

## Review Article

# Ambient Mass Spectrometry for Forensic Analysis

Lijun Xie<sup>1</sup>, Huanwen Zhao<sup>2</sup>, Peng Zhou<sup>1</sup>, Tenggao Zhu<sup>1</sup>, Yongzi Liu<sup>2</sup> and Huanwen Chen<sup>1\*</sup>

<sup>1</sup>Department of Chemistry, East China Institute of Technology, China

<sup>2</sup>Jiangxi Institute of Forensic Science, Nanchang, China

## \*Corresponding author

Huanwen Chen, Department of Applied Chemistry, East China Institute of Technology, 56 Xuefu Road, Fuzhou 344000, China, Email: chw8868@gmail.com

Submitted: 13 February 2015

Accepted: 10 August 2015

Published: 03 October 2015

ISSN: 2378-9476

Copyright

© 2015 Chen et al.

OPEN ACCESS

## Abstract

Ambient mass spectrometry has emerged as a significant tool to facilitate forensic investigation considering its well-known advantages of rapid, direct, nondestructive, high-throughput detection of a broad range of raw samples, as well as its potential capability of miniaturization and automation. New mass spectrometry technologies include more versatile ionization sources, allowing the next generation of instrumentation to be more multipurpose and adaptable to the needs of the discipline. This review assesses and highlights forensic applications of ambient mass spectrometry. In addition, the instrumentation and principles of some popular and promising ambient ionization techniques are summarized.

## Keywords

- Ambient ionization
- Mass spectrometry
- Forensic analysis

## INTRODUCTION

Forensic science has been developed in the twentieth century and came to be recognized by the courts and law enforcement. Forensic analysis and investigation capabilities are vital in criminal and civil cases, national security, environmental protection, and public safety. The manufacture and trafficking of illicit drugs and counterfeiting of legitimate pharmaceuticals, new emerging challenges from organised crime and terrorist groups, also underline the vital need for sensitive and selective rapid identification of substances such as explosives and toxic spills in field, drug mixture. Presently, practical analytical technologies are needed to enable the “in field” screening and analysis of evidence to provide fast, accurate, scientific information to support the forensic investigation[1]. Many analytical techniques become developed for forensic application [2-8] and some are accepted by the court, including the use of infrared spectrum (IR) to test the driver’s breath gas so as to assess blood alcohol content, or high performance capillary electrophoresis (HPCE) to detect the content of methamphetamine, morphine, cocaine and heroin in blood, urine and other biological samples, or liquid chromatography mass spectrometry (LC-MS) and gas chromatography mass spectrometry (GC-MS) to qualitatively or quantitatively analyze illicit drugs and metabolites in biological matrices (e.g. blood, urine or hair).

Among the numerous modern analytical techniques, mass spectrometry (MS) is a widely used approach in forensic science [1] for its merits in identifying a large range of compounds in trace amounts with high sensitivity and short response time. However, the conventional MS experiments have proven huge inconvenience in terms of size, cost, complexity and time consuming due to laborious sample preparation or/and isolation

procedures. These drawbacks make it difficult to analyze forensic with high efficiency and effectively, leaving problems in maintaining sample integrity and traceability.

Recently, ambient mass spectrometry (ambient MS), which allows for direct and rapid analysis of raw sample in their native environment with high specificity and minimal or no effort in sample preparation, has aroused blooming interest. With ambient MS, analysis operation has been greatly simplified, and more types of samples could be interrogated. In this review, we will introduce the principles, instrumentation and forensic application of typical ambient ionization techniques, and finally discuss the future prospects and challenges of ambient MS for forensic science.

## Ambient mass spectrometry

Since the introduction of desorption electrospray ionization (DESI) by Cooks and his co-workers in 2004[9], numerous ambient ionization techniques were developed [10-16]. Till now, several groups have reviewed the principle and applications of ambient mass spectrometry [15,17-21]. According to the critical steps for energy transfer that plays the central role in the overall ionization process, the ambient ionization techniques can be distinguished into two classes, *i.e.*, electrospray ionization (ESI)-related techniques and atmospheric pressure chemical ionization (APCI)-related techniques[18]. In order to create analyte ions on solid surfaces, desorption/ionization is typically implemented using techniques such as DESI, DAPCI, etc, which allows the desorption ionization occur on a two-dimensional (2-D) surface at the native conditions. While during the extractive electrospray ionization (EESI) process, analytes in the matrix are subjected to extractive ionization in a three-dimensional (3-D) space, in which the matrix disperses over a relatively large volume. Chen

*et al.* proposed a model to illustrate the relationship between the 2-D methods and 3-D methods based on the principles of energy conservation and charge immortalization, as well as energy spread and charge transfer occurring under ambient conditions (Figure 1)[20].

Over the past ten years, ambient MS using direct ionization techniques has been applied in food analysis [22], forensic and public safety monitoring, proteomics, metabolomics [23] and clinical diagnostics, in vivo analysis[24], direct mass spectrometry imaging[25], selectively chemical reaction study [26,27] and many other fields[28]. Especially in forensic analysis, ambient MS has been successfully used for detection of explosives at nano-gram levels; chemical composition of counterfeit pharmaceutical tablets, detection of drugs of abuse from biological liquids such as urine and plasma; breath analysis of metabolites; and imaging analysis for document verification and fingerprint identification.

### Forensic applications of ambient mass spectrometry

Ambient mass spectrometry allows the in situ, real-time, online, high throughput, and low sample-consumption analysis of trace analytes in complex matrix to be performed with no/minimal sample pretreatment. In following sections, we will briefly introduce ambient mass spectrometry and their forensic applications. A summary of the major ambient MS techniques emphasized in this review is presented, in chronological order, in Table 1.

