Desorption electrospray ionization with a portable mass spectrometer: *in situ* analysis of ambient surfaces†

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Desorption electrospray ionization (DESI) is implemented on a portable mass spectrometer and used to demonstrate *in situ* detection of active ingredients in pharmaceutical preparations, alkaloids in plant tissues, explosives, chemical warfare agent simulants and agricultural chemicals from a variety of surfaces; air monitoring applications using DESI are also introduced.

The need for *in situ* chemical analysis has increased, especially for compounds detrimental to health or to the environment. Reliability, sensitivity and specificity are crucial in detecting trace levels of compounds such as toxic industrial species, explosives, chemical warfare agents and environmental toxins. On-site detection allows early warning of a harmful release, saving time and resources and increasing safety compared to lab analysis of field samples. Portable mass spectrometers are already the subject of intense interest for air monitoring, and capabilities for analysis of condensed-phase samples would greatly increase their value.[1,2]

DESI has previously been applied using commercial mass spectrometers to pharmaceutical agents, natural products, explosives and chemical warfare agents (CWAs).[3–10] In the present study, DESI is applied to detect low volatility and non-volatile compounds such as explosives, herbicides and pesticides using a custom-built field-portable instrument. Alternative ambient mass spectrometric techniques such as direct analysis in real time (DART)[11] and atmospheric-pressure solids analysis probe (ASAP)[12] also allow direct analysis, but neither they nor DESI have previously been applied using instrumentation suited to field analysis.

DESI is carried out by directing charged microdroplets generated in a pneumatically-assisted electrospray of an appropriate solvent onto a surface. Neutral analytes present on the surface can be released as secondary ions and detected under ambient conditions without any sample pretreatment. Since field-ready surface analysis with such sensitivity and selectivity has not been demonstrated before, coupling an ambient ionization technique such as DESI to a portable mass spectrometer is an important step to further the useful applications of mass spectrometry.

Experiments were carried out using a custom-built portable mass spectrometer fitted with a miniature cylindrical ion trap (CIT) mass analyzer. As previously reported,[13] this instrument features an atmospheric pressure inlet, allowing the use of atmospheric pressure chemical ionization (APCI) and spray ionization methods. To provide the large pressure differential needed, a three-stage, differentially-pumped vacuum manifold is employed, utilizing two small turbomolecular pumps and a rotary vane roughing pump. The vacuum system, ion optics, mass analyzer, control electronics system, and detection system have all been designed and built in-house. Besides demonstrating good analytical performance and having an inherent MS^n capability,[14] miniature CITs not only allow, but require operation at increased pressures ($\sim 10^{-4}$ Torr) for effective trapping of externally-generated ions. This reduces the vacuum requirements for a portable instrument featuring a direct atmospheric inlet. A modified OmniSpray™ ion source (Prosolia, Inc., Indianapolis, IN) was used for DESI on this instrument.

Previous DESI studies carried out using a ThermoFinnigan (San Jose, CA) LTQ bench-top mass spectrometer gave optimum results for small molecules when the capillary temperature, spray voltage and N_2 gas flow were set to 275 °C, 5 kV and 150 psi, respectively. Using the portable mass spectrometer, DESI was performed at ambient capillary temperature, a lower spray voltage ($\sim$3 kV) and a nebulizing N_2 gas flow of 80–120 psi; these lower power conditions are better suited to field analysis. The solvent spray and ion transfer capillary were positioned as reported in previous studies,[6] and the solvent used throughout the study was methanol–water (1 : 1). Both instruments gave similar spectra although water adducts were observed at ambient capillary temperatures.

The powerful high explosive RDX (trinitrohexahydro-1,3,5-triazine) is used as the base for several military explosive compositions.[5] It has a very low volatility and is difficult to analyze by traditional ionization methods. The ability to analyze RDX in trace quantities on ambient surfaces, even from mixtures, has been previously demonstrated by DESI.[5] Detection of RDX from three different surfaces (paper, plastic and metal) was demonstrated using the present portable instrument in the positive ion detection mode, with the fast analysis times (5–10 s) characteristic of DESI. The result obtained for 10 ng of material is shown in the Fig. 1a. The peak observed at *m*/*z* 223 corresponds to the $(M + H)^+$ ion. The limit of detection (LOD) established for this study was found to be <1 ng absolute deposited over an area of 1 cm^2 on a paper surface (Fig. 1b), with the actual area sampled by the nebulizing spray being significantly smaller.

