The author(s) shown below used Federal funding provided by the U.S. Department of Justice to prepare the following resource:

Document Title: Vibrational Spectroscopy of Gunshot Residue

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Document Number: 304616

Date Received: April 2022

Award Number: 2016-DN-BX-0166

Department of Justice

NIJ 2016-DN-BX-0166

Vibrational Spectroscopy of Gunshot Residue

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Office for Sponsored Programs, MSC 312

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Final Summary Overview

1 DESIGN AND METHODS

The ultimate goal of this study is to develop a novel method based on Raman spectroscopy for the detection, identification and characterization of gunshot residue (GSR) for forensic purposes. During this grant period, we have developed a novel two-step method for the detection and identification of organic GSR (OGSR) and demonstrated a great potential of vibrational spectroscopy to link GSR particles to the type of ammunition discharged. We also validated and tested the reliability of our Raman spectroscopic mapping approach on adhesive tape, and established that using this method we could differentiate between potential false positives known for standard forensic analysis techniques used currently for GSR detection and identification [1]. We have further developed our Raman spectroscopic approach for GSR analysis by determining the optimal excitation wavelength for probing specifically OGSR originated by discharging several different types of ammunition. We conducted a comparative study using Raman spectroscopy and attenuated total reflectance Fourier transform-infrared spectroscopy (ATR FT-IR) for the analysis of organic GSR which demonstrated that Raman spectroscopy possesses superior capability for the classification of individual GSR particles based on ammunition manufacturer. We also demonstrated the superior ability of Raman spectroscopy to characterize OGSR as current literature has identified this subtype of GSR as a more informative and promising type of forensic trace evidence than inorganic GSR (IGSR), which is the focus of currently accepted forensic methods [2-4].

In addition, we investigated the effect of firearm on OGSR chemical composition, and examine its Raman spectroscopic characteristics in particular. It was concluded in this work that the firearm used in a discharge event does not appear to have a statistically significant effect on the Raman spectra of resulting OGSRs. We furthermore conducted an exploratory work in which we assessed the ability of laser induced breakdown spectroscopy (LIBS) to differentiate between OGSR stemming from three closely related cartridge cases. Finally, we have laid the groundwork to probe the relationship between the unburnt propellant precursor to their respective OGSRs and to probe the relationship between OGSRs/propellants with similar and contrasting parameters which may be of interest to forensic investigators. In order to facilitate these studies we have developed a sample preparation method based on the smokeless powder analyses performed by the National Center for Forensic Science in Orlando, FL at the University of Central Florida and by Lopez-Lopez et al.'s study [5, 6].

During the course of all these activities we have consulted with our collaborators at the New York State Police Forensic Investigation Center to ensure that our work was addressing topics of interest to the forensic community. We have also consulted closely with the Environmental Health and Safety Department at the University of Albany to identify the proper precautions for storing and preparing smokeless powders for Raman spectroscopic analysis.

OGSR samples and smokeless powder samples were obtained with the assistance of our collaborators at the New York State Police (NYSP) Forensic Investigation Center (FIC). A cotton cloth substrate placed at a distance of approximately 0.3 m was fired into in order to collect the OGSR samples. OGSR particles were prepared for Raman spectroscopic analysis by adhering them to double sided adhesive tape which was mounted on aluminum covered microscope slides. The smokeless powders were obtained using a bullet puller. Smokeless powder samples were dissolved in a solvent to create a solution which was spotted onto aluminum covered microscope slides and allowed to evaporate. The formed smokeless powder cast film was analyzed using Raman microspectroscopy. The obtained spectral datasets were subjected to comprehensive data analysis including advanced statistics.

2 DATA ANALYSIS

In order to address the objectives of the current grant we studied the spectral profiles of various OGSR samples and used advanced statistical methods to help in our analysis and differentiation between ammunition classes. Specifically, we used Eigenvector PLS-Toolbox within the MATLAB® computational environment. In addition, we used OMNICxi software from Thermo Fisher Scientific for creating hyperspectral images based on fluorescence mapping data as the first step for the detection of OGSR particles on the adhesive tape.