### Desorption electrospray ionization (DESI) and its forensic applications

DESI [9] is an interesting ambient ionization technique combining both the ESI process and the surface desorption process. with ease to be implemented on many types of commercially available MS instruments, the simple DESI experiment (Figure 2) uses an aqueous spray directing at the surface of samples under ambient conditions. The spray impacts the surface, desorbs the analytes into the gas phase and subsequently ionises them. The desorbed ions are then transported to a commercial mass spectrometer through an atmospheric pressure interface. The experimental results show that DESI-MS spectra are very similar to those generated by ESI, and thus the ESI spectra can be used as the reference spectra for DESI analysis. DESI has been widely used for direct detection of various compounds. The principles, instrumental setup, and the applications of DESI have been reviewed previously [16-18,29-34]. Several tutorial papers have been reported about the forensic applications of DESI [35-37]. Morelato *et al.* assessed and highlighted the great advantages of DESI in detection of illicit drugs, explosives, chemical warfare agents, inks and documents, fingerprints, gunshots residues and drugs of abuse in urine or plasma specimens [37].

### Surface desorption atmospheric pressure chemical ionization (DAPCI) and its forensic applications

DAPCI [38], combining the process of surface desorption and atmospheric pressure chemical ionization (APCI), has been

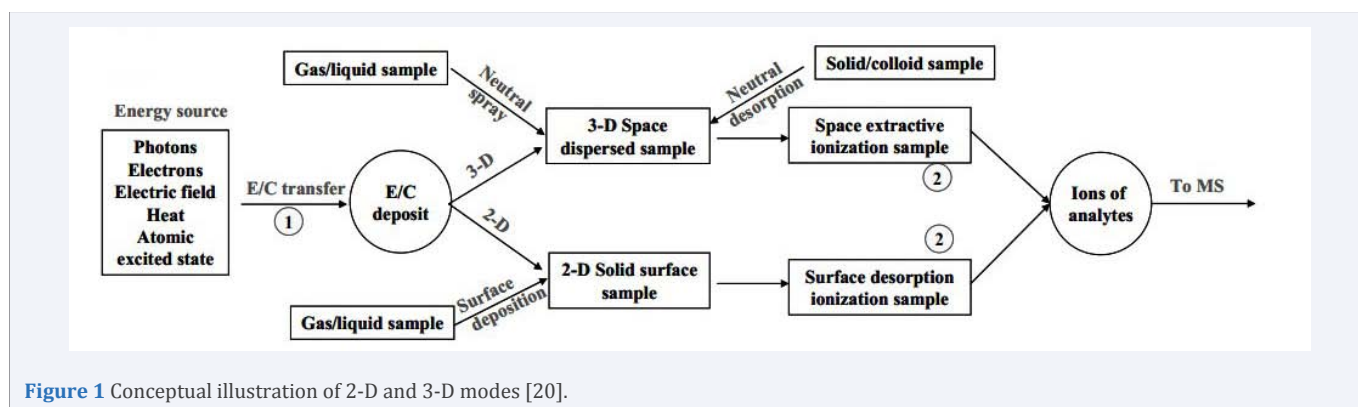


Figure 1 Conceptual illustration of 2-D and 3-D modes [20].

Ambient method	Basic technique	Year introduced	Desorption/ionization principles	Forensic application	Ref.
DESI	ESI	2004	Charged spray-jet	toxic industrial compounds, chemical warfare agents, illicit drugs and formulations, explosives, foodstuff, inks, fingerprint, skin	35-37
DAPCI	APCI	2005	Electric plasma species	explosives, chemical warfare, pharmaceutical, signatures	30,41,44
DART	GDI	2005	Metastable-thermal/indirect plasma	explosives	10
EESI	ESI	2006	Ambient gas/ extractive ESI	cocaine, explosives ,aerosol illegal drug, fingerprinting	74-81
DBDI	GDI <sup>a</sup>	2007	Electric plasma species	explosives	40
LTP	PI <sup>b</sup>	2008	Low-temperature plasma	drugs	14,88

<sup>a</sup> GDI, gas discharge ionization; <sup>b</sup> PI, photon ionization.

considered as a variant of DESI. Instead of using liquid as solvent spray, gaseous solvent vapor is ionized by corona discharge in the alternative procedure, and the resulting plasma is used to create ions directly from the surface of interest. DAPCI is thus one type of plasma-based ambient MS techniques[39]. Quite different from spray techniques, plasma-based sources employ various modes of electro-discharge instead of charged droplets to generate plasma gas that contains radicals, excited/metastable state atoms, and electrons.

As for the forensic applications, plasma-based ambient MS

methods (e.g. DAPCI, DART[10], DBDI[40] and LTP[14]) have a clear advantage in trace explosive determination. In situ trace detection of peroxide explosives by DAPCI was first performed by Cooks and coworkers [30], then was used to detect nitroaromatic explosives by monitoring their ion/molecule reaction products with reagent ions produced from acetonitrile and air [41]. DAPCI has also been used for detecting peroxide-based explosives (HMTD and TATP), where 15 ng of each explosive deposited on paper in a total area of 1 cm<sup>2</sup> was detected with or without ammonium acetate added as dopant to the carrier gas