Herbicides and pesticides used extensively in large-scale farming can result in the contamination of food stuffs and water supplies through groundwater run-off.[15,16] Direct and reliable on-site analysis of such chemicals from the surfaces of leaves, fruits or vegetables has yet to be demonstrated. In the present study,

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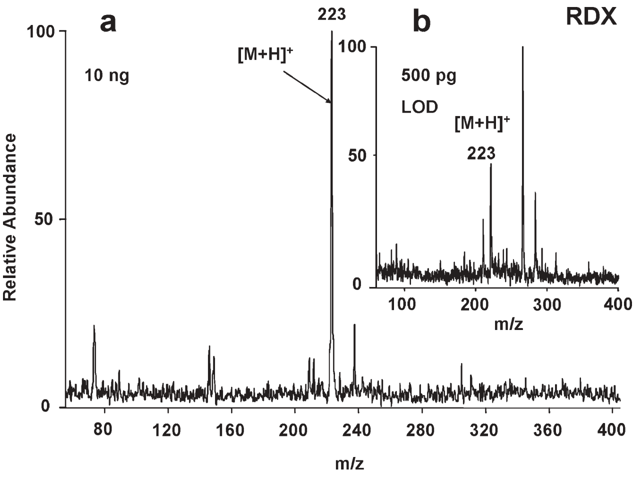

Fig. 1 Positive ion DESI mass spectrum of: (a) 10 ng of RDX deposited on 1 cm^2 of paper surface; (b) 500 pg of RDX (the LOD for this study) deposited on 1 cm^2 of paper surface.

DEET, alachlor and atrazine were detected from different surfaces, including direct analysis from leaf and vegetable surfaces.

DEET (*N*,*N*-diethyl-*m*-toluamide), an aromatic amide, is a commonly used insect repellent which is found in several topical products and insecticide sprays.[17] Alachlor (2-chloro-2′,6′-diethyl-*N*-(methoxymethyl)-acetanilide) is a widely used anilide pesticide which gives rise to a large number of transformation products which are potential pollutants in ground and surface waters.[18] Atrazine (2-chloro-4-(ethylamino)-6-(isopropylamino)-1,3,5-triazine) is a triazine herbicide which is used extensively to control broad-leaf weeds.[19] Trace quantities of each of these compounds could be analyzed from different surfaces by DESI using the portable MS. A DESI spectrum of 10 ng of DEET initially deposited onto paper can be seen in Fig. 2a, with the peak at *m*/*z* 192 corresponding to the $(M + H)^+$ ion. A fresh cornstalk leaf was spiked with the same quantity of DEET, and the resulting mass spectrum is shown in Fig. 2b. DEET (10 ng) was also detected from the surface of a tomato, a similar mass spectrum was obtained with the base peak at *m*/*z* 192 corresponding to the molecular ion.[12] Fig. 2c shows an MS/MS analysis of *m*/*z* 192, yielding the characteristic fragment ion at *m*/*z* 119 by loss of a neutral secondary amine of mass 73. A similar study was undertaken for the analysis of alachlor, which is discussed in the Supplementary Material.†

