# Detection of explosives on skin using ambient ionization mass spectrometry†

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**Single nanogram amounts of the explosives TNT, RDX, HMX, PETN and their mixtures were detected and identified in a few seconds on the surface of human skin without any sample preparation by desorption electrospray ionization (DESI) using a spray solution of methanol–water doped with sodium chloride to form the chloride adducts with RDX, HMX, and PETN while TNT was examined as the radical anion and tandem mass spectrometry was used to confirm the identifications.**

Explosives detection, a topic of current concern, requires speed, sensitivity, and selectivity. Ion mobility has been the method of choice for explosives detection.[1,2] Although it has many attractive characteristics, it has somewhat limited selectivity. To achieve rapid analysis, the experiment should be done *in situ*, without requiring sample preparation. In the past this would have ruled out mass spectrometry as a suitable method, but the development of ambient ionization methods like desorption electrospray ionization (DESI) has changed this. Desorption electrospray ionization has been applied successfully to the analysis of explosives from a variety of surfaces.[3–7] Explosives have also been detected using Direct Analysis in Real Time.[8] The experiments do not require any prior sample preparation. A review of ambient mass spectrometry includes the detection of explosives in trace amounts from paper, plastic, and metal.[9] Skin presents a complex matrix, but applications of DESI to the characterization of various analytes in complex matrices is already well established, including alkaloids in natural products,[10] pesticides on leaf,[11] active ingredients in anti-malarial tablets,[12] and active ingredients in pharmaceutical tablets.[13] Coupling DESI to an IMS-ToF-MS has allowed for direct analysis of pharmaceutical drug formulations[14] and confident protein identifications.[15] In addition, forensic analysis has been successfully performed using an ion mobility spectrometer.[16] DESI has also been coupled to FT-ICR for peptide and protein analysis.[17] An early observation was that drugs taken orally could be detected on skin.[18] In the present study, we show the applicability of DESI-MS to the detection of trinitrotoluene [(TNT) ($C_6H_2CH_3(NO_2)_3$)], trinitrohexahydro-1,3,5-triazine [(RDX) ($C_3H_6N_3(NO_2)_3$)], octahydro-1,3,5,7-tetranitro-1,3,5,7-tetrazocine [(HMX) ($C_4H_8N_4(NO_2)_4$)], and pentaerythritol tetranitrate [(PETN) ($C(CH_2ONO_2)_4$)] on human skin.

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Methanol was purchased from Mallinckrodt (Phillipsburg, NJ, USA), sodium chloride from Aldrich (St. Louis, MO, USA) and water was purified using a MilliQ-water system (Millipore, Billerica, MA, USA). All the explosives were purchased from AccuStandard® (New Haven, CT, USA). Explosives standards were prepared by dilution using methanol to the 1.0 μg $mL^{-1}$ level and were then placed on the unwashed finger of the subject using a micropipette so that the final amount of explosive never exceeded a few nanograms. The area on the finger that was examined in these experiments is approximately 12 $mm^2$. Experiments were conducted using a Thermo Finnigan LTQ mass spectrometer (San Jose, CA, USA) operated in the negative ion detection mode. The mass spectrometer was equipped with a DESI source (OmniSpray® Source, Prosolia Inc, Indianapolis, IN, USA) consisting of a coaxial nozzle for delivering the solvent and the nebulizing gas ($N_2$), an ion transport tube, a high voltage power supply, and two x,y,z moving stages for independent control of the position of the ion source in relation to the inlet of the mass spectrometer. The sample holder stage was removed to allow finger placement near the inlet of the mass spectrometer. The spray from the ion source was then directed at the subject's finger. The temperature of the inlet was maintained at 80–100 °C (much lower than used in most previous studies, ~200 °C. Note, however, that the sample is not heated in this or any DESI experiments.) At this temperature, one cannot feel the heat from the mass spectrometer inlet as the finger is positioned about 3–5 mm away from the instrument inlet. Under these conditions, the spray forms a spot approximately 2 mm in diameter, less than that previously reported[3] as the capillary diameter in this case is half the previous size. Gas pressure was maintained between 80–110 psi. The incident angle was 55° and the spray voltage was 4.5 kV. All of the conditions were milder than those reported in previous studies.

Experiments were conducted under a human subject protocol approved by the Institutional Review Board of Purdue University.

