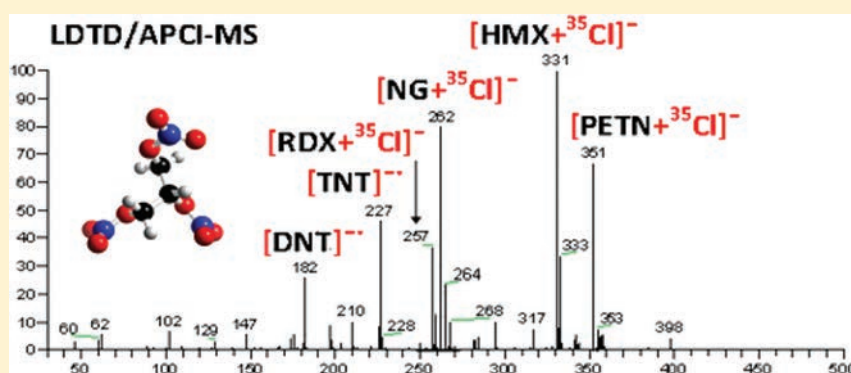# High-Throughput Trace Analysis of Explosives in Water by Laser Diode Thermal Desorption/Atmospheric Pressure Chemical Ionization-Tandem Mass Spectrometry

Koffi Badjagbo* and Sébastien Sauvé

Department of Chemistry, Université de Montréal, CP 6128 Centre-ville, Montréal, QC, Canada, H3C 3J7

ABSTRACT: Harmful explosives can accumulate in natural waters in the long term during their testing, usage, storage, and dumping and can pose a health risk to humans and the environment. For the first time, attachment of small anions to neutral molecules in laser diode thermal desorption/atmospheric pressure chemical ionization was systematically investigated for the direct determination of trace nitroaromatics, nitrate esters, and nitramine explosives in water. Using ammonium chloride as an additive improved the instrument response for all the explosives tested and promoted the formation of several characteristic adduct ions. The method performs well achieving good linearity over at least 2 orders of magnitude, with coefficients of determination greater than 0.995. The resulting limits of detection are in the range of 0.009−0.092 μg/L. River water samples were successfully analyzed by the proposed method with accuracy in the range of 96−98% and a response time of 15 s, without any further pretreatment or chromatographic separation.

Explosive compounds most commonly used in warfare, terrorist attacks, mining industries, and civilian applications belong to various chemical classes including nitroaromatics such as 2,4,6-trinitrotoluene (TNT) and dinitrotoluenes (DNT), nitrate esters such as pentaerythritol tetranitrate (PETN) and nitroglycerine (NG), and nitramines such as hexahydro-1,3,5-trinitro-1,3,5-triazine (RDX) and octahydro-1,3,5,7-tetranitro-1,3,5,7-tetrazocine (HMX). Explosives are found on firing points, training ranges, and impact areas.[1,2] Explosives can cause groundwater and surface water contaminations, posing environmental and public health risks due to their toxicity, mutagenicity, and carcinogenicity.[3−5] Detection of trace levels of explosives is of great importance in areas suspected to be contaminated by such compounds in order to assess the extent of the contamination before remediation begins, to monitor the quality of groundwater and surface water, and to prevent poisoning of humans and animals.

Determination of explosive compounds in water samples involves preconcentration procedures such as solid phase extraction (SPE),[6−8] solid phase microextraction (SPME),[9,10] and single drop microextraction.[10] Once the target analytes have been extracted, they are generally separated using gas chromatography (GC)[8−10] or liquid chromatography (LC).[6]

GC methods are more sensitive, but reproducibility suffers especially for thermally labile compounds such as RDX and HMX.[11] Moreover, explosives have different vapor pressures, ranging from 4.4×10^{-9} Torr at room temperature for RDX to 5.8×10^{-6} Torr for TNT to 3.1×10^{-4} Torr for NG.[12] This variability in vapor pressures complicates their analysis by a single method. The LC can be interfaced to an ultraviolet detector (UV) or a mass spectrometer. The response of the UV detector is dependent on the molar absorptivity of each analyte and thus is susceptible to interferences especially at trace levels, limiting the selectivity and sensitivity of the LC-UV method. In LC-MS of explosive compounds, both electrospray ionization (ESI) and atmospheric pressure chemical ionization (APCI) seem to produce an array of ions, even under similar experimental conditions, resulting in the production of rather inconsistent mass spectra. In addition, the relative abundances of the ions fluctuate to a significant extent, depending on explosive concentration, the presence of impurities in the mobile phase, and contamination of the LC system.[13,14]