3 STATEMENT OF RESULTS

3.1 Objective 1: *Chemical characterization of unburnt ammunition propellant and unspent primers with vibrational spectroscopy (prior to firearm discharge).*

We successfully obtained Raman spectroscopic characteristics of unburnt smokeless powders obtain from 12 different ammunitions. The investigated set of ammunitions varied both by the type of calibers, grain weights, and the manufacturers. Although the sample set of ammunitions was small relative to what was available on the market, it provided a good representation of common calibers and manufacturers based on our consultation with the New York State Police for the method development and evaluation. We are currently conducting the analysis of the acquired Raman spectral data including their visual inspection and advanced statistical analyses. We intend to complete the analysis before the project end date.

3.2 Objective 2: Specificity of GSR samples as related to the discharged material

i. Determination of the optimal excitation wavelength for Raman spectroscopic analysis of OGSR

In our previous studies we had significant issues with analysis of dark GSR particles using the 785-nm wavelength [7]. This is a problem as ideally forensic investigators would need to analyze all types of OGSR particles recovered at a crime scene using Raman spectroscopy. We performed a study using OGSR particles stemming from 5 different calibers of ammunition in order to determine the optimal excitation wavelength for the Raman spectroscopic analysis of OGSR evidence. The Raman spectroscopic characterization of the 5 OGSR samples was completed using the Renishaw InVia

Confocal Raman microscope and 4 different excitation wavelengths were assessed for OGSR particle analysis. Thus, in this study we focused on analysis of OGSR particles with a variety of colors as well as different wavelengths including 785 nm, 457 nm, 514 nm, and 647 nm. The 5 different OGSR samples were analyzed using these wavelengths and overall the 457 nm wavelength was found to be the optimal for the analysis of OGSR particles. Excitation with the 457 nm light worked well regardless of the particle color and resulted in high quality Raman spectra typical for OGSR. Overall, this study aimed to assist in method optimization for the Raman spectroscopic analysis of OGSRs and provided key information for the later Raman spectroscopic analyses of OGSR listed in *Objective 2*. This work was presented as a master's thesis by Ashley Hull and a manuscript is currently in preparation for publication.

ii. Raman spectroscopic analysis of OGSR samples

Since OGSR can stem from cartridge cases of many calibers, grain weights, and brand names it is important to assess the ability of Raman spectroscopy to characterize the parameters that could potentially link GSR to specific ammunition cartridges. The Raman spectroscopic analysis of OGSR samples stemming from 4 different manufacturers, and two different calibers (9 mm and 0.38) was completed using a Renishaw InVia Confocal Raman microscope with a laser wavelength of 457 nm. These calibers in particular we selected at the advisement of our collaborators at that New York State Police Forensic Investigation Center as they are very popular calibers that are often seen in police work. The Raman spectral dataset is currently in the process of being analyzed and will be compared to the propellant spectral dataset obtained in Objective 1. We are evaluating the specificity of the OGSR with regards to Raman spectroscopic features, and will determine the possibility to statistically differentiate OGSR samples originating from different propellants. This work will be completed before the submission of the final report.

3.3 Objective 3: Elimination of propellant and primer mixtures as generating a "crime scene" GSR sample.

i. Creation of Raman spectroscopic library

The creation of a Raman spectroscopic library is key in order to compile the information that we glean in Objectives 1 and 2 in a format that is easy to use for practical purposes. We are working on creating a Raman spectral library of unburned propellants and OGSRs from different types of investigated ammunitions and associated OGSR, which can be used to narrow down the possible types of ammunition that were involved in the firearm discharge process. We are doing this by assessing the data collected from Objectives 1 and 2 using advanced chemometrics. This work will be completed before the submission of the final report.

ii. *Assessment of the effect of different firearms on Raman spectra of OGSRs*

The potential effect of a specific firearm on the generated GSR has been a subject of discussion by the forensic community for long time. A comprehensive study on the effects of "weapon memory" on OGSRs has been recently published by López-López et al. [8], who reported that weapon memory had a negligible effect on the analysis of OGSRs using Raman spectroscopy [8]. We investigated a different concept by assessing the effect of a specific firearm upon the Raman spectroscopic signature of OGSR. This was done by the analysis of OGSR particles stemming from the same ammunition which were fired from three distinct firearms. The three firearms in question were all 9 mm caliber firearms, the following firearms were used: a Ruger Model P85 from the United States, Heckler & Koch Model P748 from West Germany, and a Browning firearm of an unspecified model from Belgium

Raman spectroscopic analysis was performed using the Renishaw InVia confocal Raman microscope and a laser wavelength of 785 nm. A PLSDA model with 4 latent variables (LVs) was used in order to assess the potential to differentiate between the three different OGSR samples. We concluded based on this analysis that the there was no significant difference between the Raman spectra in these three sample classes. This study made an important conclusion for using Raman spectroscopy for the analysis of GSR: Raman spectra of OGSR are mainly determined by the ammunition used in the firing event rather than the firearm, which was used. This work has been completed and a manuscript is in preparation for publication.

