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Detection and identification of immobilized low-volatility organophosphates by desorption ionization mass spectrometry

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ABSTRACT

Two desorption ionization mass spectrometry (MS) techniques – ultraviolet laser desorption/ionization (LDI) and desorption electrospray ionization (DESI) – have been used to detect and identify low-volatility organophosphates when deposited on surfaces or loaded into the pore volume of porous inorganic or polymeric organic powders. The insecticides malathion and dicrotophos were chosen for this study as simulants of low vapor pressure chemical warfare agents which are inherently difficult to detect directly by traditional methods. Both liquid and powdered forms of either insecticide were readily detected by LDI or DESI MS. LDI MS was performed on a miniaturized home-built time-of-flight (TOF) mass spectrometer and a commercial TOF/TOF instrument. For DESI MS, a home-built ion source was interfaced to a commercial quadrupole ion trap. In LDI, intact molecular ion signatures could be acquired by using an appropriate cationizing agent and powder additive in positive ion mode. Tandem MS was used to confirm the identity of each analyte based on the observed characteristic fragmentation pattern. In DESI, less than 100 pg of the liquid insecticides spotted on clean surfaces were detected, while detection limits for the powder-loaded preparations were lower than 1 μg. The effects of sample surface, salt additives, nanoparticle admixtures, and analyte solubility on the LDI and DESI MS sensitivity have been investigated as well.

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1. Introduction

The rapid and confident detection and identification of toxic chemicals is critically important to homeland security, chemical warfare (CW) countermeasures, environmental monitoring, and industrial accident remediation. One key class of toxic analytes is the organophosphate pesticides and nerve agents. Detection of G-class agents with relatively high vapor pressures (e.g., Sarin and Soman) is relatively straightforward by techniques such as ion mobility spectrometry, surface acoustic wave detection, and electron ionization mass spectrometry [1–3]. As the vapor pressure of such toxic materials decreases below $\sim 10^{-4}$ torr (e.g., VX), their detection becomes much more problematic. Detection is further complicated when pesticides or CW agents are immobilized onto organic or inorganic carriers prior to deployment, creating a particulate aerosol that can be inhaled or trapped in small spaces [4,5]. This newer type of potential CW threats requires newer CW sensor methodologies. Such sensor methodologies can also be utilized for analysis of powdered substrates employed as carriers for transport and delivery of pesticides, insecticides, and pharmaceuticals. In addition, rapid response in the case of an industrial accident involving hazardous chemicals also requires the capability to confidently analyze powdered substrates (sand, cement, flour, etc.) for the presence of toxic chemicals.

Conventional CW sensors are based on a variety of detection technologies, including ion mobility spectroscopy (IMS), surface acoustic wave, flame photometric detection (FPD), photoionization detection, mass spectrometry (MS), Fourier transform infrared spectroscopy, etc. [2]. The vast majority of these CW detection devices are configured as vapor detectors and do not easily accommodate low vapor pressure materials that may be dispersed as liquid or dry aerosols. Certain FPD devices are claimed to be effective for aerosol detection, but FPD provides information only for the elemental constituents (e.g., phosphorous, sulfur), and is not specific to individual compounds. Heated inlet systems for IMS, MS, and gas-chromatography/MS instruments have been designed to avoid condensation and facilitate desorption of low vapor pressure analytes, but these systems only provide limited success. A number of desorption/ionization techniques have been developed over the years for the MS analysis of non-volatile molecules, predominantly peptides and proteins. Among those are a variety of LDI techniques [6,7] or particle impact-induced desorption/ionization

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[8]. Recently, DESI (and a host of related ambient ionization methods; see [9] and references therein) has emerged as a powerful tool for studying condensed-phase analytes.

LDI has been traditionally used for the MS detection and structural characterization of low mass non-volatile compounds (synthetic as well as natural products) for more than three decades [10–13]. Several papers describe LDI MS-based detection of environmental contaminants (including pesticides) either from surfaces [14] or adsorbed as residues on individual particles [15,16]. Recently, individual particle LDI TOF MS was applied to detection of CW simulants in micro-sized droplets, aerosolized from liquids [17].

DESI is a versatile atmospheric pressure ionization technique for the rapid *in situ* MS detection of condensed-phase analytes [18,19]. In contrast to LDI, DESI has been developed fairly recently. DESI employs a high-velocity jet of electrosprayed droplets directed toward a sample deposited on a surface placed proximal to the capillary inlet of a mass spectrometer. These droplets impact the sample and cause the analyte to be desorbed from the surface, ionized, and transferred into the mass spectrometer for detection. While the mechanisms of DESI remain the topic of current investigations [9,18–20], this ionization method provides for fast, direct analysis of samples at atmospheric pressure without the need for complex sample cleanup or preparation. Recently, DESI has been successfully interfaced to a miniature rectilinear ion trap MS for possible field applications [21]. DESI has been used previously to analyze a wide variety of substances: pharmaceuticals [18,22–24], illicit drugs [25–28], explosives [18,29–32], polymers [33,34], peptides/proteins [18,35–37], microorganisms [38], and tissue samples [39,40]. Recent work has shown that DESI MS is also useful for the sensitive detection of CW agents, simulants, and their hydrolysis products [31,41–43]. However, these studies investigated only the relatively high-volatility CW simulants and agents, such as DMMP and G-series nerve agents (vapor pressure >0.04 torr), and did not determine the effect of immobilizing the analytes on powdered substrates.