Most research studies describe different preconcentration and chromatography techniques for the determination of organic explosives and residues in water, but only a few deal with direct analysis without any pretreatment and chromatographic separation step.[15] The present paper describes the development of a highly sensitive and reliable laser diode thermal desorption (LDTD)/APCI-tandem mass spectrometry (MS/MS) method for the direct analysis of explosives in water. A 5 μL aliquot of sample is directly deposited into the bottom of a well of the LazWell (96-well plate) and is allowed to dry at room temperature for 4 min. The LDTD/APCI-MS/MS then uses an infrared laser diode to desorb samples that have been previously dried into the well. The desorbed gas-phase analytes are carried over into the APCI region, where they are ionized and then transferred into the mass analyzer for separation, fragmentation, and detection.[16] We have also investigated the potential of ammonium chloride (NH_4Cl) to promote the formation of characteristic adduct ions in order to improve unambiguous identification of the explosives and enhance sensitivity. The proposed method has been validated and successfully applied to the analysis of river water samples.

■ EXPERIMENTAL SECTION

Standards and Reagents. Solutions of individual explosives of 2,4,6-TNT of purity >99.9% at a concentration of 1 mg/mL in methanol/acetonitrile (50:50), 2,4-DNT of purity >99.9% at 1 mg/mL in methanol/acetonitrile (50:50), PETN of 99.3% purity at 1 mg/mL in methanol, NG of 99.4% purity at 1 mg/mL in ethanol/methanol (97:3), RDX of 99.4% purity at 1 mg/mL in methanol/acetonitrile (50:50), and HMX of 98.1% purity at 1 mg/mL in methanol/acetonitrile (50:50) were purchased from AccuStandard (New Haven, CT) and used as sources of primary standards. Calibration standards were prepared by serial dilution of aliquots of the solutions using HPLC-grade water (Fisher Scientific, Fair Lawn, NJ) resulting in individual concentrations from 0.5 to 100 μg/L. Deuterated 2,4-DNT-3,5,6-d_3 used as internal standard (IS) was supplied by CDN Isotopes (Pointe-Claire, QC, Canada). The IS was added to the calibration standards at a final concentration of 5 μg/L. NH_4Cl (Fisher Scientific) dissolved in HPLC-grade methanol (Fisher Scientific) was spiked into the calibration standards at 0.5 mM.

LDTD/APCI-MS/MS Optimization. All experiments were carried out on a TSQ Quantum Ultra AM triple quadrupole mass spectrometer (Thermo Fisher Scientific, Waltham, MA) equipped with the LDTD/APCI interface (Phytronix Technologies, Quebec, QC, Canada). The system was operated in the negative-ionization mode and controlled by the Phytronix Technologies LazSoft 4.0 software. In order to maximize ionization, collision-induced dissociation (CID) and transmission for explosives and ion source conditions as well as compound-specific parameters such as collision energy and tube lens offset, all important parameters for sensitive detection in the selected reaction monitoring (SRM) mode, were optimized using the Thermo Fisher Scientific Xcalibur 2.0 software. The potential of NH_4Cl in helping the formation of unique characteristic adduct ions was investigated. The concentration of NH_4Cl was optimized manually by spiking the explosive standards with different concentrations of additive. The LDTD/APCI sample optimization for MS and MS/MS conditions was performed to improve signal intensity for aliquots (5 μL) of standards spiked with NH_4Cl. The following experimental parameters were chosen: corona

discharge voltage of −5 kV, ion transfer capillary temperature of 130 °C, and collision gas (argon) pressure of 1.5 mTorr. The peak-width of precursor and product ions was set to 0.7 u at half-height. Carrier gas temperature was set at 27 °C; carrier gas flow was set at 3.5 L/min, and the laser pattern programming consisted of a 2 s stabilization time at 0%, a 1 s ramp from 0% to 30%, held at 20% for 2 s, decreased to 0% in 0.1 s, and held at 0% for 1.5 s.