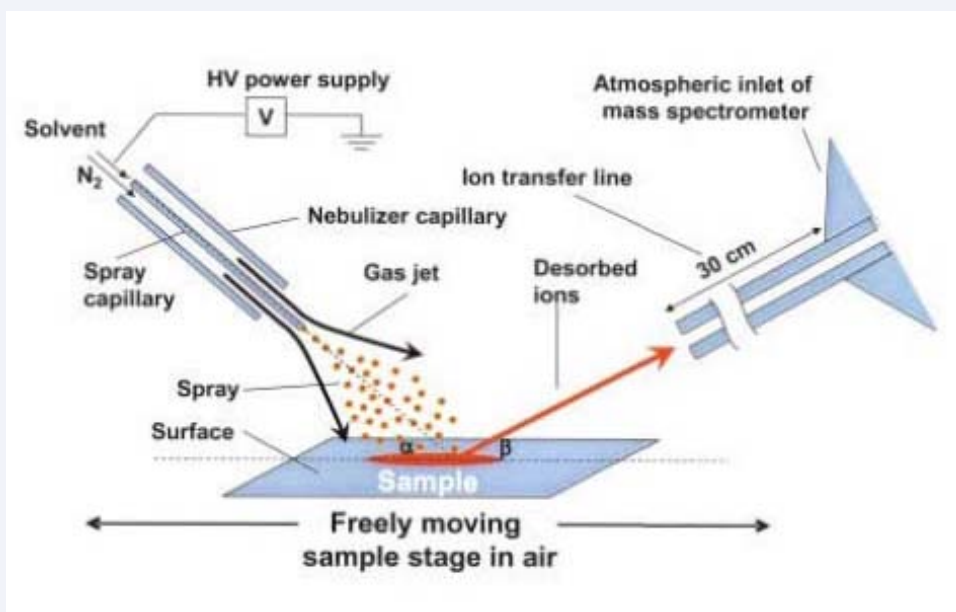


Figure 2 Schematic of typical DESI experiment [9].

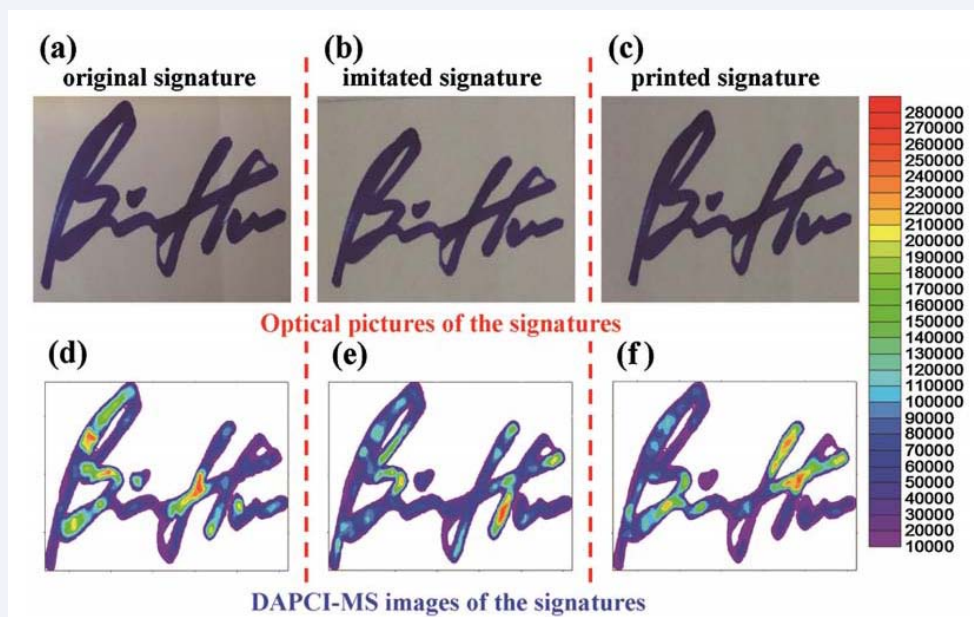


Figure 3 Detection of forged signatures by DAPCI-MS imaging. a, d: original signatures; b, e: imitated writings; c, f: facsimiled writings on a printed copy by using the same pen. (The peak at  $m/z$  136 was monitored for analysis).

(N<sub>2</sub>). With a relatively low proton affinity (PA), the TATP molecule cannot efficiently capture a proton from the ionized methanol/nitrogen plasma during DAPCI. While through doping the DAPCI gas with a reagent gas which can provide reagent ions such as the ammonium ion NH<sub>4</sub><sup>+</sup>, the sensitivity was greatly improved [42], so that DAPCI can directly detect chemical warfare agent stimulant, explosives and human-related samples with a detection limit of sub-pg level. Besides, many pharmaceutical powder compounds are desirable for analysis in gasless DAPCI without toxic chemical contamination [43]. Recently, Li *et al.* for the first time reported the use of DAPCI imaging in document authentication at the molecular level [44]. Among many signals detected, the peak at m/z 136, which is absent from the blank spectrum, is of the highest intensity (4.89 × 10<sup>6</sup> cps), indicating that this signal might be ascribed to the major component of the blue ink. Thus, the peak at m/z 136 was selected as target ion for handwriting analysis. Non-destructive forensic analysis of forged signatures either handwritten or computer-assisted was

achieved according to the difference of the contour in DAPCI images, which was attributed to the strength personalized by different writers (Figure 3). Many experimental results show that DAPCI-MS imaging provides rich information at the molecular level and thus can be used for the reliable document analysis in forensic applications [45].