Here we report data from the evaluation of two desorption/ionization techniques – ultraviolet (UV) LDI and DESI – for the rapid MS analysis and identification of low-volatility organophosphate pesticides when deposited on surfaces or loaded into the pore volume of porous inorganic or polymeric organic powders. We note that detection by either LDI or DESI MS of liquid organophosphate analytes loaded into the pore volume of solid particles, such that the powder remains free flowing and non-agglomerated, has not been demonstrated so far. Related studies have utilized secondary ion mass spectrometry [44,45] or single-particle aerosol time-of-flight (TOF) MS [16] to detect the nerve agent VX, the blister agent HD, or pesticides, adsorbed onto the surface of soil particles. Previously, DESI has been applied to detect analytes separated by silica-based thin layer chromatography (TLC) [46,47], which may be related to the silica powder immobilizing substrate employed in these studies. However, effects of the silica plate binder (often an organic polymer or calcium sulfate) and mobile phase salt (ammonium acetate) on DESI from such particle-containing TLC substrates is not known. Additionally, the exact loadings of analyte to particulate are more difficult to evaluate in the TLC studies than in the current work.

2. Experimental

2.1. Materials

Malathion (99% purity; MW_{mono} 330.0 Da; vapor pressure at 25 °C 3.4×10^{-6} torr) and dicrotophos (99% purity; MW_{mono} 237.1 Da; vapor pressure at 25 °C 1.6×10^{-4} torr) were obtained from Chem Service (West Chester, PA) and used without further purification. These were diluted as required for MS analysis (see below for details). Hydrophobic, food-grade modified silicon dioxide powder (Hi-Sil H303, 25 μm median particle size) was kindly provided by PPG Industries Inc. (Pittsburgh, PA). Diatomaceous earth (Celite 521, 3.5 μm median particle size), and alumina (activity grade I, type WN-6, neutral, ~50–200 μm particles) were obtained from Sigma–Aldrich (St. Louis, MO). Polyethylene powder (<20 μm particle size) was purchased from Micro Powders Inc. (Tarrytown, NY). Additional immobilizing agents, including talcum powder and cornstarch (particle sizes unknown) were obtained from local food markets and used without purification. In addition, an insecticide rose dust (Bonide brand) containing 3.00% malathion by weight in an unspecified inert background was purchased from a local garden supply store and analyzed directly. High-purity solvents were purchased from Sigma–Aldrich. 30 nm Si particles (Meliorum Technologies, Rochester, NY) were washed with acetonitrile and resuspended in acetonitrile for a final concentration of ~2 mg/mL.

2.2. Immobilized organophosphate preparation

Dicrotophos or malathion was immobilized on each of the powdered substrates by combining the appropriate amount of pesticide dissolved in methylene chloride with each immobilizing agent in a 50 mL round-bottom flask. In general, three different concentrations of pesticide in each immobilizing agent were prepared: approximately 10%, 1%, and 0.1% by weight (exact concentrations specified in the text). This mixture was stirred for 30 min. The solvent was evaporated using a rotovap equipped with a glass–wool-packed adapter to minimize migration of the immobilized pesticide. The resulting solid was placed under vacuum (0.1 torr) using a glass–wool-packed adapter for 90 min to remove residual solvent. Immobilized preparations were stored in air-tight containers until analysis.

2.3. LDI mass spectrometry

A home-built miniaturized reflectron TOF instrument [48] or a commercial TOF/TOF instrument (Autoflex, Bruker Daltonics, Billerica, MA) were used to acquire spectra in positive ion mode using a N_2 laser at 337 nm. The typical accelerating voltages for each instrument were 10 or 20 kV, respectively, and delayed extraction (~100 ns delay time) was used in the commercial instrument. For tandem TOF/TOF MS, ions were first extracted at 6 kV in the first leg of the instrument. The respective precursor ion and the fragment ions were then selected (isolated) in an ion gate, before re-acceleration in the second (reflectron) leg to 23 keV total energy for a singly charged precursor ion [49]. From several tens to several hundred single laser shot traces were summed for each MS or MS/MS spectrum. Standard commercial (Bruker Daltonics) or in-house written (for the home-built instrument) software was used for post-acquisition MS data analysis. CsI cluster ions were used for calibration up to m/z 1000. Samples for LDI MS were deposited on metal (Al or steel) substrates either neat or mixed with the Si nanoparticle solution and a saturated NaCl solution in ethanol (2:2:1 sample:Si:NaCl, by volume) and allowed to air dry.

2.4. DESI mass spectrometry

DESI MS and MS/MS data were acquired on a Thermo Finnigan LCQ Deca XP Plus quadrupole ion trap mass spectrometer interfaced to a home-built DESI source. The DESI source was essentially

identical to the device described by Cooks and co-workers [18]. The DESI sprayer consisted of a Swagelok tee and a fused silica 150 μm o.d., 50 μm i.d. external-taper tip capillary (New Objective, Woburn MA), which protruded ~0.5 mm from an outer fused silica capillary (360 μm o.d./250 μm i.d.). A 1:1 mixture of water:methanol was pumped at 1.5 μL/min through the inner capillary, while the outer capillary was used to supply a coaxial spray of high-pressure nitrogen gas (100 psi measured at the tank regulator). 4.5 kV was applied to the solution through a conductive union placed behind the DESI sprayer. The capillary inlet to the mass spectrometer was held at 30 V and 250 °C.