Method Validation. Performance characteristics, including linearity, limit of detection (LOD), limit of quantification (LOQ), intraday and interday precision, and accuracy, were assessed to validate this method under the optimized conditions. Five-point calibration curves (peak average area ratios of analyte over IS versus the analyte concentration) were constructed for each explosive. Calibration equations were calculated using a linear regression method. For each compound, the LOD was determined as three times the standard deviation (SD) of the signal obtained from five replicate analyses of the lowest standard concentration, divided by the slope of the calibration curve. LOQs were calculated using 10-fold SD. The relative standard deviation (RSD) was adopted for intraday and interday precision assessment. The intraday precision was tested for each compound by analyzing five replicates of the lowest standard concentration within 5 h. The interday precision was estimated by analyzing five replicates over five days. Because standard reference materials for target explosives were not available, the accuracy was evaluated by analyzing a laboratory reference sample prepared by spiking a river water sample with a standard mixture of TNT (10 μg/L), DNT (10 μg/L), HMX (20 μg/L), RDX (20 μg/L), NG (20 μg/L), and PETN HMX (20 μg/L). The reference sample thus prepared with a known nominal concentration of each compound was analyzed as an unknown sample by our method. Accuracy values were calculated using the eq 1, where C_{Meas} is the measured concentration and C_{Exp} represents the expected concentration:

$$\text{accuracy (\%)} = 100 - \left| \frac{C_{Meas} - C_{exp}}{C_{exp}} \times 100 \right| \tag{1}$$

Method Application. The applicability of the method to real-world samples was evaluated through analysis of river water samples collected from St-Lawrence River in Montreal, Canada. The samples were collected in 250 mL all-brown glass bottles, transported to the laboratory in a cooled box, stored at 4 °C, and analyzed by LDTD/APCI-MS/MS within 5 h. The method was also applied to river water samples contaminated with explosive mixtures at literature reported concentrations for waters from military sites:[17,18] 10 μg/L for nitroaromatics and 20 μg/L for nitrate esters and nitramines. Prior to the analysis, the IS was added to each sample at 5 μg/L and the NH_4Cl was spiked into the sample at a final concentration of 0.5 mM.