### Extractive electrospray ionization (EESI) and its forensic applications

As schematically shown in Figure 4, extractive electrospray ionization (EESI) [12] has a unique design utilizing two sprays and aligning them along a certain angle with respect to the mass spectrometer. A number of studies have investigated the ionization mechanism during EESI process in detail. Liquid samples, such as raw urine, milk and waste water, can be directly monitored by EESI mass spectrometry without sample contamination by toxic chemicals. However, it was difficult for EESI to analyze solid surfaces until recently Chet *et al* have further developed the EESI ion source to allow analysis of many

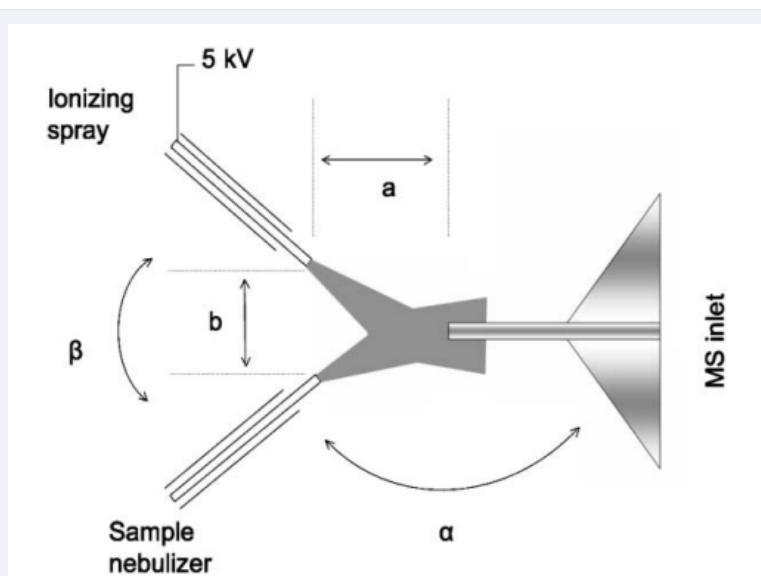


Figure 4 Schematic diagram of a traditional EESI ion source for direct liquid sample analysis[12].

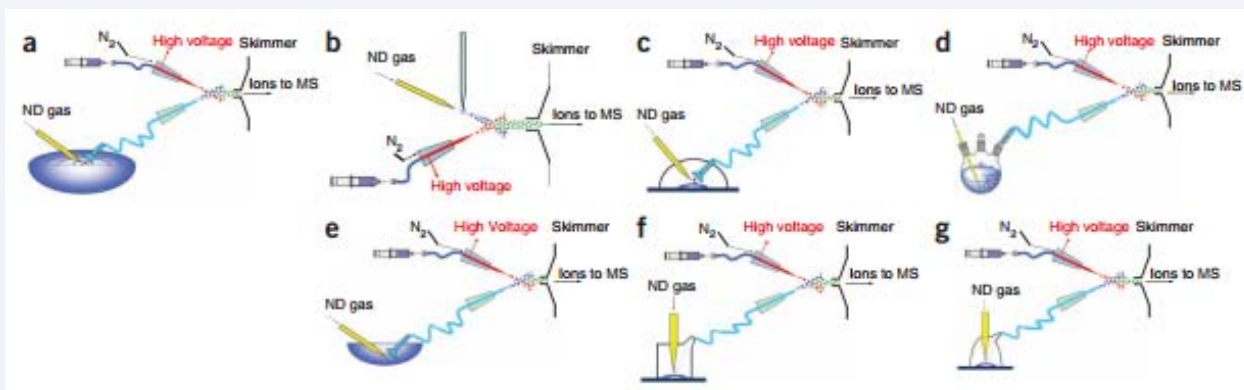
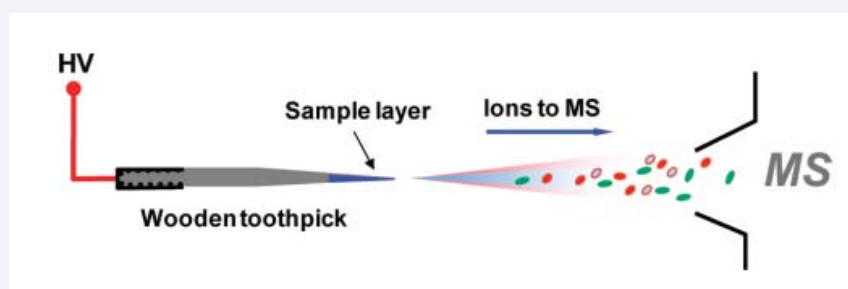


Figure 5 Schematic diagrams of seven types of ND devices.





**Figure 6** Experimental setup of ESI using a wooden tip [83].

kinds of samples (solid, cream, gel, liquid, gas or aerosols) with a neutral desorption (ND) sampling gas beam (Figure 5) [46]. The ND-EESI-MS analysis process requires no sample pretreatment because it can tolerate an extremely complex matrix due to the separation of sampling and ionization processes in both space and time, thus allowing real-time, online chemical profiling of highly viscous samples under ambient conditions. Thereby, EESI mass spectrometry provides a platform for multiple disciplines including food analysis [47-52], consumer product safety [53-57], environmental investigation [58-61], proteins [62-64], metabolomics [65-70], chemical reaction monitoring [71-73], forensic analysis and public safety [12,74-81].

Without sample pretreatment, a novel air-tight neutral desorption enclosure has been fabricated to noninvasively sample picograms of explosives 2,4,6-trinitrotoluene (TNT), hexahydro-1,3,5-trinitro-1,3,5-triazine (RDX), octahydro-1,3,5,7-tetranitro-1,3,5,7-tetraazocine (HMX), triacetone triperoxide (TATP), and nitroglycerin (NG) from human skin using a nitrogen carrier gas over a 4m distance. Selective ion/molecule reactions can be easily implemented in the EESI process, resulting in enhanced specificity for the detection of trace amounts of explosives present in complex matrices such as biological surfaces [74]. Nano-EESI, evolving from EESI, developed also by Chen's group, requires nebulizing gas to produce the reagent ion plume and the neutral sample aerosols, allows proper analytical performance using manual sample introduction with no gas assistance cite the ref only. Intrinsically, nanoEESI has advantages, including high sensitivity, good tolerance of matrices, readiness for miniaturization and integration, simple maintenance, easy operation, and low cost. The LOD for cocaine was found to be 7-15 fg for various effervescent drink samples [76].

