Effect of Spray Plume Characteristics on Desorption and Ionization in DESI

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OVERVIEW

- Desorption electrospray ionization mass spectrometry (DESI-MS) is rapidly developing as a surface sampling/ ionization source for the interrogation of a wide variety of analytes on a broad range of surfaces under ambient conditions
- Here we investigate the fundamental physical and chemical characteristics of the DESI plume under a variety of sampling conditions
  - Physical characteristics of the solvent/gas jet desorption/ionization plume
    - Under typical DESI-MS conditions the solvent/gas jet desorption ionization plume forms an elliptical desorption/ionization region on the surface, with most effective desorption/ionization obtained from a smaller elliptical area within the larger impact region. Maximum signal from a given amount of material on a surface can be observed when the diameter of the sample spot is less than the diameter of this high efficiency desorption/ionization region. Solvent and gas flow out of the desorption/ionization region limits analyte accessibility to this area via a "washing effect" when analytes are on smooth surfaces or on surfaces for which the analyte has little affinity. Scan speed and surface scanning direction during an analysis are important for maximizing signal levels and signal reproducibility on particular surface types
  - Chemical Characteristics
    - Certain types of compounds are found to undergo oxidation during DESI-MS analysis, with the extent of oxidation directly correlated to the high voltage applied to the emitter. This oxidation may be due to reactive oxygen species (ROS) generated in the emitter

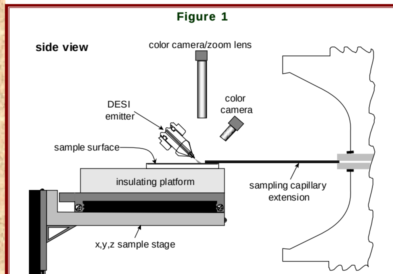
INTRODUCTION

- This research is focused on understanding the fundamental characteristics of the DESI plume, and how these characteristics affect sampling using desorption electrospray ionization mass spectrometry [1-3].
- Previous investigations into the fundamental characteristics of the DESI plume have focused on the effect of spray-to-surface distance and impact angles on signal intensities, as well as the diameter of the impact plume as a function of spray tip diameter [2]. The effect of sprayer-to-surface distance, spray voltage, nebulizing gas pressure and solvent flow rate on size and velocity distributions of droplets in the DESI spray has also been investigated [4]. Analyte oxidation during DESI has been noted [5], as has adduct formation with a variety of analyte molecules [6,7]. No detailed studies on the DESI plume impact region or on the chemical characteristics of the DESI plume have been completed.
- In this work we
  - Map the effectiveness of desorption/ionization within the DESI impact plume region under typical DESI-MS conditions
  - Describe the physical regions of the DESI plume
  - Examine the relationship of these plume impact regions, sample spot size, sample surface characteristics, analyte surface interaction, and surface scan direction and speed with respect to analyte signal level in a surface scanning mode
  - Describe oxidative processes that can occur during sampling