3.4 **Objective 4:** Investigate the combined approach of tape lifting and Raman microspectroscopic chemical mapping as a tool for GSR collection and detection.

1. *Raman microscopectroscopic mapping*

Our research group had previously published a novel method for the detection of GSR via tape lifting combined with Raman microspectroscopic mapping and multivariate analysis [9]. During the course of this grant period the validation study was performed to investigate the specificity and reproducibility of the proposed approach. First, the possibility of using the developed spectral library for another Raman instrument was investigated. Raman spectroscopic mapping was used to detect both IGSR and OGSR on adhesive tape, and was performed on an independent Raman microscope which had not been used to analyze the training set data. The Raman microscope that was used to collect the data for the training set was the Thermo Fisher Scientific DXR Raman microscope and the measurements were undertaken using a 780 nm excitation wavelength. The Raman microscope that was used to conduct the analysis of the validation dataset was the Horiba LabRAM HR Evolution Raman microscope and an excitation wavelength of 785 nm was used for these experiments. The measurement parameters that were used for the training set analysis were replicated for the validation set analysis excepting for the autofocus and step size of the measurements. The independently collected validation spectra were classified against our original training dataset using support vector machine discriminant analysis (SVM-DA). Our results showed classification rates of 100%. Such results demonstrated the reproducibility of our technique. This study also proved that our technique was not dependent upon a specific instrument and additionally provided external validation for our approach.

Additionally, in this study we used the same procedure for GSR collection (tape lifting) to collect samples from the clothing and hands of mechanics. These items have the potential to act as false positives for current GSR analysis techniques. This is because materials associated with tires and automotive brakes often contain the key elements targeted by current GSR detection techniques. It was determined in our study that Raman spectroscopic analysis was not susceptible to misclassifications from these particles. Results from these validation experiments illustrate the great potential of Raman microspectroscopic mapping used with tape lifting as a viable tool for GSR detection and characterization.

Our method demonstrated a very high specificity, and we were able to differentiate the samples obtained from automotive mechanics from GSR particle samples. This study was published in 2018 [1].

2. *Novel two-step method for OGSR detection using fluorescence and Raman hyperspectral mapping*

We have also developed a novel two-step method for the detection and identification of OGSR particles on adhesive tape [10]. This work was done in collaboration with Thermo Fisher Scientific and we utilized the Thermo Scientific DXRxi Raman Imaging Microscope using a 455 nm excitation wavelength. In this study we were able to analyze two distinct samples on adhesive tape substrates mounted on aluminum covered microscope slides. One sample had a known amount of OGSR samples on it and one sample had an unknown amount of OGSR particles on it. Both samples were subjected to our two-step detection and identification technique. The samples were first analyzed using fluorescence spectroscopy and hyperspectral color maps were created to visualize areas of high fluorescence intensity. Based on these maps we could visually see the areas where OGSR particles were present. These target areas were then subsequently interrogated using Raman spectroscopy to map only on the specified potential particles. Our method was shown to have great ability to detect and identify OGSR particles in a fast and easy manner. The method was shown to also be able to distinguish between environmental contaminants and OGSR particles. We posit that this technique has the potential to be implemented in a forensic laboratory context to help save examiners time and effort in detecting and identifying OGSR particles. A manuscript on this research project was published in 2019 [10].

3.5 Additional work

We have additionally collaborated with Dr. Mathieu Baudelet at the National Center for Forensic Science at the University of Central Florida to complete work on the analysis of OGSR stemming from three closely related ammunition classes using both Raman spectroscopy and Laser Induced Breakdown Spectroscopy (LIBS). We were able to utilize the variable selection technique of Genetic Algorithm (GA) to build a PLSDA model with 4 latent variables in order to successfully differentiate between the three different sample classes of ammunition used in the study. The ammunition used in this study consisted of three samples of Winchester 9 mm ammunition with different brandings. Each particle was confirmed to be OGSR based on its Raman spectral signature prior to analysis using LIBS. Prior to analysis with LIBS high resolution microscopic images were also captured for each particle and these images helped to confirm that visual differentiation between the samples was not possible. The purpose of this work was to investigate the potential for LIBS to achieve more specific differentiation of ammunition as the three samples used were all from the same manufacturer and had the same caliber. Two of the samples used in this case also had the same grain weight parameter. This work is being drafted into a manuscript for publication.