### Other newly emerging ambient MS

In the past two decades, noncapillary emitters have been developed to avoid the clogging problem in conventional capillary based ESI and for more convenient sample loading. Some materials have been successfully developed as emitters for sample loading and ionization [82-87], such as paper spray [82] and disposable wooden tips [83]. The wooden tip can be directly connected to nano-ESI ion sources of various mass spectrometers. Upon application of high voltage to the tip, desirable mass spectra could be obtained (Figure 6). This new technique is applicable for analysis of various samples, which brings a new vision to ambient MS technique. Moreover, the slim and hard properties of the wooden tip enable sampling from specific location such as

corners and small opening, as indicates potential application in forensic investigation.

### SUMMARY

Ambient mass spectrometry techniques, including DESI-MS, DAPCI-MS and EESI-MS, have emerged as important tools in different areas of forensic analysis. Features such as in situ, real time, online, high throughput and nondestructive analysis of raw samples, enable ambient MS techniques meet the requirement for short timer, sample integrity and traceability, having a huge development potential for forensic analysis. The new emerging ambient MS technology is still in the theoretical and laboratory research stage and most evidence analysis are simulation using standard materials (such as explosive, illegal drugs). With the further development of novel ionization technique, it is expected to have universal application of mass spectrometer to the actual field and provide credible evidence for forensic investigation.

### ACKNOWLEDGMENT

This work is supported by Program for Changjiang Scholars and Innovative Research Team in Universities (PCSIRT).

### REFERENCES

1. Brettell TA, Butler JM, Almirall JR. Forensic science. *Anal Chem.* 2011; 83: 4539-4556.
2. Izake EL. Forensic and homeland security applications of modern portable Raman spectroscopy. *Forensic Sci Int.* 2010; 202: 1-8.
3. Yáñez-Sedeño P, Agüí L, Villalonga R, Pingarrón JM. Biosensors in forensic analysis. A review. *Anal Chim Acta.* 2014; 823: 1-19.
4. Tagliaro F, Pascali J, Fanigliulo A, Bortolotti F. Recent advances in the application of CE to forensic sciences: a update over years 2007-2009. *Electrophoresis.* 2010; 31: 251-259.
5. O'Mahony AM, Wang J. Electrochemical Detection of Gunshot Residue for Forensic Analysis: A Review. *Electroanalysis* 2013, 25, 1341-1358.
6. Barron L, Gilchrist E. Ion chromatography-mass spectrometry: A review of recent technologies and applications in forensic and environmental explosives analysis. *Anal. Chim. Acta* 2014; 806: 27-54.
7. Orellana FA, Galvez CG, Orellana FA, Galvez CG, Roldan MT, Garcia-RuizC, et al. Applications of laser-ablation-inductively-coupled plasma-mass spectrometry in chemical analysis of forensic evidence. *TrAC, Trends Anal. Chem.* 2013; 42: 1-34.
8. Al-Hetlani E. Forensic drug analysis and microfluidics. *Electrophoresis.* 2013; 34: 1262-1272.