EXPERIMENTS

- **Chemicals.** HPLC grade acetonitrile was purchased from Burdick & Jackson (Muskegon, MI). LC/MS grade methanol was obtained from Mallincrodt Baker, Inc. (Phillipsburg, NJ). Water was purified with a Milli-Q system (Millipore Corp., Billerica, MA). Rhodamine 6G was purchased from Eastman Kodak Company (Rochester, NY). All other compounds were purchased from Sigma-Aldrich (St. Louis, MO) and used as received.
- **Imaging Printed Lines on Copy Paper.** Lines were printed on copy paper (Hammermill Great White Copy, Item # 86700, International Paper Company, Memphis, TN) using an Epson Stylus Color 600 printer with its default S020089 color cartridge. The distribution of the most intense n-mer (*m/z* 689.3) of a polymer additive in the ink was monitored in positive ion mode.
- **Scanning Sampling Studies.** Samples were prepared for DESI analysis by spotting surfaces using a MJ-ATP dispensing device (50 µm orifice diameter, 65 pL droplets) controlled by a JetDrive™ III Controller (Microfab Technologies, Inc., Plano, TX). For scan-direction experiments a series of 3.2 nL (50 droplets) spots of a 1 mM solution of rhodamine 6G was deposited on glass slides and a normal-phase HPTLC plate. Each spot contained 3.2 pmol (1.4 ng) of rhodamine 6G. Spots on the TLC plates were ~ 235 µm in diameter and spots on glass slides ranged from ~ 220 – 280 µm in diameter. For TLC/DESI-MS analysis, 6.5 nL spots of a 250 µM solution of an alkaloid standard mixture (1.6 pmol of each alkaloid) were deposited on normal-phase aluminum-backed HPTLC plate. Each spot was initially ~300 µm in diameter. The plates were developed following the procedure outlined in ref. 9. Development of each plate was stopped after the solvent front had progressed a predetermined distance, from 0.5 to 3.0 cm. Two plates were left undeveloped.
- **Relative sampling efficiency and oxidation studies.** Samples were prepared by spotting PTFE-printed slides (Electron Microscopy Sciences, Fort Washington, PA) using 0.25 µL Drummond microcaps (Fisher Scientific). Sample solutions were 1 mM in concentration (unless otherwise noted) and were prepared in isopropyl alcohol.
- **DESI-MS.** The manual- and computer-controlled x, y, z sample stage is shown in Figure 1.

Figure 1

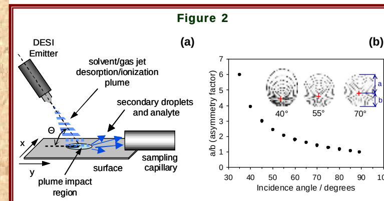


- The mass spectrometer used was a ThermoFinnigan LCQ Deca ion trap (Thermo-Finnigan, San Jose, CA, USA).
- The extended atmospheric sampling heated capillary allowed the instruments to be interfaced with automated MS2000 x, y, z robotic platforms (Applied Scientific Instrumentation Inc., Eugene, OR) for scanning purposes. For more details on instrumental setup see ref. 8 and 9.

RESULTS AND DISCUSSIONS

- **DESI plume impact.** The DESI plume impacts the surface at an acute angle, Θ, to the surface; thus the region of plume impingement has an ovoid shape (Figures 2a and b).

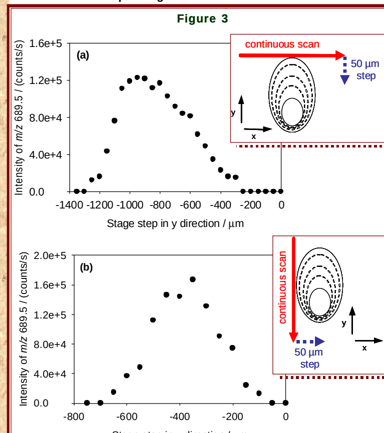
Figure 2



(a) Overview of DESI plume impact. (b) Simulated asymmetry factor of the plume impact region as a function of incidence angle, Θ. + indicates predicted region of highest desorption/ionization efficiency.

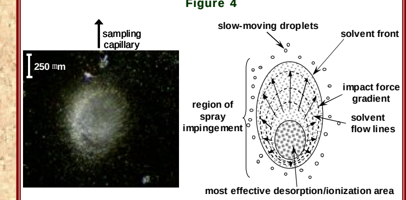
- **Imaging the DESI plume impact region.**
  - Mapping experiments, combined with close visual observation of plume and analyte behavior, indicate that the DESI plume impact region is comprised of three major areas (Figures 3 and 4):
    1. Inner region of highly effective desorption/ionization
    2. Solvent "jets" emanating from the inner region of the plume
    3. Large, slow moving droplets at the outer periphery of the impact region

Figure 3



Mapping of DESI plume on paper using an ink-printed line. Signal intensity of the polymeric ink component when the printed line was scanned through parallel to (a) the y-axis, and (b) the x-axis.