We have also collaborated with Ángela Lizeth Álvarez Jiménez, a PhD student visiting from Chile, in order to investigate the potential for Raman spectroscopy to differentiate between ammunition of different classes. This study compared photoacoustic spectroscopy (PAS), ATR FT-IR, and Raman spectroscopy and assessed their abilities to differentiate between GSR from three different ammunition manufacturers. The ammunition samples that were used in this study were from the three manufacturers of Remington, Maxxtech, and Fiocchi. The chemometric technique which was used to help differentiate between the spectral datasets from these samples was soft independent modeling of class analog (SIMCA). From this particular study it was concluded that Raman spectroscopy had superior differentiation capability between OGSR from the three ammunition samples. A manuscript has been completed on this work and is to be submitted soon.

4 PROJECT FINDINGS

Significant progress was made towards the development of a novel method based on Raman spectroscopy for the detection, identification and analysis of GSR for forensic purposes. Specifically, we further developed and improved the spectral acquisition stage by determining the optimal excitation wavelength for detection and analysis of OGSR. We also better defined the relationship between the ammunition and firearm, and the Raman characteristics of the resulting OGSR. We further developed and refined a Raman spectroscopic mapping technique and demonstrated that the developed methodology is not subjected to false positives caused by environmental interferences reported for a currently used method. A novel two-step approach for the detection and identification of OGSR particles was also developed based on fast fluorescence mapping followed by confirmatory identification using Raman microspectroscopy. This novel technique was shown to be able to identify and differentiate OGSR particles from environmental contaminants.

In addition to the initially proposed work, we conducted a collaborative study to explore the potential for LIBS to be used to analyze and differentiate closely related OGSR samples. We also compared the ability of three different vibrational spectroscopic methods to differentiate between different ammunition samples, these techniques included Raman spectroscopy, photoacoustic spectroscopy (PAS) and ATR FT-IR spectroscopy. We have completed experimental work and are working now on data analysis to probe the relationship between smokeless powders and corresponding OGSRs and to establish the relationship between cartridge casing parameters and Raman spectral signatures of OGSRs and propellants.

5 IMPLICATIONS FOR CRIMINAL JUSTICE POLICY AND PRACTICE

With regards to criminal justice policy and practice we anticipate that our novel methodology, when fully developed and implemented to the practice, will help forensic scientists to detect, identify and analyze OGSR making it a new important type of evidence. We also anticipate that the developed method optimization and standardization including the selection of an optimal excitation wavelength for the Raman spectroscopic analysis of OGSRs is a crucial step in moving towards eventual implementation of this technique in the forensic laboratory context and court admissibility of such evidence. As aforementioned, the topic of OGSR analysis is a much talked about area in forensics and is of great interest to forensic professionals now. In fact a task force on OGSR analysis has been formed by the National Institute of Standards and Technology (NIST) with a goal to improve the methodology for this important area of forensic analysis. Training a new generation of forensic scientists with broad expertise and background in modern methods of analytical chemistry and spectroscopy as well as in advanced statistical analysis is another important mission of our research program. During this reported period, two PhD students from our laboratory were hired by the New York State Police Forensic Investigation Center. This was in addition to two other students who had been hired earlier. We were also invited to attend a New York State Police journal club meeting during this grant period and were able to share the advancements in technology and research that we have developed with regards to OGSR analysis using Raman spectroscopy.

Scholarly Products from Funded Project

I. Publications

1. Khandasammy, S. R., Fikiet, M. A., Mistek, E., Ahmed, Y., Halámková, L., Bueno, J., & Lednev, I. K. (2018). Bloodstains, Paintings, and Drugs: Raman Spectroscopy Applications in Forensic Science. *Forensic Chemistry*, doi:10.1016/j.forc.2018.02.002

2. Fikiet, M. A., Khandasammy, S. R., Mistek, E., Ahmed, Y., Halámková, L., Bueno, J., & Lednev, I. K. (2018). Review Article: Surface enhanced Raman spectroscopy: A review of recent applications in forensic science. *Spectrochimica Acta Part A: Molecular And Biomolecular Spectroscopy*, doi:10.1016/j.saa.2018.02.046

3. Doty, Kyle & K. Lednev, Igor. (2017). Raman spectroscopy for forensic purposes: Recent applications for serology and gunshot residue analysis. TrAC *Trends in Analytical Chemistry*. 103. 10.1016/j.trac.2017.12.003.