9. Takáts Z, Wiseman JM, Gologan B, Cooks RG. Mass spectrometry sampling under ambient conditions with desorption electrospray ionization. *Science*. 2004; 306: 471-473.
10. Cody RB, Laramée JA, Durst HD. Versatile new ion source for the analysis of materials in open air under ambient conditions. *Anal Chem*. 2005; 77: 2297-2302.
11. Shiea J, Huang MZ, Hsu HJ, Lee CY, Yuan CH, Beech I, et al. Electrospray-assisted laser desorption/ionization mass spectrometry for direct ambient analysis of solids. *Rapid Commun Mass Spectrom*. 2005; 19: 3701-3704.
12. Chen HW, Venter A, Cooks RG. Extractive electrospray ionization for direct analysis of undiluted urine, milk and other complex mixtures without sample preparation. *Chem Commun*. 2006; 2042-2044.
13. Na N, Zhao M, Zhang S, Yang C, Zhang X. Development of a dielectric barrier discharge ion source for ambient mass spectrometry. *J Am Soc Mass Spectrom*. 2007; 18: 1859-1862.
14. Harper JD, Charipar NA, Mulligan CC, Zhang X, Cooks RG, Ouyang Z. Low-temperature plasma probe for ambient desorption ionization. *Anal Chem*. 2008; 80: 9097-9104.
15. Harris GA, Nyadong L, Fernandez FM. Recent developments in ambient ionization techniques for analytical mass spectrometry. *Analyst*. 2008; 133: 1297-1301.
16. Huang MZ, Cheng SC, Cho YT, Shiea J. Ambient ionization mass spectrometry: a tutorial. *Anal Chim Acta*. 2011; 702: 1-15.
17. Cooks RG, Ouyang Z, Takats Z, Wiseman JM. Detection Technologies. Ambient mass spectrometry. *Science*. 2006; 311: 1566-1570.
18. Venter A, Nefliu M, Cooks RG. Ambient desorption ionization mass spectrometry. *Trac-Trends in Analytical Chemistry* 2008; 27: 284-290.
19. Huang MZ, Yuan CH, Cheng SC, Cho YT, Shiea J. Ambient ionization mass spectrometry. *Annu Rev Anal Chem (Palo Alto Calif)*. 2010; 3: 43-65.
20. Chen HW, Hu B, Zhang X. Principle and Application of Ambient Mass Spectrometry for Direct Analysis of Complex Samples. *Chinese J. Anal. Chem*. 2010; 38: 1069-1088.
21. Ifa DR, Wu C, Ouyang Z, Cooks RG. Desorption electrospray ionization and other ambient ionization methods: current progress and preview. *Analyst*. 2010; 135: 669-681.
22. Handberg E, Chingin K, Wang N, Dai X, Chen H. Mass spectrometry imaging for visualizing organic analytes in food. *Mass Spectrom Rev*. 2014.
23. Bedair M, Sumner LW. Current and emerging mass-spectrometry technologies for metabolomics. *Trac-Trends in Analytical Chemistry* 2008; 27: 238-250.
24. Nemes P, Vertes A. Ambient mass spectrometry for in vivo local analysis and in situ molecular tissue imaging. *TrAC, Trends Anal. Chem*. 2012; 34: 22-34.
25. Li LP, Feng BS, Yang JW, Chang CL, Bai Y, Liu HW. Applications of ambient mass spectrometry in high-throughput screening. *Analyst*. 2013; 138: 3097-3103.
26. Ma X, Zhang S, Zhang X. An instrumentation perspective on reaction monitoring by ambient mass spectrometry. *TrAC Trends in Analytical Chemistry* 2012; 35: 50-66.
27. Espy RD, Wleklinski M, Yan X, Cooks RG. Beyond the flask: Reactions on the fly in ambient mass spectrometry. *TrAC, Trends Anal. Chem*. 2014; 57: 135-146.
28. Trimpin S, Wang B, Lietz CB, Marshall DD, Richards AL, Inutan ED. New ionization processes and applications for use in mass spectrometry. *Crit Rev Biochem Mol Biol*. 2013; 48: 409-429.
29. Chen H, Talaty NN, Takáts Z, Cooks RG. Desorption electrospray ionization mass spectrometry for high-throughput analysis of pharmaceutical samples in the ambient environment. *Anal Chem*. 2005; 77: 6915-6927.
30. Takáts Z, Wiseman JM, Cooks RG. Ambient mass spectrometry using desorption electrospray ionization (DESI): instrumentation, mechanisms and applications in forensics, chemistry, and biology. *J Mass Spectrom*. 2005; 40: 1261-1275.
31. Venter A, Sojka PE, Cooks RG. Droplet dynamics and ionization mechanisms in desorption electrospray ionization mass spectrometry. *Anal Chem*. 2006; 78: 8549-8555.
32. Chen H, Gamez G, Zenobi R. What can we learn from ambient ionization techniques? *J Am Soc Mass Spectrom*. 2009; 20: 1947-1963.
33. Weston DJ. Ambient ionization mass spectrometry: current understanding of mechanistic theory; analytical performance and application areas. *Analyst*. 2010; 135: 661-668.
34. Harris GA, Galhena AS, Fernández FM. Ambient sampling/ionization mass spectrometry: applications and current trends. *Anal Chem*. 2011; 83: 4508-4538.
35. Ifa DR, Jackson AU, Paglia G, Cooks RG. Forensic applications of ambient ionization mass spectrometry. *Anal Bioanal Chem*. 2009; 394: 1995-2008.
36. Green FM, Salter TL, Stokes P, Gilmore IS, O'Connor G. Ambient mass spectrometry: advances and applications in forensics. *Surf. Interface Anal*. 2010; 42: 347-357.
37. Morelato M, Beavis A, Kirkbride P, Roux C. Forensic applications of desorption electrospray ionisation mass spectrometry (DESI-MS). *Forensic Sci Int*. 2013; 226: 10-21.
38. Takáts Z, Cotte-Rodriguez I, Talaty N, Chen H, Cooks RG. Direct, trace level detection of explosives on ambient surfaces by desorption electrospray ionization mass spectrometry. *Chem Commun (Camb)*. 2005; 1950-1952.
39. Ding X, Duan Y. Plasma-based ambient mass spectrometry techniques: The current status and future prospective. *Mass Spectrom Rev*. 2015; 34: 449-473.
40. Na N, Zhang C, Zhao M, Zhang S, Yang C, Fang X, et al. Direct detection of explosives on solid surfaces by mass spectrometry with an ambient ion source based on dielectric barrier discharge. *J Mass Spectrom*. 2007; 42: 1079-1085.
41. Song Y, Cooks RG. Atmospheric pressure ion/molecule reactions for the selective detection of nitroaromatic explosives using acetonitrile and air as reagents. *Rapid Commun Mass Spectrom*. 2006; 20: 3130-3138.
42. Cotte-Rodriguez I, Hernandez-Soto H, Che H, Cooks RG. In situ trace detection of peroxide explosives by desorption electrospray ionization and desorption atmospheric pressure chemical ionization. *Anal. Chem*. 2008; 80: 1512-1519.
43. Chen H, Zheng J, Zhang X, Luo M, Wang Z, Qiao X. Surface desorption atmospheric pressure chemical ionization mass spectrometry for direct ambient sample analysis without toxic chemical contamination. *J. Mass Spectrom*. 2007; 42: 1045-1056.
44. Li M, Jia B, Ding L, Hong F, Ouyang Y, Chen R, et al. Document authentication at molecular levels using desorption atmospheric pressure chemical ionization mass spectrometry imaging. *J Mass Spectrom*. 2013; 48: 1042-1049.