■ RESULTS AND DISCUSSION

LDTD/APCI-MS/MS of Explosives. A number of research studies have been performed demonstrating the analysis of explosives in water using LC-APCI-MS.[15] Inorganic additives which bind with analytes are often used to control the ionization process and produce easily identifiable adducts for explosives that do not readily undergo electron capture, to give molecular ion $M^{-\bullet}$, or proton transfer to form deprotonated ion $[M - H]^-$. However, LC-APCI-MS of nitramines and nitrate esters have been found to be sensible to any impurities
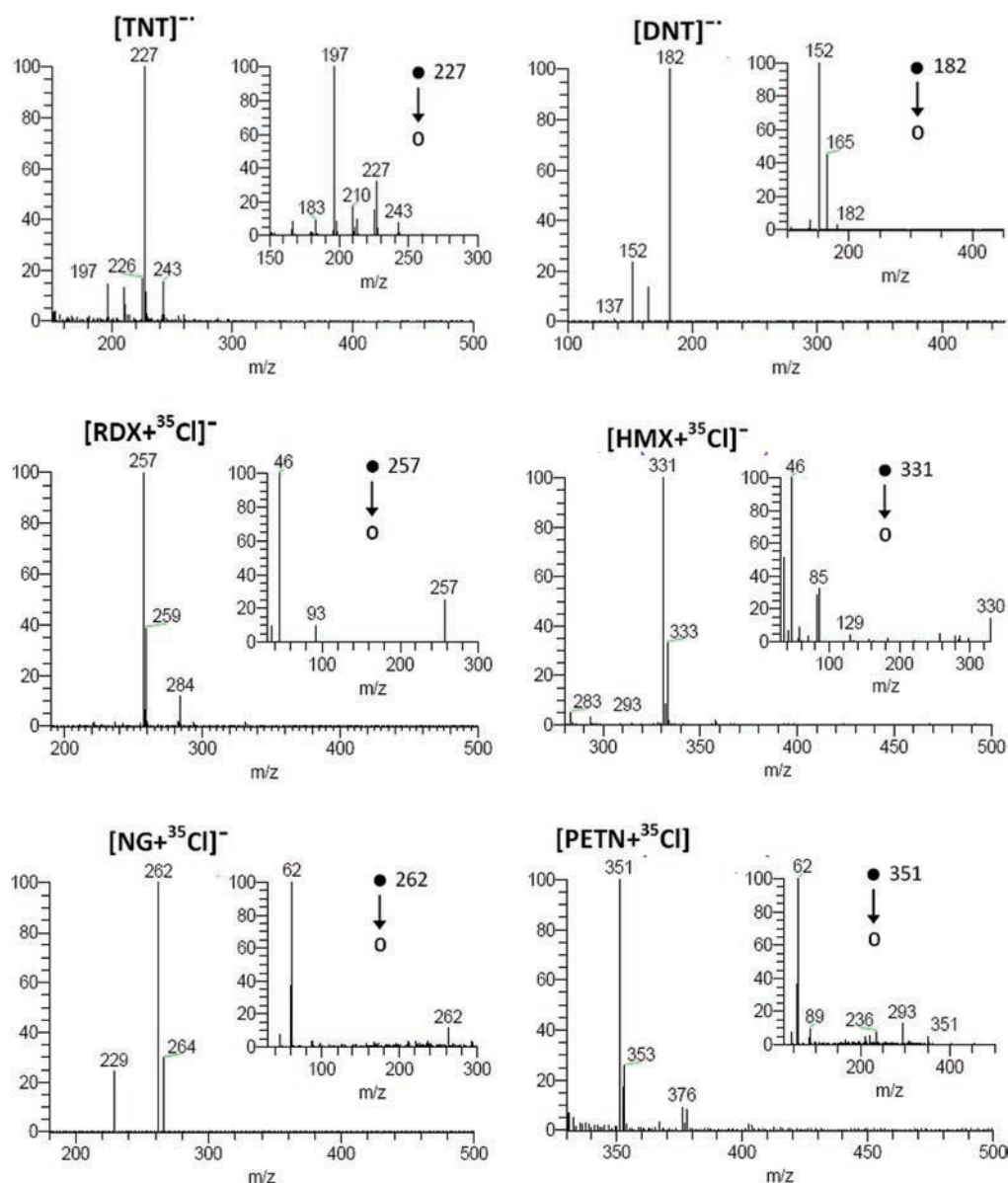
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Figure 1. Negative-ion LDTD-APCI mass spectra for 5 μL of 10 μg/L solutions of TNT, DNT, RDX, HMX, NG, and PETN spiked with 0.5 mM NH$_4$Cl. Insets show the MS/MS of precursor ions m/z 227, 182, 257, 331, 262, and 351.

in the mobile phase.[14] When the concentration of the additive is low, the adduct ion is accompanied by additional adducts formed from impurity anions present in the mobile phase, resulting in the formation of an array of ions. An increase in the concentration often resulted in mass spectra dominated by ions of the additive, making the identification of explosives in complex mixtures difficult.[13] LDTD/APCI is a solvent-free ionization source and hence generates MS spectra which are much cleaner than LC-based APCI and can thus prevent the production of superfluous ions and enhance the efficiency of the ionization. Our investigation began with an examination of how chloride anions can be used to improve the detection of explosives in negative LDTD/APCI. We first examined the competition between the formation of the M$^{-\bullet}$ and the chloride adducts [M + Cl]$^-$.

Figure 1 shows LDTD/APCI mass spectra obtained for 10 μg/L solutions of TNT and DNT. The mass spectra show base peaks M$^{-\bullet}$ at m/z 227 for TNT and m/z 182 for DNT, as observed previously in APCI for both nitroaromatics.[19,20] In

fact, TNT and DNT molecules have positive electron affinity (EA $\approx$ 2.5 eV for TNT and 1.6 eV for DNT)[21] and, thus, are able to stabilize a thermal electron in the APCI region via an associative electron capture process, giving M$^{-\bullet}$. These compounds which EA exceeds that of O$_2$ (0.45 eV)[21] can also undergo simple charge exchange with the APCI primary reagent ion O$_2$$^{-\bullet}$ to produce M$^{-\bullet}$.[15]