4. Fikiet, M. A., Khandasammy, S. R., Mistek, E., Ahmed, Y., Halámková, L., Bueno, J., & Lednev, I. K. (2018) Forensics: evidence examination via Raman spectroscopy. *Physical Sciences Reviews*, doi: https://doi.org/10.1515/psr-2017-0049

5. Mistek, E., Fikiet, M.A., Khandasammy, S.R., & Lednev, I. K. (2018) Toward Locard's exchange principle: Recent developments in forensic trace evidence analysis, *Analytical Chemistry*, doi: 10.1021/acs.analchem.8b04704

6. Khandasammy, S. R., & Lednev, I. K. Chapter 2. (2019) Vibrational Spectroscopy: The New Horizon for Gunshot Residue Analysis. *Forensic Analysis of Gunshot Residue, 3D-Printed Firearms, and Gunshot Injuries: Current Research and Future Perspectives*, NOVA Science Publishers

7. Khandasammy, S.R., Rzhevskii, A., & Lednev, I.K. (2019) A Novel Two-Step Method for the Detection of Organic Gunshot Residue for Forensic Purposes: Fast Fluorescence Imaging Followed by Raman Microspectroscopic Identification, *Analytical Chemistry*, doi: 10.1021/acs.analchem.9b02306

8. Master's Thesis: Optimal Excitation Wavelength for Raman Spectroscopic Analysis of Organic Gunshot Residue Evidence Hull, Ashley. State University of New York at Albany, ProQuest Dissertations Publishing, 2020. 27993299.

9. Bueno, J., Halámková, L., Rzhevskii, A., & Lednev I.K. (2018) Raman microspectroscopic mapping as a tool for detection of gunshot residue on adhesive tape. *Anal Bioanal Chem* doi: https://doi.org/10.1007/s00216-018-1359-1

II. Conference Presentations

1. **Invited Talk** I.K. Lednev at the annual meeting of the American Society of Crime Lab Directors (ASCD); April 30, 2017, Dallas, TX *"The University at Albany - NY State Police Crime Laboratory collaboration on forensic research and development"*

2. **Invited Talk** I.K. Lednev at the 5th Conference on Advanced Applied Raman Spectroscopy (RamanFest) at the Purdue University; June 1-2, 2017, West Lafayette, IN.
3. **Invited Talk** I.K. Lednev at the International Conference on Advanced Vibrational Spectroscopy (ICAVS); June 11-16, 2017, Victoria, BC, Canada *"Raman Microspectroscopy for Forensic Purposes"*
4. **Invited Talk** I.K. Lednev at the 5th Conference on Advanced Applied Raman Spectroscopy (RamanFest). Purdue University, June 1-2, 2017 *"Raman Hyperspectroscopy for Forensic Purposes and Medical Diagnostics"*.
5. **Poster presentation** Shelby Khandasammy at the NIJ Forensic Science Research & Development Poster Session during Pittcon 2018 entitled, "The Detection and Identification of Organic Gunshot Residue via Fluorescence and Raman Imaging Microscopy for Forensic Purposes"
6. **Poster presentation** Ashley Hull at the SUNY Undergraduate Research Conference and the University at Albany Undergraduate Research Conference entitled, "Raman Spectroscopic Analysis of Organic Gunshot Residue Spanning a Range of Excitation Wavelengths"
7. **Invited Talk** I.K. Lednev, at Pittsburgh Conference on Analytical Chemistry and Applied Spectroscopy (Pittcon 2018), February 26 - March 1, 2018, Orlando, FL.
   "Vibrational Spectroscopy and Advanced Statistics for Detection and Characterization of Gunshot Residue"
8. **Oral Presentation** I.K. Lednev at the 70th Annual Scientific Meeting of American Academy of Forensic Sciences, February 19-24, 2018, Seattle, Washington. "Raman

Microspectroscopy and Advanced Statistics for Detection and Characterization of Gunshot Residue (GSR)"