Liquid samples were diluted in methanol or 1:1 methanol:water (see text) and 0.5–1 μL was spotted and dried on a sample slide. Multiple types of sample slides were tested for this study, including: glass, PTFE, kapton, and paper. PTFE and kapton were found to provide the highest signal levels and reproducibility under our conditions and were selected for further sample and methods characterization. For the immobilized powder samples, approximately 1 mg of each was affixed to double-sided tape (Scotch 3 M brand) on a kapton slide. Excess powder was manually removed by lightly scraping the surface. All sample slides were mounted on an *x*, *y*, *z*-stage which allowed for manual optimization of sample position relative to the DESI sprayer. Typical sample distances and angles were 2 mm needle-sample distance at an angle of 45° and 0.5 mm sample-inlet distance at an angle of <5°.

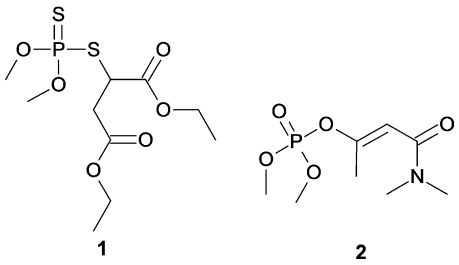
DESI MS spectra were acquired in positive ion mode in the range from 50 to 500 *m*/*z* using Xcalibur v1.3 (Thermo Finnigan). Neither malathion nor dicrotophos was sensitively detected in the negative ion mode. Automatic gain control was set to 3 microscans with a maximum of 200 ms injection time. Spectra were continuously collected as the sample stage was slowly moved across the DESI spray, resulting in a total MS collection time of approximately 30 s. For MS/MS, the precursor ion was isolated (±3 *m*/*z* window) and then fragmented by collision-induced dissociation (CID) at a relative collision energy of 25–35% (arbitrary units). Only minute quantities (<1 mg) were handled and analyzed by DESI MS to avoid significant exposure.

2.5. Safety considerations

Malathion and dicrotophos are organophosphate insecticides and are known to be moderately toxic to humans. They should be handled carefully by trained personnel under controlled conditions in a chemical fume hood.

3. Results and discussion

Here we evaluate two desorption ionization techniques; direct laser desorption/ionization (LDI) and desorption electrospray ionization (DESI) for the rapid MS-based detection, identification, and confirmation of low vapor pressure organophosphate chemicals in both a liquid and powder-immobilized state. UV LDI MS and tandem MS (MS/MS) were performed on a commercial lab-grade TOF/TOF instrument. We further evaluated the applicability of a field-portable LDI TOF instrument [48], initially designed for MALDI MS-based detection of bioagents [50], as a versatile detector of low vapor pressure chemicals. For DESI MS, a home-built ion source was interfaced to a commercial quadrupole ion trap. In the present study, two widely used organophosphate insecticides, malathion and dicrotophos (Scheme 1), were selected due to their relatively low vapor pressure (<10^{-4} torr) and high stability, which both contribute to extended environmental persistence. Using MS and MS/MS instruments, interfaced to either LD or DESI ion sources, we successfully detected dicrotophos and malathion deposited on surfaces (such as paper and plastics) and when loaded into the pore volume of commonly available inorganic or polymeric powders.



Scheme 1. Structures of malathion (1) and dicrotophos (2).

3.1. LDI MS of organophosphate standard solutions

LDI MS was performed without any instrument modifications by utilizing a commercially available TOF instrument and a prototype miniature TOF instrument. Further, we compared the effect of Si nanoparticle additives [51] on the overall LDI molecular ion yields from such organophosphate compounds.

A characteristic feature of both infrared and UV direct LDI is the predominance of alkali metal adduct molecular ions in the positive ion mass spectra of non-volatile compounds [52,53]. In our studies, direct positive ion LDI MS of neat malathion and dicrotophos yielded $[M+H]^+$ ions as well as alkali cation adduct ions. For neat malathion (99% purity), the $[M+H]^+$ ion signals were weak, while the predominant molecular ion species were alkali cation adducts: $[M+Na]^+$ and $[M+K]^+$ (Fig. 1(a)). $[M+H]^+$ ion signals were more pronounced for neat dicrotophos (99% purity) deposited directly onto a stainless steel slide. Addition of salts (e.g., NaCl) to the neat samples promoted alkali cation adduct ion formation, but did not significantly improve detection sensitivity (not shown). Overall detection sensitivity for these samples without additives was relatively poor: limits of detection (LODs) were observed to be ~100 μg deposited onto several mm^2 surface area.

The use of nanoparticles for enhancing LDI yields from non-volatile compounds (such as intact proteins) has been demonstrated early on by Tanaka et al. [54], and a variety of nanoscale structures (including nanoparticle substrates) enhancing LDI ion yields have been reviewed recently [55]. In our studies, addition of the 30 nm Si nanoparticle suspensions to the sample surface increased significantly the cationized molecular ion yields in positive mode for either TOF instrument (Figs. 1(b), 2(b), and 3), thus facilitating compound detection at lower concentrations. The LODs for malathion and dicrotophos mixed with salt and Si nanoparticles were estimated to be approximately 20 ng spotted on the slide, representing a 5000-fold increase in sensitivity as compared to without the additives. TOF/TOF MS of the $[M+Na]^+$ species of malathion (inset Fig. 1(b)) showed several intense fragment peaks that can be rationalized by losses of the thiophosphate moiety, e.g., at *m*/*z* 229 (loss of $C_2H_6O_2PS$) and *m*/*z* 197 (loss of $C_2H_6O_2PS_2$). Similarly, TOF/TOF MS of the $[M+Na]^+$ species of dicrotophos (inset Fig. 2(b)) resulted in two characteristic fragments that were identical to the fragments observed in DESI tandem MS of the same species (see below for explanation). Analogous solutions were also analyzed in parallel on the miniature TOF instrument. A comparison of Figs. 1 and 2 with Fig. 3 illustrates that, although the sensitivity of the miniature prototype TOF instrument is lower than that of the commercial, laboratory-scale instrument, the spectra are very comparable and show promise for further development of field-portable LDI–TOF detectors for this class of chemical compounds.