Although TNT and DNT do not form [M + Cl]$^-$ when NH$_4$Cl was used as additive, due to their gas-phase basicities (ΔG_{base} = 1293 $\pm$ 9.2 kJ/mol for TNT)[22] being lower than that of the chloride anion Cl$^-$ (ΔG_{base} = 1372.8 $\pm$ 0.42 kJ/mol),[22] the addition of NH$_4$Cl led to an increase in abundance of the M$^{-\bullet}$ species by a factor of about three. We hypothesize that, under negative LDTD/APCI, NH$_4$Cl (EA = 0.54 eV)[23] undergo an associative electron capture process to yield NH$_4$Cl$^{-\bullet}$, the excess electron being bound by the cationic site. It was demonstrated that, in the NH$_4$Cl$^{-\bullet}$, the unpaired electron is polarized and destabilized by the presence of the nearby Cl$^-$ anion, and the electron binding energy decreases to

Table 1. Performance Parameters of the LDTD-APCI-MS/MS for Explosive Determination in Water

analytes	calibration range (μg/L)	coefficients R^2	LOD (μg/L)	LOQ (μg/L)	intraday precision (RSD%)	interday precision (RSD%)	accuracy (%)
TNT	1−100	0.9998	0.009	0.023	6	7	98
DNT	1−100	0.9991	0.056	0.162	5	7	97
RDX	0.5−50	0.9989	0.019	0.048	8	8	98
HMX	0.5−50	0.9953	0.022	0.056	10	12	96
NG	0.5−50	0.9968	0.092	0.271	6	8	97
PETN	0.5−50	0.9974	0.037	0.093	10	9	96

0.51 eV.[24] Since TNT and DNT possess EA higher than that of NH$_4$Cl, these compounds then undergo charge exchange with the NH$_4$Cl$^{-\bullet}$ to give M$^{-\bullet}$, in addition to the associative electron capture process. From our data, it is clear that the addition of NH$_4$Cl improves the M$^{-\bullet}$ signals in LDTD/APCI for the two nitroaromatics.

CID-fragmentation of precursor ions at m/z 227 in TNT and m/z 182 in DNT gave very clean MS/MS spectra (Figure 1), consistent with the literature report of MS/MS spectra from the same ions by APCI,[19] CI,[25] and ESI.[26] The major product ions obtained correspond to the losses of OH$^\bullet$ and NO$^\bullet$ from M$^{-\bullet}$ and were observed at m/z 197 and m/z 210 for TNT and at m/z 152 and m/z 165 for DNT, which represent good candidate transitions for detection of both explosives. Following optimization, subsequent quantification of TNT was performed with a tube lens set at −46 V by recording the transition m/z 227 → 197 and using a collision energy of 14 V. Quantification of DNT was performed with a tube lens set at −47 V by recording the transition m/z 182 → 152 with a collision energy set at 17 V.

Single molecular ions were not present in the LDTD/APCI mass spectra obtained for RDX, HMX, NG, and PETN. No easily identifiable characteristic ions could be detected in the mass spectra. In contrast with TNT and DNT, the nitramines and nitrate esters investigated are unable to produce M$^{-\bullet}$ species via an associative electron capture process,[15] because of their low electron affinities (EA < 0 eV for RDX and HMX).[21] Moreover, these explosive molecules cannot undergo proton transfer reaction with the strong gas-phase base O$_2^{-\bullet}$ to produce [M − H]$^-$ ion,[15] since their gas-phase acidities (ΔH_{acid} > 400 kcal/mol for RDX and HMX)[21] are higher than that of HO$_2^\cdot$ (ΔH_{acid} = 353 kcal/mol).[21]