45. Li M, Jia B, Ding LY, Hong F, Ouyang YZ, Chen R, et al. Document authentication at molecular levels using desorption atmospheric pressure chemical ionization mass spectrometry imaging. *J. Mass Spectrom.* 2013; 48, 1042-1049.
46. Li X, Hu B, Ding J, Chen H. Rapid characterization of complex viscous samples at molecular levels by neutral desorption extractive electrospray ionization mass spectrometry. *Nat. Protoc.* 2011; 6: 1010-1025.
47. Chen H, Wortmann A, Zenobi R. Neutral desorption sampling coupled to extractive electrospray ionization mass spectrometry for rapid differentiation of biosamples by metabolomic fingerprinting. *J. Mass Spectrom.* 2007; 42: 1123-1135.
48. Huang XY, Fang XW, Zhang X, Dai XM, Guo XL, et al. Direct detection of chloramphenicol in honey by neutral desorption-extractive electrospray ionization mass spectrometry. *Anal Bioanal Chem.* 2014; 406: 7705-7714.
49. Wu Z, Chingin K, Chen H, Zhu L, Jia B, Zenobi R. Sampling analytes from cheese products for fast detection using neutral desorption extractive electrospray ionization mass spectrometry. *Anal. Bioanal. Chem.* 2010; 397: 1549-1556.
50. Zhu L, Gamez G, Chen H, Chingin K, Zenobi R. Rapid detection of melamine in untreated milk and wheat gluten by ultrasound-assisted extractive electrospray ionization mass spectrometry (EESI-MS). *Chem Commun (Camb).* 2009; : 559-561.
51. Zhu L, Hu Z, Gamez G, Law WS, Chen HW, Yang SP. Simultaneous sampling of volatile and non-volatile analytes in beer for fast fingerprinting by extractive electrospray ionization mass spectrometry. *Anal. Bioanal. Chem.* 2010; 398: 405-413.
52. Li M, Hu B, Li J, Chen R, Zhang X, Chen H. Extractive electrospray ionization mass spectrometry toward in situ analysis without sample pretreatment. *Anal Chem.* 2009; 81: 7724-7731.
53. Chingin K, Chen H, Gamez G, Zhu L, Zenobi R. Detection of diethyl phthalate in perfumes by extractive electrospray ionization mass spectrometry. *Anal Chem.* 2009; 81: 123-129.
54. Ding J, Gu H, Yang S, Li M, Li J, Chen H. Selective Detection of Diethylene Glycol in Toothpaste Products Using Neutral Desorption Reactive Extractive Electrospray Ionization Tandem Mass Spectrometry. *Anal. Chem.* 2009; 81: 8632-8638.
55. Liu Y, Zhang X, Ouyang Y, Hu Z, Ma L, Zhang J, et al. Trace detection of hormones and sulfonamides in viscous cosmetic products by neutral desorption extractive electrospray ionization tandem mass spectrometry. *J. Mass Spectrom.* 2011; 46: 794-803.
56. Zhang X, Liu Y, Zhang J, Hu Z, Hu B, Ding L, et al. Neutral desorption extractive electrospray ionization mass spectrometry for fast screening sunscreen agents in cream cosmetic products. *Talanta.* 2011; 85: 1665-1671.
57. Zhang X, Wang N, Zhou Y, Liu Y, Zhang J, Chen H. Extractive electrospray ionization mass spectrometry for direct characterization of cosmetic products. *Analytical Methods* 2013; 5: 311-315.
58. Li J, Zhou Y, Ding J, Yang S, Cheng H. Rapid Detection of Toluene-2,4-diisocyanate in Various Sports Fields Using Extractive Electrospray Ionization Mass Spectrometry. *Chinese J. Anal. Chem.* 2008; 36: 1300-1304.
59. Liu C, Hu B, Shi J, Li J, Zhang X, Chen H. Determination of uranium isotopic ratio ( $^{235}\text{U}/^{238}\text{U}$ ) using extractive electrospray ionization tandem mass spectrometry. *J. Anal. At. Spectrom.* 2011; 26: 2045-2051.
60. Liu C, Zhang X, Xiao S, Jia B, Cui S, Shi J, et al. Detection of trace levels of lead in aqueous liquids using extractive electrospray ionization tandem mass spectrometry. *Talanta.* 2012; 98: 79-85.
61. Luo M, Hu B, Zhang X, Peng D, Chen H, Zhang L, et al. Extractive electrospray ionization mass spectrometry for sensitive detection of uranyl species in natural water samples. *Anal Chem.* 2010; 82: 282-289.
62. Chen H, Yang S, Li M, Hu B, Li J, Wang J. Sensitive detection of native proteins using extractive electrospray ionization mass spectrometry. *Angew Chem Int Ed Engl.* 2010; 49: 3053-3056.
63. Hu B, Yang S, Li M, Gu H, Chen H. Direct detection of native proteins in biological matrices using extractive electrospray ionization mass spectrometry. *Analyst.* 2011; 136: 3599-3601.
64. Li M, Jiang H, Li HM, Xu R. The Application and Perspective of Extractive Electrospray Ionization on The Protein Analysis. *Prog. Biochem. Biophys.* 2012; 39: 194-198.
65. Chen H, Wortmann A, Zhang W, Zenobi R. Rapid in vivo fingerprinting of nonvolatile compounds in breath by extractive electrospray ionization quadrupole time-of-flight mass spectrometry. *Angew Chem Int Ed Engl.* 2007; 46: 580-583.
66. Chen H, Zenobi R. Direct analysis of living objects by extractive electrospray mass ionization spectrometry. *Chimia.* 2007; 61: 843-843.
67. Ding J, Yang S, Liang D, Chen H, Wu Z, Zhang L, Ren Y. Development of extractive electrospray ionization ion trap mass spectrometry for in vivo breath analysis. *Analyst.* 2009; 134: 2040-2050.
68. Gamez G, Zhu L, Disko A, Chen H, Azov V, Chingin K, Krämer G. Real-time, in vivo monitoring and pharmacokinetics of valproic acid via a novel biomarker in exhaled breath. *Chem Commun (Camb).* 2011; 47: 4884-4886.
69. Gu H, Chen H, Pan Z, Jackson AU, Talaty N, Xi B, Kissinger C. Monitoring diet effects via biofluids and their implications for metabolomics studies. *Anal Chem.* 2007; 79: 89-97.
70. Zhou Z, Jin M, Ding J, Zhou Y, Zheng J, Chen H. Rapid detection of atrazine and its metabolite in raw urine by extractive electrospray ionization mass spectrometry. *Metabolomics.* 2007; 3: 101-104.
71. Law WS, Chen H, Ding J, Yang S, Zhu L, Gamez G, Chingin K. Rapid characterization of complex viscous liquids at the molecular level. *Angew Chem Int Ed Engl.* 2009; 48: 8277-8280.
72. Marquez CA, Wang H, Fabbretti F, Metzger JO. Electron-transfer-catalyzed dimerization of trans-anethole: detection of the distonic tetramethylene radical cation intermediate by extractive electrospray ionization mass spectrometry. *J. Am. Chem. Soc.* 2008; 130: 17208-17209.
73. Zhu L, Gamez G, Chen HW, Huang HX, Chingin K, Zenobi R. Real-time, on-line monitoring of organic chemical reactions using extractive electrospray ionization tandem mass spectrometry. *Rapid Commun. Mass Spectrom.* 2008; 22: 2993-2998.
74. Chen H, Hu B, Hu Y, Huan Y, Zhou Z, Qiao X. Neutral desorption using a sealed enclosure to sample explosives on human skin for rapid detection by EESI-MS. *J Am Soc Mass Spectrom.* 2009; 20: 719-722.
75. Chen H, Yang S, Wortmann A, Zenobi R. Neutral desorption sampling of living objects for rapid analysis by extractive electrospray ionization mass spectrometry. *Angew Chem Int Ed Engl.* 2007; 46: 7591-7594.
76. Hu B, Peng X, Yang S, Gu H, Chen H, Huan Y, et al. Fast quantitative detection of cocaine in beverages using nanoextractive electrospray ionization tandem mass spectrometry. *J Am Soc Mass Spectrom.* 2010; 21: 290-293.