Fig. 1 shows the negative ion mass spectra of TNT, HMX, RDX, and PETN, recorded from skin. In each experiment 2 ng total explosive material was present on the skin surface. In each case, molecular ions of the explosives are evident and it is clear that 2 ng does not represent the detection limit. Note that naturally occurring endogenous compounds are present in the background spectrum, see Supplementary Material. The detection of TNT is evident from the radical anion, at *m*/*z* 227, as seen in previous studies on other surfaces.[11] The other three explosives, HMX (*m*/*z* 331/333), RDX (*m*/*z* 257/259), and PETN (*m*/*z* 351/353), were also conveniently detected in the negative ion mode but through the formation of the chloride-adduct. The source of chloride was the NaCl-doped solution used as the spray solvent in the DESI source,

 

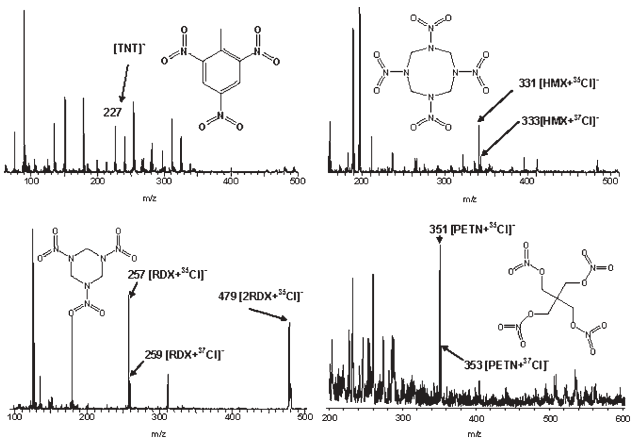


**Fig. 1** Negative ion DESI mass spectra of 2.0 ng absolute of TNT, HMX, RDX, and PETN on skin. Methanol : water (1 : 1) + 1 mM NaCl was used as the spray solvent. The capillary inlet temperature was 80 °C, the spray voltage was 4 kV, the flow rate was 2.5 μL $min^{-1}$, and the gas pressure was 110 psi.

and the characteristic 3 : 1 isotope ratio is evident in the three mass spectra in Fig. 1. In addition to these peaks, the mass spectrum obtained for RDX shows a peak at *m/z* 479/481 representing the chloride–RDX dimer. A background spectrum (Supplementary Material), taken of the skin prior to applying the explosive material, showed that there were no significant isobaric interferences with the peaks of interest for the four explosives studied here. Under these conditions, the negative ion mode background spectrum for skin was relatively free of the lipids expected for this surface although some of these compounds were found to be present in the positive ion mode.

Fig. 2 shows the negative ion DESI mass spectrum of ~500 pg of RDX on the finger surface. Even at this level, there is still adequate signal to identify RDX by the RDX.$Cl^-$ peaks at *m/z* 257 and 259. Tandem mass spectrometry experiments at this level (inset in Fig. 2) confirmed the identification of RDX by observation of fragments of the chlorinated RDX dimer (*m/z* 479) under collision-induced dissociation (CID) to give RDX.$Cl^-$ at *m/z* 257.[4]

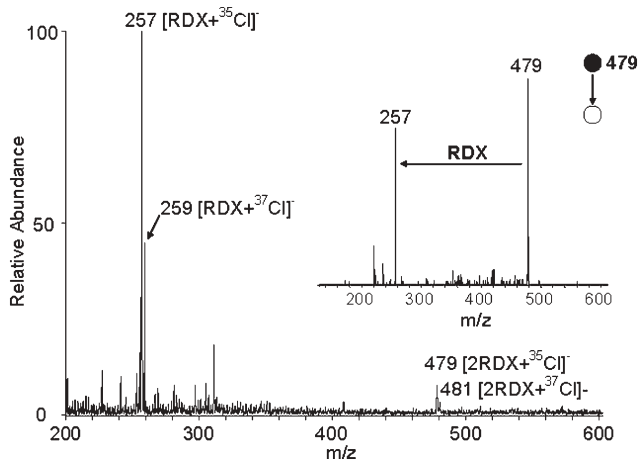


**Fig. 2** Negative ion DESI mass spectrum of sub-ng (~500 pg) of RDX on skin. Inset shows the MS/MS data confirming the presence of RDX.