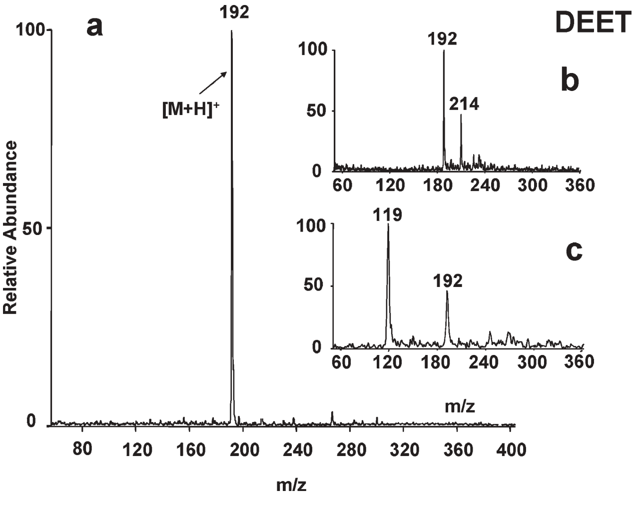

Fig. 2 Positive ion DESI mass spectrum of: (a) 10 ng of DEET deposited on 1 cm^2 of paper; (b) 10 ng of DEET deposited onto a cornstalk leaf. The peak at *m*/*z* 192 corresponds to $(M + H)^+$ and the peak at *m*/*z* 214 is from the leaf; (c) MS/MS analysis of *m*/*z* 192, showing a characteristic fragment at *m*/*z* 119.

A mixture containing equal proportions of DEET, alachlor and atrazine was prepared, and a sample containing 10 ng of each was deposited on Whatman® grade 5 filter paper with the resulting DESI mass spectrum shown in Fig. 3a. The spectrum shows the presence of all three analytes from the surface even at such low concentrations. From a previous study which compared APCI and ESI for the detection of pesticides and herbicides,[20] difficulty in analyzing all three compounds was shown when using just one ionization method and one ion detection mode (+ or −). However, using DESI, these compounds are detected in a single positive ion scan, showing DEET, atrazine and alachlor at *m*/*z* 192, 216 and 270, respectively. The chlorine isotopic signature was observable for both alachlor and atrazine, which contain one chlorine atom each. Due to the gentle ambient ionization conditions, little or no fragmentation is observed.

An Excedrin® tablet was also subjected to DESI analysis, as shown in Fig. 3b. In this case several adducts were observed,[4,11] most likely due to the low capillary temperature, causing incomplete evaporation of the solvent. Water adducts for all three active ingredients of Excedrin® (acetaminophen, aspirin and caffeine) were seen since each has the ability to form hydrogen bonds with excess water. These results differ from those of a previous study[4] when the temperature of the capillary was maintained at 275 °C and significant fragmentation and little or

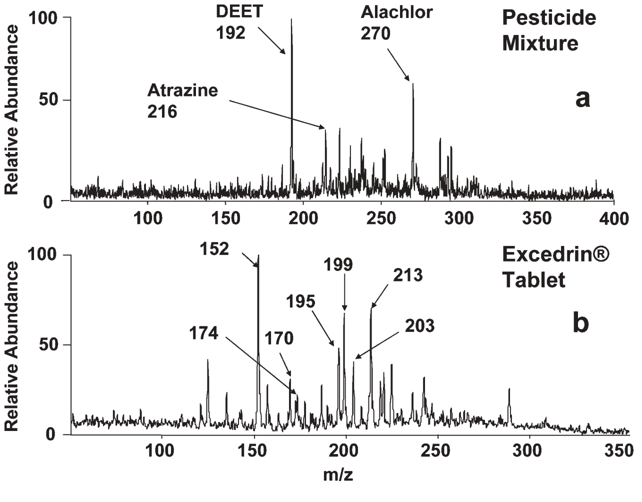

Fig. 3 (a) Positive ion DESI mass spectrum of a pesticide mixture containing 10 ng of each pesticide deposited directly onto 1 cm^2 of paper surface. The peaks at *m*/*z* 192, 216 and 270 correspond to DEET, atrazine and alachlor. (b) Positive ion DESI mass spectrum of an Excedrin® tablet containing acetaminophen (MW = 151), aspirin (MW = 180) and caffeine (MW = 194). The peaks at *m*/*z* 152, 170 and 174 correspond to protonated acetaminophen, its hydration product and (acetaminophen + $Na)^+$. The peaks at *m*/*z* 199 and 203 correspond to the hydration product of aspirin and (aspirin + $Na)^+$. The peaks at *m*/*z* 195 and 213 correspond to protonated caffeine and its hydration product, respectively.

