC, Valentine SJ, Counterman AE, Clemmer DE (1999) Anal Chem 71:291–301
40. Srebalus CA, Li J, Marshall WS, Clemmer DE (1999) Anal Chem 71:3918–3927
41. Valentine SJ, Counterman AE, Clemmer DE (1999) J Am Soc Mass Spectrom 10:1188–1211
42. Hoaglund-Hyzer CS, Li J, Clemmer DE (2000) Anal Chem 72: 2737–2740
43. Srebalus CA, Li J, Marshall WS, Clemmer DE (2000) J Am Soc Mass Spectrom 11:352–335
44. Srebalus Barnes CA, Clemmer DE (2001) Anal Chem 73:424–433
45. Hoaglund-Hyzer CS, Clemmer DE (2001) Anal Chem 73:177–184
46. Wu C, Siems WF, Asbury GR, Hill HH Jr (1998) Anal Chem 70:4929–4938
47. Asbury GR, Hill HH Jr (2000) Anal Chem 72:580–584
48. Wu C, Siems WF, Hill HH Jr (2000) Anal Chem 72:396–403

49. Asbury GR, Wu C, Siems WF, Hill HH Jr (2000) Anal Chim Acta 404:273–283
50. Asbury GR, Klasmeier J, Hill HH Jr (2000) Talanta 50:1291–1298
51. Wu C, Siems WF, Klasmeier J, Hill HH Jr (2000) Anal Chem 72:391–395
52. Asbury GR, Hill HH Jr (2000) J Microcol Sep 12:172–178
53. Gillig JK, Ruotolo B, Stone EG, Russell DH, Fuhrer K, Gonin M, Schultz AJ (2000) Anal Chem 72:3965–3971
54. Bluhm BK, Gillig KJ, Russell DH (2000) Rev Sci Instrum 71: 4078–4086
55. Collins DC, Lee ML (2001) Ultrahigh speed separations using gas-phase electrophoresis, 24th Int Symp Capillary Chromatography and Electrophoresis, Las Vegas, NV
56. Collins DC, Lee ML (2001) Fresenius J Anal Chem 369:225–233
57. Carr TW (1977) Thin Solid Films 45:115
58. Carr TW, Needham CD (1978) Analysis of organic surface contamination by plasma chromatography–mass spectrometry, 4th Int Symp Contamination Control, Washington DC
59. Carr TW (1980) Analysis of organic surface contaminants by plasma chromatography-mass spectroscopy and Raman microprobe techniques, 8th Ann Proc IEEE, Reliability physics, New York, p 186
60. Carr TW, Corl EA, Liu CL, Majtenyi CG (1978) Quantitative H_2O determination in components using a plasma chromatograph-mass spectrometer, 16th Ann Proc IEEE, Reliability physics, New York, p 59
61. Purves RW, Guevremont R, Day S, Pipich CW, Matyjaszczyk (1998) Rev Sci Instrum 69:1–12
62. Ells B, Barnett DA, Froese K, Purves RW, Hrudey S, Guevremont R (1999) Anal Chem 71:4747–4752
63. Guevremont R, Purves RW (1999) J Am Soc Mass Spectrom 10:492–501
64. Barnett DA, Ells B, Guevremont R (1999) J Am Soc Mass Spectrom 10:1279–1284
65. Purves RW, Guevremont R (1999) Anal Chem 71:2346–2357
66. Purves RW, Barnett DA, Ells B, Guevremont R (2000) J Am Soc Mass Spectrom 11:738–745