9. **Webinar** I.K. Lednev on January 23, 2018 entitled, "Raman Microspectroscopy for Forensic Purposes a medical diagnostics." In total, 323 people registered: 151 from the US, with all other attendees originating from 52 other countries. The webinar video can be downloaded at:
    a. https://www.dropbox.com/s/bbsuj0rgk0btxip/Raman%20Microspectroscopy%20For%20Forensic%20Purposes%20and%20Medical%20Diagnostics%20-%20VIDEO.mp4?dl=0
10. **Interview** Dr. Lednev was interviewed by Pittcon TV on March 27, 2018 regarding the impact that vibrational spectroscopy and advanced statistics for the detection and characterization of gunshot residue will have upon the field of forensic chemistry. This interview is available on YouTube though the channel WebsEdgeEducation, and can be viewed using the link below.
    a. https://www.youtube.com/watch?v=V6CsQ5N51D8
11. **Oral presentation** Shelby R. Khandasammy, Alex Rzhevskii, and Igor K. Lednev at Joint Pittcon/FACSS Session: Raman Spectroscopy and Forensics at SciX 2018 (Scientific Exchange Conference), October 21-26 in Atlanta, Georgia.
    a. "The Detection and Identification of Organic Gunshot Residue via Fluorescence and Raman Imaging Microscopy for Forensic Purposes"
12. **Oral presentation** Shelby R. Khandasammy, Alex Rzhevskii, and Igor K. Lednev at the 2018 Eastern Analytical Symposium & Exposition in the technical session entitled, "Advance Solutions in the Analysis of Forensic Samples" November 11-14, 201 in

Princeton, NJ “The Detection of Organic Gunshot Residue Using Raman Spectroscopy and Fluorescence”

13. **Oral presentation** Ashley N. Hull, Shelby R. Khandasammy, Vladimir Ermolenkov, and Igor K. Lednev at SUNY Albany Undergraduate Research Symposium on October 18, 2018 in Albany, NY. “Raman Spectroscopic Analysis of Organic Gunshot Residue Spanning a Range of Excitation Wavelengths”

14. **Oral presentation** I.K. Lednev at Forensic Incubator and Journal Club. A total of five students in addition to NYSP staff members attended, and a talk on Raman applications for forensic science was discussed with the NYSP Journal Club on October 16, 2018 in Albany, NY.

15. **Oral presentation** I.K. Lednev. at Kuwait University in Kuwait on December 23, 2018. “Raman Spectroscopy and Advanced Statistics for Forensic Applications”
16. **Oral presentation, Keynote lectures** I.K. Lednev. at the National Science Camps for High School Students in Bengaluru and Bhopal, India, December 8 and 10, 2018. “A Great Potential of Raman Spectroscopy to Revolutionize Forensic Science and Medical Diagnostics”
17. **Oral presentation, Keynote Lecture** I.K. Lednev. at 26th International Conference on Raman Spectroscopy (ICORS) in Jeju Island, South Korea, August 24-31, 2018.
18. **Poster Presentation** Shelby R. Khandasammy, Alex Rzhevskii, and Igor K. Lednev, “The Detection and Identification of Organic Gunshot Residue (OGSR) Via Fluorescence Mapping and Raman Spectroscopy” at the 71st Annual American Academy of Forensics Sciences (AAFS) Conference in Baltimore, MA

19. **Poster Presentation** Shelby R. Khandasammy, Alex Rzhevskii, and Igor K. Lednev, Gunshot Residue Detection and Characterization via Spectroscopic Mapping for Forensic Purposes" at Pittcon 2019 at the NIJ Forensic Science Research & Development Poster Session in Philadelphia, PA"
20. **Oral Presentation** Shelby R. Khandasammy, Alex Rzhevskii, and Igor K. Lednev , "Detection and identification of organic gunshot residue via fluorescence mapping and Raman spectroscopy" at ACS NERM 2019 at the Forensic Analysis in the Lab and at the Crime Scene session in Saratoga, NYP
21. **Invited Seminar** I.K. Lednev, at the Department of Chemistry, University of Mississippi, Oxford MS, April 18, 2019.
22. **Invited talk** I.K. Lednev "Raman Spectroscopy for Forensic Applications" at National Webinar Series - Emerging Research: Forensic Chemistry. Organized by Forensic Technology Center of Excellence, Research Triangle Park, NC, April 4, 2019.
23. **Invited talk** I.K. Lednev, "Raman spectroscopy for forensic applications"
24. Invited talk I.K. Lednev, at the Forensic Science Research and Development Symposium. National Institute of Justice at the 71st Annual Scientific Meeting of the American Academy of Forensic Sciences. February 19, 2019. Baltimore, Maryland. "Raman Microspectroscopy and Advanced Statistics for Detection and Characterization of Gunshot Residue"
25. **Oral Presentation** Shelby R. Khandasammy, at SciX 2019 Palm, Springs, CA "New Horizons in Gunshot Residue Analysis"