Figure 4



(a) Optical image of DESI plume impingement

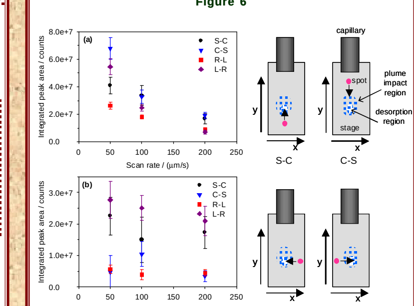
(b) Representation of DESI plume impact region

- **Implications for surface scanning analyses.**
  - Solvent jets can prevent analyte from reaching the inner region of the DESI plume impact region, affecting sampling efficiency
  - A "washing effect" is more pronounced on non-retaining surfaces
  - Scan direction should be chosen such that analyte approaches the spray in a direction opposite of the prevailing flow of the solvent jets

Figure 5

Washing effect: rhodamine 6G being sampled from a Ni-coated slide.

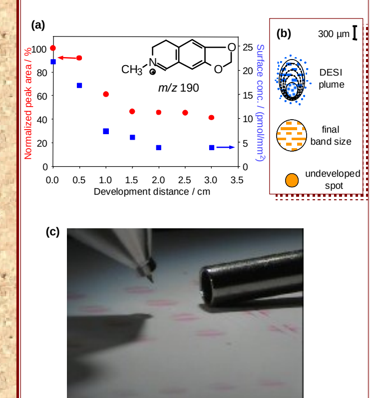
Figure 6



Integrated peak areas of the ion current profile for rhodamine 6G desorbed from (a) normal phase HPTLC plate, and (b) glass as a function of scan rate at a gas flow rate of 194 m/s.

- **Effect of DESI plume characteristics on sampling.**
  - Cannot effectively sample an analyte if spot size is larger than the region of most effective desorption/ionization in the DESI impact plume
  - Surface concentration (mol/unit area) for a given amount of analyte is dictated by spot size
    - Smaller spots lead to more effective desorption/ionization for a given amount of material

Figure 7



(a) Normalized peak area and surface concentration of hydrastinine eluted on a normal-phase aluminum-backed TLC plate as a function of elution distance.

(b) Size of the undeveloped spot and fully developed band as a function of elution distance.

(c) DESI analysis of rhodamine 6G spotted on a TLC plate.

- **Analyte response comparison between ESI and DESI.**
  - The surface introduces an additional factor for consideration when comparing DESI to ESI
  - Relative analyte response in DESI can be different than in ESI
    - Degree of protonation and sodiation may differ
    - Surface effects (morphology and chemistry) may result in differences in analyte response and ion identities between surfaces
    - Oxidative processes may play a more important role in DESI than in ESI
  - Verapamil, buscopan, tamoxifen and prednisilone were used as model compounds with known response factors in ESI

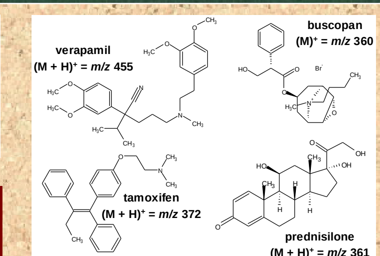
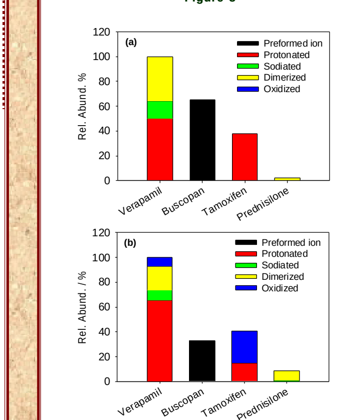


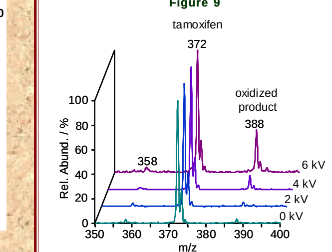
Figure 8



Relative response comparison between (a) ESI, and (b) DESI (250 pmol analyte; PTFE-printed slide). Spray solvent: methanol; solvent flow rate: 5 µL/min; spray voltage: 4 kV.