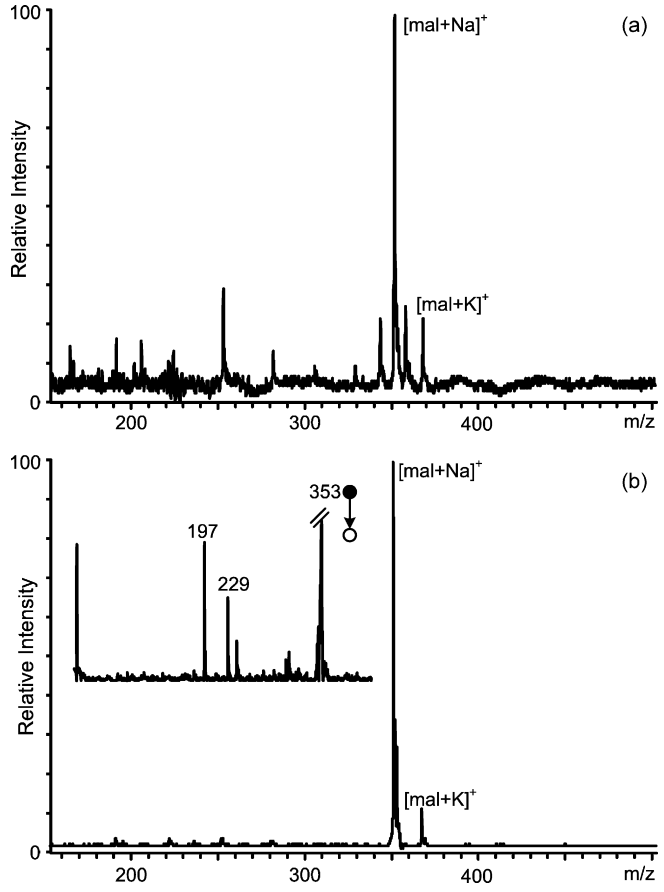


Fig. 1. (a) LDI mass spectrum of neat malathion; (b) LDI mass spectrum of 1 mg/mL solution of malathion in methanol mixed with silicon nanoparticles and NaCl (see text). Inset: LIFT MS/MS of the sodiated malathion species. Spectra were acquired on commercial TOF instrumentation.

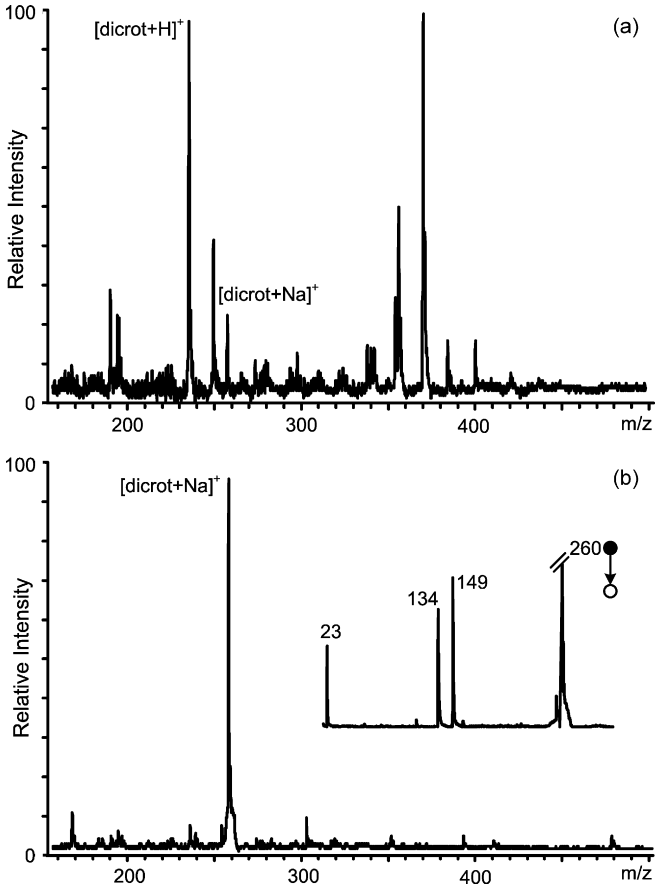


Fig. 2. (a) LDI mass spectrum of neat dicrotophos; (b) LDI mass spectrum of 1 mg/mL solution of dicrotophos in 50:50 methanol:water mixed with silicon nanoparticles and NaCl (see text). Inset: LIFT MS/MS of the sodiated dicrotophos species. Spectra were acquired on commercial TOF instrumentation.