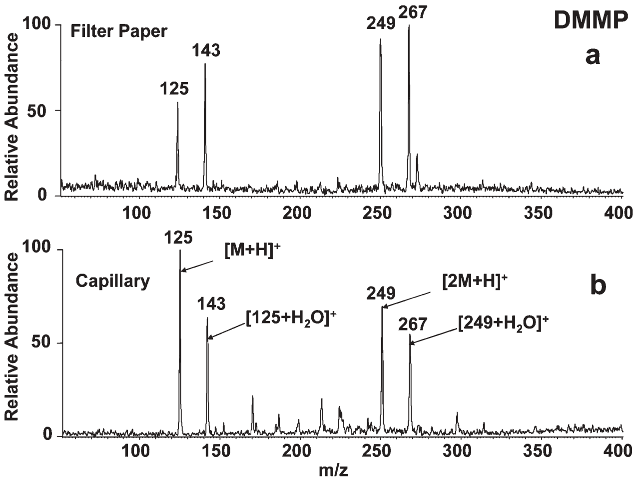

Fig. 4 DESI mass spectrum of 111 ppb of DMMP in air deposited onto: (a) Whatman® grade 5 filter paper; (b) 508 μm inner diameter, 7 mm long stainless steel capillary.

no water adduct formation were observed. However, sodium adducts were observed in both studies for acetaminophen and aspirin due the presence of sodium in the tablet matrix. Direct analysis of plant tissue was also demonstrated by examining a poison hemlock seed; the results are discussed in the Supplementary Material.† Combining portable mass spectrometry and DESI could be useful in high-throughput pharmaceutical analysis and in screening plants for active pharmaceuticals outside the laboratory. This could also prove useful in forensic analysis and law enforcement applications.

Air monitoring is important to *in situ* analysis, especially for high toxicity compounds.[21] The ability to detect vapors in air has not been demonstrated by DESI. A "load and release" technique was designed in which ambient air samples were passed through a sorbent material, preconcentrating analytes for later desorption and ionization by DESI. The analyte was loaded onto two separate media, Whatman® grade 5 filter paper and a stainless steel capillary (508 μm ID, 7 mm long). Dimethyl methylphosphonate (DMMP), a common surrogate for Sarin, a highly toxic organophosphate CWA, was studied. Vapor samples of DMMP with known concentration were generated by the dilution of saturated headspace using mass flow controllers.

Preconcentration onto filter paper is routinely used in air monitoring.[22] A mass spectrum following this "load and release" analysis applied to filter paper is seen in Fig. 4a, where 111 ppb dimethyl methylphosphonate (DMMP) in OSHA D breathable air was passed through a SKC® air monitoring cassette using a gas throughput of 5.72 L min^{-1}. After two minutes of loading ($\sim$7 μg of total analyte passed through the filter paper), the filter paper was subjected to DESI, showing both the protonated monomer and dimer of DMMP, as well as water adducts of each.

Using the same concentrations, gas throughput and sampling time as for the filter paper studies, a DMMP sample was allowed to pass through a stainless steel capillary. After sample loading, the capillary was placed in-line with the capillary inlet. When the pneumatically-assisted electrospray from the DESI source was directed into the entrance of the capillary, trapped analyte molecules were desorbed and the resultant ions were transferred through the capillary into the instrument, and they gave rise to the spectrum shown in Fig. 4b. The DESI mass spectrum of DMMP from the capillary and the filter paper showed very similar characteristics at the same concentration of analyte. Future work will include the use of capillaries with suitable sorbent phases and thermally-assisted desorption.

The first coupling of DESI to a field-portable instrument has been successfully demonstrated. Sensitive, selective and rapid detection can be achieved for surface compounds relevant to field analysis, such as chemical warfare agents, explosives and agricultural chemicals. A novel approach to air monitoring has also been investigated. Further applications could prove invaluable to process monitoring, homeland security, forensics, environmental and industrial hygiene, as well as food safety.

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