A mixture of explosives was tested to ascertain the feasibility of detecting more than one explosive in a single DESI spectrum. A typical result is shown in Fig. 3. A mixture of 500 pg each of RDX and TNT (total of 1 ng of explosives), was placed on the finger and a DESI analysis was performed. Fig. 3a shows the resulting mass spectrum. Both TNT (the radical anion at *m/z* 227) and RDX (the chlorinated monomer and dimer at *m/z* 257/259 and 479/481, respectively) were observed. The relative abundances of the ions RDX.$Cl^-$ and $TNT^{\bullet -}$ reflect differences in ionization efficiency. Tandem mass spectrometry was used to confirm the assignment of the peak at *m/z* 227 to TNT (inset in Fig. 3a). This fragmentation pattern matches that observed previously under similar conditions.[4]

A second mixture included 500 pg RDX, 5 ng TNT, and 50 ng PETN, on the finger. The resulting negative ion mass spectrum is shown in Fig. 3b. Peaks at *m/z* 227, 257/259, and 351/353 correspond to $TNT^{\bullet -}$, RDX.$Cl^-$, and PETN.$Cl^-$, respectively. This figure demonstrates the ability to use DESI to detect three different explosives at three different concentrations.

The plastic explosive C4, which contains both HMX and RDX, stabilizers and plasticizers, was also examined. A very small amount of C4 was placed on the skin and the negative ion DESI mass spectrum was recorded (Fig. 4).

Fig. 4 shows that the plastic additives present in C4 do not interfere with the detection of the explosive material in the negative mode.

Ion mobility is widely used in explosives monitoring;[1,2] however, this method is insufficiently selective to be ideal. This applies particularly to trace identification in complex matrices, where mass

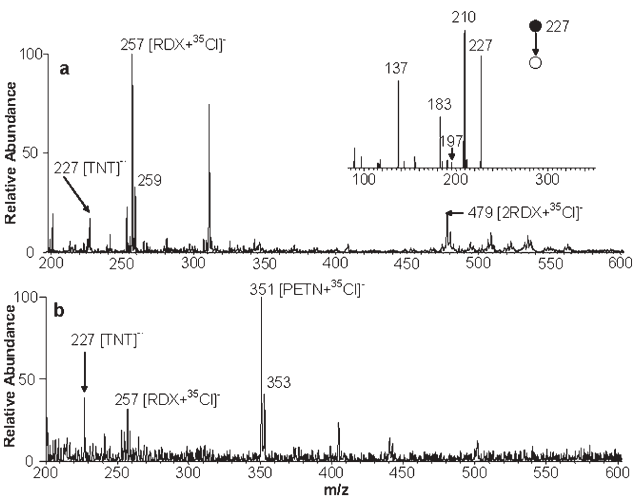


**Fig. 3** a) Negative ion DESI mass spectrum of a mixture of 1 ng total (500 pg each) of RDX and TNT on skin. Methanol : water (1 : 1) + 1 mM NaCl was used as solvent. The capillary inlet was maintained at a temperature of 80 °C, the spray voltage was 4 kV, the flow rate was 2.5 μL $min^{-1}$ and the gas pressure was 110 psi. The inset shows the tandem mass spectrum of TNT at this concentration (the entire analysis was completed in about 5 seconds). The peaks at *m/z* 210 and 197 correspond to loss of OH and NO, respectively. b) Negative ion DESI mass spectrum of 500 pg RDX, 5 ng TNT and 50 ng of PETN on skin. Methanol : water (1 : 1) + 1 mM NaCl was used as solvent. The capillary inlet was maintained at a temperature of 80–100 °C, the spray voltage was 4.5 kV, the flow rate was 3 μL $min^{-1}$ and the gas pressure was 100 psi.

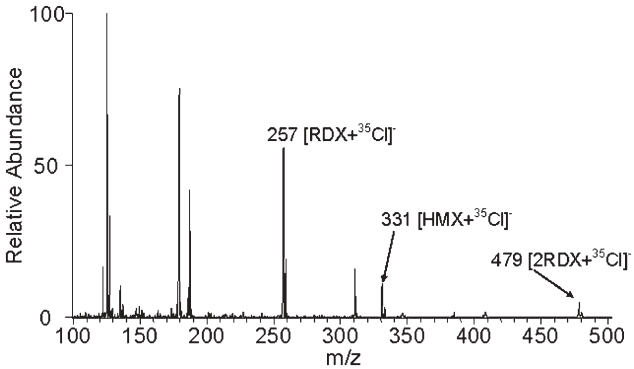


**Fig. 4** Negative ion DESI mass spectrum of a small amount (10 μg) of the plastic explosive, C4, on skin showing the presence of RDX and HMX.

spectrometry based methods have been available but slow (because of sample preparation) and ion mobility has been widely used. Recent demonstrations showing that DESI has the ability to provide both speed and specificity for explosives on environmental surfaces, have now been extended to their detection on skin. In spite of the natural and xenobiotic background, these data demonstrate that it is possible to detect multiple explosive compounds, at varying concentrations, simultaneously. Tandem mass spectrometry adds to the already considerable specificity of the mass spectrometry experiment.

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