    Winner of Elsevier Award for Best Oral Presentation in Forensic Chemistry at SciX 2019

26. **Poster Presentation** Shelby R. Khandasammy, at SciX 2019, *Palm Springs, CA* "The Potential for Forensic Organic Gunshot Residue Evidence Analysis Using Raman Spectroscopy"
27. **Invited Lecture** I. K. Lednev at the Eastern Analytical Symposium and Exposition, *Plainsboro, NJ* "Raman Hyperspectroscopy for Biomedical Diagnostics and Forensic Purposes"
28. **Keynote Lecture** I. K. Lednev at the Annual Life Science Undergraduate Research Symposium 2019, *Albany, NY* "Raman Spectroscopy for Forensic Purposes"
29. **Invited Seminar** I.K. Lednev at the New England Society for Applied Spectroscopy (NESAS), *Chelmsford, MA* "Raman Hyperspectroscopy for Biomedical Diagnostics and Forensic Purposes"
30. **Plenary Lecture** I. K. Lednev at the 7th Taiwan International Symposium on Raman Spectroscopy, *Taipei, Taiwan* "Raman Spectroscopy and Advanced Statistics for Forensic Purposes and Medical Diagnostics"
31. **Invited Lecture** I.K. Lednev at the Taiwan Association of Raman Spectroscopy Summer Camp, *Great Roots Forestry Resort, Taiwan* "Raman Spectroscopy and Advanced Statistics for Forensic Purposes and Medical Diagnostics"
32. **Invited Talk** I.K. Lednev at the 42nd Northeast Regional Meeting of the American Chemical Society (NERM 2019), *Saratoga Springs, NY* "Raman Hyperspectroscopy is a Universal Tool for Forensic Purposes and Medical Diagnostics"
33. **Invited Lecture** I.K. Lednev at the 3rd Annual NIJ Forensic Science Symposium, Pittsburgh Conference on Analytical Chemistry and Applied Spectroscopy (Pittcon 2020),

Chicago, IL "Vibrational spectroscopy and Advanced Statistics for Detection and Characterization of Gunshot Residue"

34. **Selected Talk** I.K. Lednev at the 72nd Annual Scientific Meeting of American Academy of Forensic Sciences (AAFS 2020), Anaheim, CA "Detection, Identification, and Characterization of Gunshot Residue (GSR) Using Raman Spectroscopy"
35. **Co-authored Talk** Jacob Shelley, I. K. Lednev, and Shelby R. Khandasammy at the NIJ (National Institute of Justice) - Innovations in Technology to Advance Forensic Science (Pittcon 2020), Chicago, IL Analysis and Classification of Organic Gunshot Residues (OGSRs) with Mass Spectrometry and Raman Spectroscopy
36. **Poster Presentation** Ashley Hull, Shelby R. Khandasammy, and Igor K. Lednev at (Pittcon 2020), Chicago, IL "Optimal Exictation Wavelength for Raman Spectroscopic Analysis of Organic Gunshot Residue Evidence"

Participants

Dr. Igor K. Lednev, Professor – Principal Investigator.

Shelby R. Khandasammy, Ph.D. Student – Experimental design, experimental work, advanced statistical analysis, preparation of reports and manuscripts, and conference presentations.

Dr. Lenka Halamkova, Research Scientist – Advanced statistical analysis of spectroscopic data, preparation of reports and manuscripts, and conference presentations.

Mathew Boll, Undergraduate student – Experimental work, preparation of reports. Not supported from the grant. Works on related forensic project.

Ashley Hull, Undergraduate Student/Master's Student – Experimental work, preparation of reports. Not supported from the grant. Works on related forensic project.

Nathan Bartlett, Undergraduate Student/Master's Student – Experimental work, preparation of reports. Not supported from the grant. Works on related forensic project.

Ángela Lizeth Álvarez Jiménez, Visiting Student – Experimental work, preparation of reports. Not supported from the grant. Worked on related forensic project.

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