77. Wang H, Zhao H, Qu Y, Zhang X, Chen H. Applications of new mass spectrometry techniques in analyzing forensic evidence. *Scientia Sinica Chimica*. 2014; 44: 719.
78. Gu H, Hu B, Li J, Yang S, Han J, Chen H. Rapid analysis of aerosol drugs using nano extractive electrospray ionization tandem mass spectrometry. *Analyst*. 2010; 135: 1259-1267.
79. Law WS, Chen HW, Balabin R, Berchtold C, Meier L, Zenobi R. Rapid fingerprinting and classification of extra virgin olive oil by microjet sampling and extractive electrospray ionization mass spectrometry. *Analyst*. 2010; 135: 773-778.
80. Law WS, Wang R, Hu B, Berchtold C, Meier L, Chen H, et al. On the mechanism of extractive electrospray ionization. *Anal Chem*. 2010; 82: 4494-4500.
81. Gu H, Yang S, Li J, Hu B, Chen H, Zhang L, et al. Geometry-independent neutral desorption device for the sensitive EESI-MS detection of explosives on various surfaces. *Analyst*. 2010; 135: 779-788.
82. Liu J, Wang H, Manicke NE, Lin JM, Cooks RG, Ouyang Z. Development, characterization, and application of paper spray ionization. *Anal Chem*. 2010; 82: 2463-2471.
83. Hu B, So PK, Chen H, Yao ZP. Electrospray ionization using wooden tips. *Anal Chem*. 2011; 83: 8201-8207.
84. Liu J, Wang H, Cooks RG, Ouyang Z. Leaf spray: direct chemical analysis of plant material and living plants by mass spectrometry. *Anal Chem*. 2011; 83: 7608-7613.
85. Huang YQ, You JQ, Yuan BF, Feng YQ. Sample preparation and direct electrospray ionization on a tip column for rapid mass spectrometry analysis of complex samples. *Analyst*. 2012; 137: 4593-4597.
86. Zhang J, Li Z, Zhang C, Feng B, Zhou Z, Bai Y, et al. Graphite-Coated Paper as Substrate for High Sensitivity Analysis in Ambient Surface-Assisted Laser Desorption/Ionization Mass Spectrometry. *Anal Chem*. 2012; 84: 3296-3301.
87. Chakrabarty S, Pagnotti VS, Inutan ED, Trimpin S, McEwen CN. A new matrix assisted ionization method for the analysis of volatile and nonvolatile compounds by atmospheric probe mass spectrometry. *J Am Soc Mass Spectrom*. 2013; 24: 1102-1107.
88. Jackson AU, Garcia-Reyes JF, Harper JD, Wiley JS, Molina-Díaz A, Ouyang Z, Cooks RG. Analysis of drugs of abuse in biofluids by low temperature plasma (LTP) ionization mass spectrometry. *Analyst*. 2010; 135: 927-933.
89. Zhang H, Gu HW, Yan FY, Wang NN, Wei YP, Xu JJ, Chen HW. Direct characterization of bulk samples by internal extractive electrospray ionization mass spectrometry. *Sci Rep*. 2013; 3: 2495.
90. Zhang H, Chingin K, Zhu L, Chen HW. Molecular characterization of ongoing enzymatic reactions in raw garlic cloves using extractive electrospray ionization mass spectrometry. *Anal Chem*. 2015; 87: 2878-2883.

Cite this article

Xie L, Zhao H, Zhou P, Zhu T, Liu Y, et al. (2015) Ambient Mass Spectrometry for Forensic Analysis. *Ann Forensic Res Anal* 2(2): 1021.