3.2. DESI MS of organophosphate standard solutions

Solutions containing malathion and dicrotophos were analyzed to determine the characteristic MS and MS/MS ion signatures for each compound. The DESI mass spectrum of malathion (1 μL deposited from 10 μg/mL solution in methanol onto PTFE) is shown on Fig. 4(a). The molecular $[M+H]^+$ and $[M+Na]^+$ ions were observed at *m/z* 331 and 353, respectively. These assignments were subsequently confirmed by CID tandem mass spectrometry (MS/MS) which showed the characteristic loss of an ethoxy group from the respective protonated malathion (see Fig. 4(a) inset) [56]. A major $[M+18]^+$ peak was also regularly observed in the DESI spectrum, which we tentatively attribute to the formation of a stable NH_4^+ adduct [31] due to impurities present in the neat pesticide stocks (although $[H_2O]^{\bullet+}$ adduct cannot be excluded). This adduct was more prevalent at lower capillary temperatures and voltages (mild desolvation). However, it could not be completely eliminated even under harsher desolvation conditions that resulted in significant in-source fragmentation. The $[M+18]^+$ adduct readily dissociated upon MS/MS, resulting in protonated malathion at *m/z* 331. Experimental conditions for further DESI MS analysis, including DESI source distances, voltages, solvent flow rate, and sample stage surface, were optimized with this sample (optimal parameters listed in Section 2).

Serial dilutions of malathion in methanol were used to establish approximate LODs for this compound under the specific conditions employed. A good quality DESI MS spectrum was observed from a 100 ng/mL solution. This corresponds to 100 pg of malathion applied to a surface with a spot area of approximately 2.5 mm^2. $[M+H]^+$ ions were observed with a S/N of >3:1 under these experimental conditions. Malathion could not be detected after further 10-fold dilutions. It should be noted, however, that the sample spotted on a surface is not completely consumed during the DESI process. Therefore this value represents a practical limit of detection, while ultimate limits may be somewhat lower, as illustrated in recent quantitative DESI studies [57]. The LOD could be improved considerably with more efficient ion collection/transfer [58], the use of more advanced ion trap designs (e.g., the linear trap configuration), or by using selection ion or selected reaction monitoring (SIM/SRM).

Similar trends were observed for serial dilutions of dicrotophos in 50/50 methanol/water. Fig. 4(b) illustrates the typical DESI spectrum resulting from a 10 μg/mL solution spotted on a kapton surface. In this case, $[M+H]^+$, $[M+18]^+$ and $[M+Na]^+$ species were also observed with high S/N at *m/z* 238, 255, and 260, respectively. Additional species attributed to noncovalent dimers (e.g., $[2M+Na]^+$) were also observed, probably due to the relatively large quantity of sample deposited. MS/MS of the protonated dicrotophos produced fragment ions at *m/z* 193 and 112, corresponding to the loss of C_2H_7N or $C_2H_7PO_4$ from the protonated species, respectively, in agreement with previous studies [56]. We established practical LOD of approximately 50 pg dicrotophos spotted onto a 2.5 mm^2 surface spot by dilutions analogous to those performed with malathion. Thus, DESI MS shows good sensitivity for detection and identification of these low-volatility organophosphate chemicals. Furthermore, MS/MS can be employed to quickly confirm the

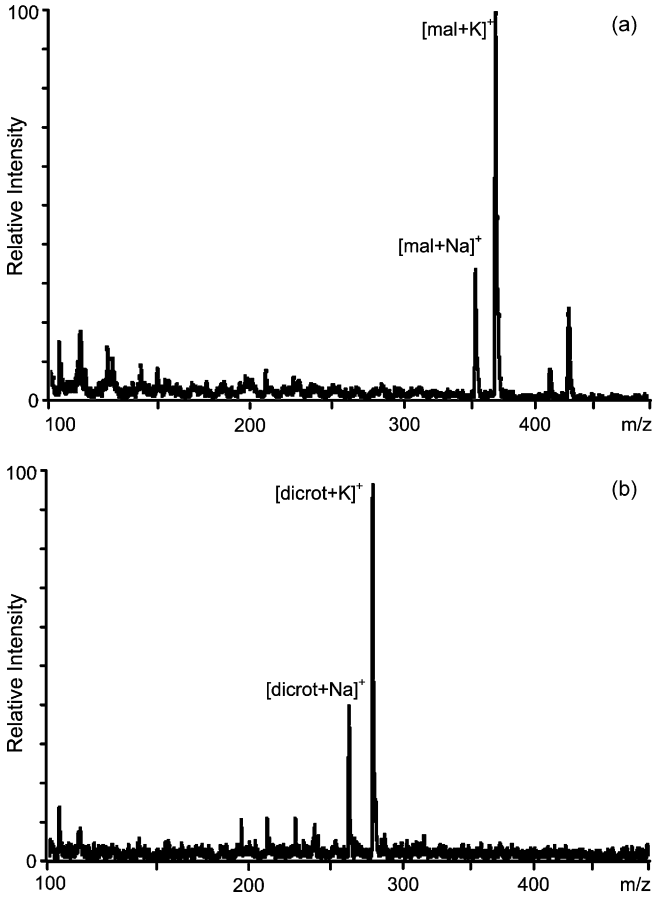


Fig. 3. LDI mass spectra obtained on a prototype miniature TOF instrument of: (a) 1 mg/mL malathion in methanol, or (b) 1 mg/mL dicrotophos in 50:50 methanol:water. In both cases, analytes were mixed with silicon nanoparticles and NaCl (see text).