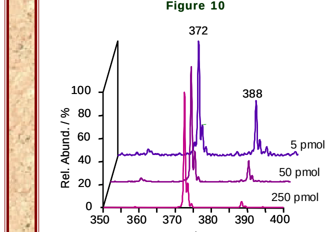
- **Oxidative processes of concern in DESI.**
  - Autoxidation may occur relatively rapidly in spotted compounds and may be photolytically initiated
    - Minimize time between analyte spotting and analysis, as well as exposure to light
  - Oxidation resulting from the DESI spray
    - Oxidation increases with spray voltage
      - Evidence for the production of reactive oxygen species in emitter?
    - Most problematic at low surface concentrations
    - Alleviate by using hydroquinone redox buffer

Figure 9



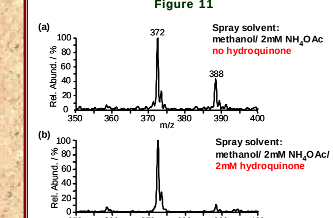
Effect of spray voltage on tamoxifen oxidation during DESI analysis. Spray solvent: 2 mM NH_4OAc in methanol, 5 µL/min; 50 pmol tamoxifen per spot; PTFE printed slide.

Figure 10



Effect of tamoxifen surface concentration on tamoxifen oxidation during DESI analysis.
Spray solvent: 2 mM NH_4OAc in methanol, 5 µL/min; spray voltage: 4 kV; PTFE printed slide.

Figure 11



Effect of hydroquinone redox buffer on oxidation of tamoxifen during DESI analysis.
(a) Spray solvent: 2 mM NH_4OAc in methanol,
(b) spray solvent: 2 mM NH_4OAc, 2 mM hydroquinone in methanol.
Solvent flow rate: 5 µL/min; spray voltage: 4 kV; 5 pmol tamoxifen per spot; PTFE printed slide.

CONCLUSION

- The DESI spray impact plume consists of three major regions, each of which has a differing desorption/ionization efficiency
  - Analyte spot size must be smaller than the region of most effective desorption/ionization in the DESI impact plume for effective sampling/ionization
- Surface characteristics (porosity, roughness) and the affinity of the analyte for the surface affect desorption/ionization efficiency
  - Desorption/ionization efficiency is influenced by spray plume characteristics and symmetry
- Relative analyte response in DESI can be different than in ESI, but correlates for some surfaces
  - Analyte ion types can differ significantly
  - Oxidation can occur, but can be controlled through the use of a redox buffer in some cases

FUTURE WORK

- Modification of DESI spray emitter for tailored plume shape and improved sampling
- Elucidate surface effects on desorption/ionization
- Examine ionization mechanisms
- Understand and eliminate spray-mediated oxidative processes in DESI

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ACKNOWLEDGMENTS

- S.P.P. acknowledges an Oak Ridge National Laboratory (ORNL) appointment through the ORNL Postdoctoral Research Associates Program.
- Dr. Mitch Doktycz is thanked for use of the MJ-ATP dispensing device and JetDrive™ III Controller.
- Dr. Julian Philips (Thermo Electron) is thanked for the loan of the LCQ DECA mass spectrometer.
- The MicroIonSpray head used to fabricate the DESI emitter was provided through a CRADA with MDS Sciex (ORNL02-0662).
- The surface scanning platform and associated software used in this study was developed with support from ORNL Technology Transfer and Economic Development (TTED) Royalty Funds.
- This work was supported by the Division of Chemical Sciences, Geosciences, and Biosciences, United States Department of Energy, Office of Basic Energy Sciences. ORNL is managed and operated by UT-Battelle, LLC, for the US Department of Energy under Contract DE-AC05-00OR22725.