LDTD/APCI analysis of 10 μg/L solutions of the nitramines and nitrate esters spiked with NH$_4$Cl gave chloride adducts [M + Cl]$^-$ as base peaks, at m/z 257/259 for RDX, m/z 331/333 for HMX, m/z 262/264 for NG, and m/z 351/353 for PETN (Figure 1). The natural isotope distribution pattern of chlorine (^{35}Cl/^{37}Cl $\sim$ 3:1) provides evidence for the presence of the chloride adducts. The formation of such species in APCI of explosives is well supported by the mass spectra data reported previously.[19,27] It was established that chlorinated solvents such as NH$_4$Cl (EA = 0.54 eV)[23] can undergo dissociative electron capture under corona discharge conditions to produce chloride anion Cl$^{-\bullet}$,[28] which initiates anion attachment with the explosive molecules. In fact, an adduct ion of the form [M − H]$^-$···H$^+$···[A]$^-$ is produced, as a complex consisting of two gas-phase anions in equilibrium with a proton, when the gas-phase basicity of the explosive [M − H]$^-$ ion is comparable to that of the anionic species [A]$^-$.[29,30] Although the ΔG_{base} of RDX, HMX, NG, and PETN are not reported in the literature, they are expected to be comparable to that of the chloride anion Cl$^-$, insofar as they form chloride adducts with NH$_4$Cl used as additive. One can argue that with these observations

our approach provides easily identifiable ions for nitramines and nitrate esters and, thus, allows unambiguous identification of these explosives.

It is noteworthy that the intensity of the peak corresponding to the chloride adduct in the mass spectra was highly influenced by the NH$_4$Cl concentration and instrumental parameters that affect the internal energy, and thus, were optimized manually. Results showed that a relatively low concentration of NH$_4$Cl was optimum for adduct ion production, whereas high concentrations resulted in signal suppression. An NH$_4$Cl concentration of 0.5 mM was chosen as the optimal concentration in the negative-ion LDTD/APCI mode. Another important parameter is the ion transfer capillary offset voltage. Explosive molecules exhibited significant drop-offs in the abundances of chloride adducts when this voltage was raised above −80 V. An elevated voltage in the relatively high-pressure region between the exit of the ion transfer capillary and skimmer causes fragmentation, thereby breaking up the chloride adduct via relatively low-energy collisions with residual gases (e.g., air). Therefore, in order to minimize decompositions of the chloride adducts prior to their arrival to the detector, their internal energy should be kept as low as possible. An ion transfer capillary offset voltage of −35 V was chosen for the analysis of explosive compounds in LDTD/APCI-MS/MS.

The MS/MS spectrum of the [M + Cl]$^-$ ion at m/z 257 in RDX contained only the precursor ion and a low-abundance product ion [NO$_2$]$^-$ at m/z 46 (Figure 1), as observed previously for RDX.[19] Simplex optimization was performed to maximize response for the transition m/z 257 → 46, which was then used for quantification of RDX with a tube lens set at −29 V and collision energy at 46 V. The MS/MS spectrum of the HMX-chlorine adduct ion at m/z 331 also showed the presence of the precursor ion and the product ion [NO$_2$]$^-$ at m/z 46 in low abundance (Figure 1). Following optimization, the transition m/z 331 → 46 was chosen for the determination of HMX with tube lens and collision energy set at −46 and 76 V, respectively.

CID-fragmentation of the [M + Cl]$^-$ ions at m/z 262 in NG and m/z 351 in PETN produced the most intense product ion [NO$_3$]$^-$ at m/z 62 in addition to the precursor ions (Figure 1), as seen in previous studies on nitrate esters.[19,27] Accordingly, subsequent quantification of NG was carried out with a tube lens set at −38 V by recording the transition m/z 262 → 62 and using a collision energy of 21 V. Quantification of PETN was performed with a tube lens set at −27 V by recording the transition m/z 351 → 62 with a collision energy set at 12 V.

Analytical Performance Characteristics. The linearity of the proposed method was evaluated from 0.1 to 100 μg/L for nitroaromatics and from 0.5 to 50 μg/L for nitrate esters and nitramines under the optimal experimental conditions described above. The calibration curves were linear in the tested ranges for all targeted analytes, with coefficients of determination (R^2) greater than 0.995 (Table 1). The response
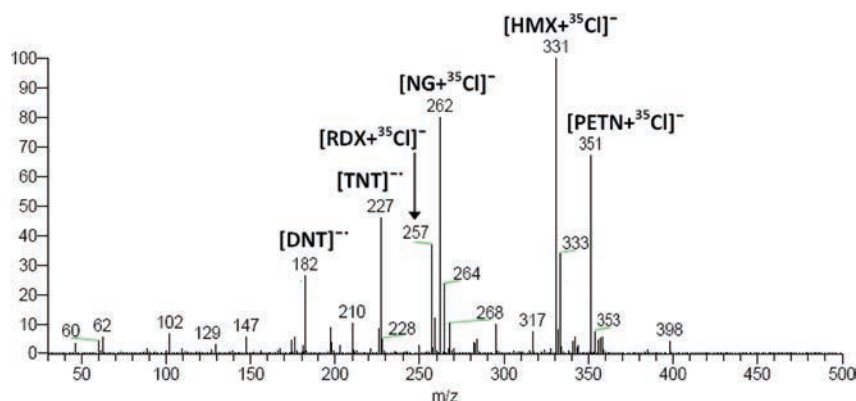
Figure 2. Typical LDTD-APCI mass spectra of a water sample from St-Lawrence River spiked with TNT, DNT, RDX, HMX, NG, PETN (10 μg/L or 20 μg/L, see text), and NH_4Cl (0.5 mM).