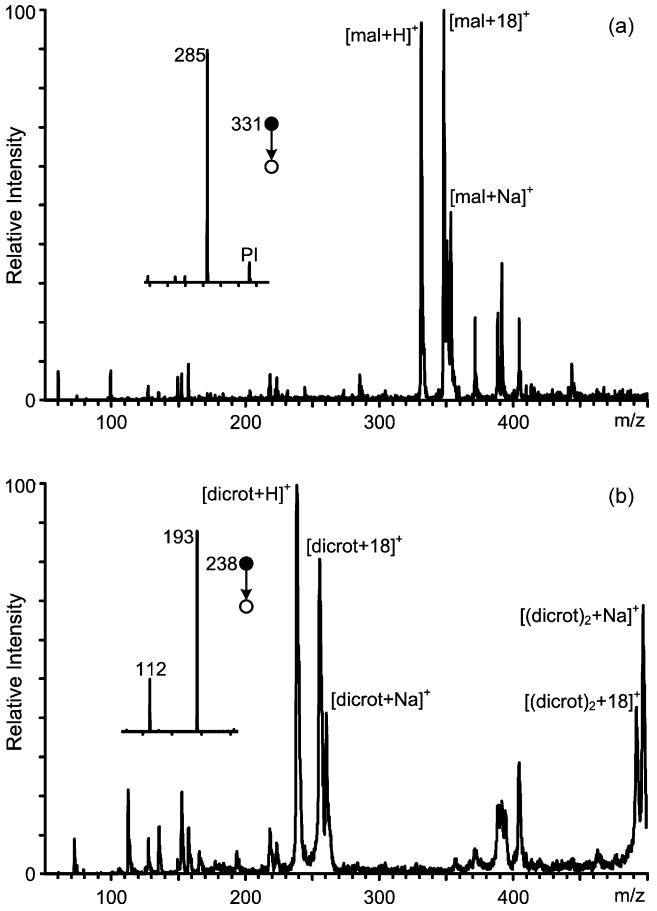


Fig. 4. (a) DESI mass spectrum from 1 μL of a 10 μg/mL solutions of malathion in methanol deposited onto a PTFE surface; inset: MS/MS of $[mal+H]^+$ precursor ion (PI) at 331 *m/z*; (b) DESI mass spectrum from 1 μL of a 10 μg/mL solutions of dicrotophos in 50/50 methanol/water deposited onto a kapton surface; inset: MS/MS of $[dicrot+H]^+$ ion at 238 *m/z*.

initial identification based on the compounds' characteristic fragmentation patterns, especially in efforts to deconvolve complex environmental mixtures.

3.3. LDI and DESI MS of particle-immobilized organophosphates

Following parameter optimization and successful detection of dicrotophos and malathion spotted on a surface, we next evaluated the LDI and DESI detection sensitivities for dicrotophos loaded into the pore volume of various powdered, solid supports. To our knowledge, neither LDI nor DESI MS have been previously applied to the detection of particle volume-loaded organophosphate chemicals. Diatomaceous earth (DE) and HiSil powder were chosen for our study due to their superior oil-absorption properties (manufacturer's specification, DE: ~150% (w/w); HiSil: ~200% (w/w)). These high oil-absorption particulates allow liquids to be converted to free-flowing powders. In this case, the vast majority of the liquid is loaded into the pore volume of the powder rather than on the surface, and insufficient liquid is present on the powder surface to cause significant agglomeration of the particles. Demonstrating the ability of LDI and DESI MS to detect the analyte loaded in the pores has been a key motivation in the present work. Other readily available powders were also used to test the effect of different classes of carrier particles (also mimicking "dirty" backgrounds). Three decades of concentrations of dicrotophos prepared on powdered solid supports (~10%, 1%, and 0.1% (w/w)) were studied to simulate a range of concentrations that might be encountered. In addition, a commercial rose dust insecticide containing 3.00% malathion (w/w) as an active ingredient was also analyzed.

DESI utilizes a high-velocity nebulization gas to facilitate analyte volatilization/desorption from the surface [19]. Therefore, care was taken to ensure that the powder samples were not blown into the capillary entrance of the mass spectrometer. This required the powders to be affixed to double-sided tape on the slide. Excess dust was manually removed by scraping the surface prior to analysis. Exposure of the sample to the DESI spray was kept to a minimum (usually <30 s). Blank samples were run after each sample to verify that no contamination of the source-inlet region of the mass spectrometer had occurred due to aerosolization of the powdered particles.

Fig. 5(a) shows a typical spectrum resulting from DESI MS analysis of 0.16% dicrotophos immobilized to DE. The most intense peak in this spectrum corresponds to the sodiated dicrotophos, which can be explained by the high amounts of sodium likely to be present in the DE. Signals for $[M+H]^+$ and a sodium-bound dimer $[2M+Na]^+$ were also seen. Similar spectra were observed for 1.36% and 8.76% dicrotophos in DE (not shown). DESI MS/MS of the $[M+Na]^+$ species produced a fragmentation pattern (Fig. 5(a) inset) that is analogous to the one observed for the protonated dicrotophos. Losses of C_2H_7N, $C_2H_7PO_3$, and $C_2H_7PO_4$ from the $[M+Na]^+$ are consistent with the fragment ions observed at *m/z* 215, 149, and 134, respectively. Although less sensitive, LDI MS was also successfully used to detect particle-immobilized dicrotophos. LDI of 8.76% dicrotophos

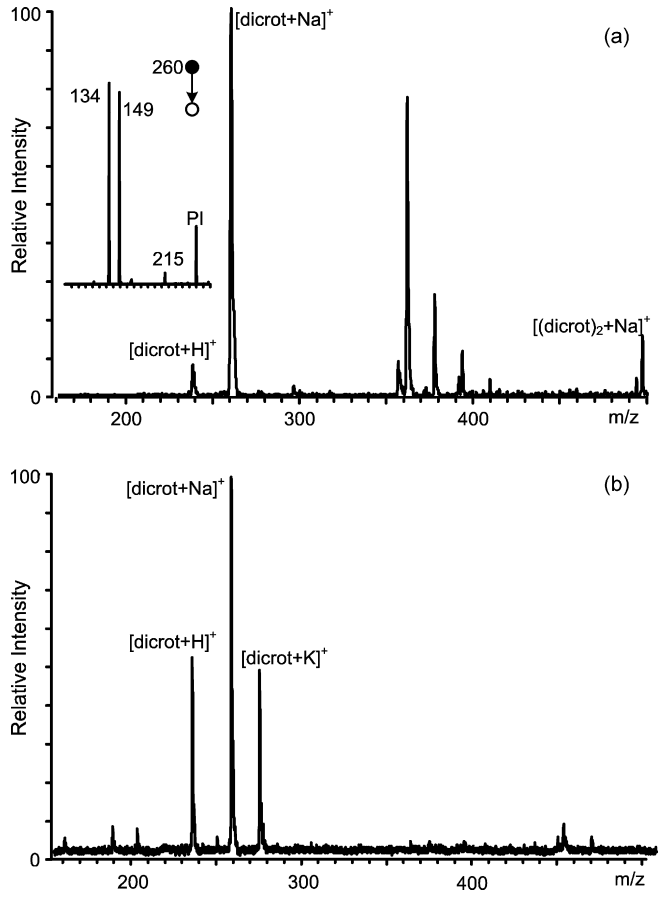


Fig. 5. (a) DESI mass spectrum of 0.16% (w/w) dicrotophos immobilized on diatomaceous earth; inset: MS/MS of $[M+Na]^+$ at 260 *m/z*; (b) LDI MS spectrum of 8.76% dicrotophos in diatomaceous earth, mixed with NaCl and nanoparticle solutions. Unlabeled peaks in (a) originate from unknown impurities present in the neat stock, the immobilizing substrate, and in the DESI solvent.

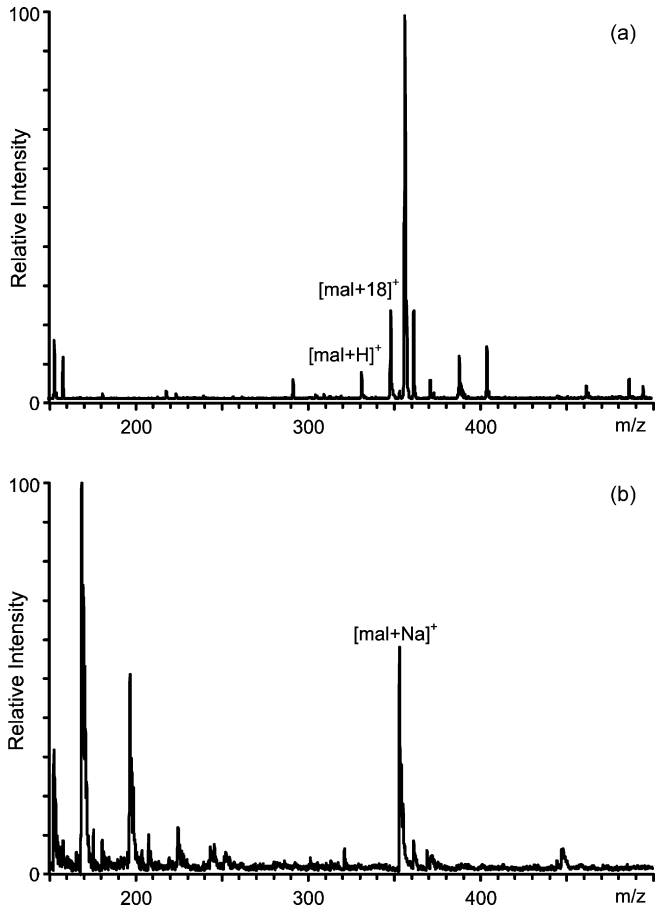


Fig. 6. (a) DESI mass spectrum of 0.17% (w/w) malathion immobilized on HiSil powder. (b) LDI mass spectrum of 9.5% malathion in HiSil with NaCl and nanoparticle solutions. Unlabeled peaks originate from impurities present in the neat stock, the immobilizing substrate, and in the DESI solvent.

immobilized on DE and mixed with Si nanoparticles and NaCl is shown on Fig. 5(b). In addition to the protonated and sodiated molecular ion species, a K^+ ion adduct is observed in this LDI spectrum as well. In an analogous fashion, the DESI and LDI positive ion mass spectra of malathion, loaded on HiSil powder, are presented on Fig. 6. In both cases, strong $[M+H]^+$ or $[M+Na]^+$ ion signals are observed.