coefficients (curve slopes) were significantly different for each of the explosives. This means that the instrument needs to be calibrated for each compound. The results attest to the quantification potential for the method over a wide concentration range of explosives in natural waters.

The method LODs determined for explosives studied were in the range of 0.009−0.092 μg/L, while LOQs ranged between 0.023 and 0.271 μg/L (Table 1). The detection performance of the present method is more than 100 times better than that of the standard LC-UV method (1−10 μg/L),[31] up to ~17 times higher than that reported for an SPME-GC-MS (e.g., 0.325 μg/L for RDX)[32] and up to ~10 times higher than that reported recently for an SPE-APCI-LC-MS method (e.g., 0.5 μg/L for DNT and 0.1 μg/L for RDX).[33] The proposed method is applicable for the monitoring of explosives in water at trace levels, and our results confirm the quantification potential for concentrations generally found in natural and contaminated waters.

As indicated in Table 1, intraday precision and interday precision ranged from 5% to 10% and from 7% to 12%, respectively, while accuracy ranged between 96% and 98%. All these results clearly demonstrated that the values were within acceptable ranges and the LDTD/APCI-MS/MS using NH_4Cl as an additive was precise and accurate.

Real-World Applications. The proposed method with the optimal operation parameters discussed above was applied for the determination of the explosives in river water samples collected from St-Lawrence River in Montreal, Canada. However, no selected analytes were detected, indicating either there were no targets in the samples or the concentrations of the targets were below the LODs. There is no reason to suspect the presence of explosives in those samples. The river water samples were therefore contaminated with the standard solutions of explosives, at known concentrations of 10 μg/L for nitroaromatics and 20 μg/L for nitrate esters and nitramines, and analyzed with the LDTD/APCI-MS/MS method. Figure 2 shows the LDTD/APCI mass spectrum of a river water sample contaminated with a mixture of selected explosives. As evidenced by accuracy values in Table 1, concentrations of analytes determined in the spiked samples agreed well with the expected values, indicating that the proposed method can meet the requirements for analysis of trace-level explosives in natural waters. The analysis took about 15 s per desorption event. For a given sample, only one plate well is desorbed and analyzed with a single desorption event for all the six explosives investigated. Thus, sample-to-sample

(well-to-well) run time for LDTD/APCI-MS/MS analysis of the explosives is performed in 15 s, making our method 60 times faster than the classical chromatographic separation prior to the explosive detection, which requires a sample-to-sample time of about 15 min.

CONCLUSION

We have developed and validated a sensitive, selective, and reliable method for the direct analysis of explosive compounds in water. Unlike the classical LC-methods, the present LDTD/APCI-MS/MS technique is solvent-free, without laborious extraction/preconcentration steps and requires very limited sample manipulation, thus limiting the risks of sample contamination. The method significantly minimizes the potential background contamination. As a consequence, much lower measurement uncertainty and better reproducibility are obtained. Moreover, results showed that by employing NH_4Cl as an additive, additional sensitivity and selectivity were illustrated using the newly developed LDTD/APCI-MS/MS. The proposed method is simple and fast, and its analytical characteristics make it suitable for the analysis of trace levels of explosive compounds and residues in water without any further pretreatment.

AUTHOR INFORMATION

Corresponding Author
*E-mail: koffi.badjagbo@umontreal.ca. Tel.: 514-343-6111 ext. 3921. Fax: 514-514 343-7586.

Notes
The authors declare no competing financial interest.

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