Dicrotophos was also analyzed when immobilized on a variety of other powdered substrates. These included both mineral- and polymer-based powders: HiSil (containing 0.139%, 1.62%, and 8.93% dicrotophos), talcum powder (0.18%, 0.94%, and 8.62%), alumina (0.14%, 1.07%, and 9.05%), polyethylene powder (2.70%), and cornstarch (0.2%, 1.14%, and 8.9% dicrotophos). Sample spectra for dicrotophos in each powdered background are shown in Supplementary Data, Fig. 1. Sodiated and protonated species clearly identify the presence of dicrotophos in each sample. Peaks in the mass spectrum attributed to unknown contaminants in the various immobilizing agents and the double-sided tape used for mounting were present in each case, but did not interfere with the detection and identification of dicrotophos. The results were somewhat different for dicrotophos mixed with the alumina. Although signal for protonated and sodiated dicrotophos was observed in a mixture of 9.05% dicrotophos in alumina (Supplementary Data, Fig. 1), no signal for intact dicrotophos was detected in either the 1.07% or 0.14% preparations (not shown). Instead, only lower molecular weight species were observed, which we attribute to interactions of the dicrotophos with the active alumina leading to significant degradation of the analyte.

A determination of the LOD for the immobilized dicrotophos mixtures was not attempted due to the imprecise nature of the mounting procedure used. We note that approximately 1 mg of powder containing 0.1% dicrotophos corresponds to less than 1 μg of dicrotophos deposited on the surface. The seemingly decreased sensitivity for the powders compared to directly deposited insecticide may be due to less efficient extraction/desorption of the analyte from the pore volume of the powdered substrates. Both increased interaction between the analyte and the particle surface as well as material porosity and impact geometry considerations could contribute to the detection limit. Further experiments to evaluate the role of different surfaces and immobilizing agents on the detection of this class of low-volatility compounds are underway.

A commercial insecticide rose dust sample (containing 3.00% malathion by weight was also analyzed by DESI MS. Intense peaks attributed to protonated and sodiated malathion as well as a solvent adduct of malathion were readily observed (Supplementary Data, Fig. 2). Numerous other species were also present in the spectrum, but these could not be definitively identified due to the lack of information concerning the makeup of the rose dust powder. Two other compounds are listed on the product label—carbaryl (MW_{mono} 201.1 Da; vapor pressure at 25 °C 1.4×10^{-6} torr) accounting for 0.50% by weight and captan (MW_{mono} 298.9 Da; vapor pressure at 25 °C 9.0×10^{-6} torr) at 5.87%. However, neither of

these compounds was positively identified in the resulting DESI MS spectrum, even though captan is present in the rose dust in higher amounts than malathion. This is likely due to a combination of effects including ion suppression from background components as well as the lower ionization efficiency of captan, as suggested by relatively high limits of detection in previous LC/ESI MS studies of captan [59]. In addition, captan has a relatively low water solubility (0.3 mg/100 mL) compared to malathion (14 mg/100 mL). One of the predominant mechanisms that has been proposed for DESI is the droplet-pickup mechanism, in which high-velocity, charged microdroplets rapidly solvate an analyte deposited on a surface, followed by ionization through traditional ESI-like mechanisms [18,20]. This mechanism implies that a compound with low solubility in the DESI solvent (water/methanol, in this case) would not be efficiently extracted from the surface. A similar effect of solubility on detection efficiency of ink dyes was also recently reported [60]. It is possible that a related ionization technique, desorption atmospheric pressure chemical ionization (DAPCI) [19,30,61] that does not involve solvent interactions with the analyte may provide better signal for analytes with poor solubility.

4. Conclusions

In this study, we have evaluated LDI and DESI MS as rapid and sensitive techniques for direct detection and identification of liquid and particle-immobilized low vapor pressure organophosphates. Demonstrating the capability of LDI and DESI MS to successfully detect the analyte loaded in the pores of powdered substrates has been a key motivation in the present work. Our results have implications in homeland protection, environmental monitoring, and other industrial and military applications. While the mechanisms of desorption and ionization for each technique may be completely different, similar types of ions and ion fragmentation were observed with both UV LDI and DESI. The predictable and reproducible fragmentation patterns produced in either LDI or DESI MS/MS allow for confident confirmation of the compound's identity. LDI MS of these compounds can be performed without modification utilizing currently available TOF instruments, initially designed for detection of much higher mass protein biomarkers for direct MALDI-based detection and identification of bioagents. Consequently, LDI MS can be a direct add-on technology, expanding the applicability of existing and/or planned MALDI–TOF MS biosensors. Neither LDI nor DESI MS require sample concentration, purification, or separation for successful detection of powder-immobilized low vapor pressure organophosphate compounds. Currently, DESI is more sensitive than LDI for this class of analytes. In DESI, typical LOD are lower than 100 pg analyte directly spotted on a surface, or less than 1 μg when immobilized on powdered substrates. In the future, we intend to investigate other nanostructured substrates in an effort to improve the LDI sensitivity for organophosphate CW simulant compounds. In addition, since DESI MS detects analytes directly at atmospheric pressure, we plan to interface DESI MS to aerosol collection devices (e.g., solid impactors) to provide a near-continuous air monitoring system for this type of hazard. A combination of a DESI ion source and IMS/TOF MS analyzer for detection of low-volatility compounds, loaded into organic or inorganic carrier particles, is also envisioned.

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Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at doi:10.1016/j.ijms.2008.04.009.

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