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Author(s):	**James Michael, Ph.D.**
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Final Research Report

Grant Title:	Ultrafast 3D visualization and fluid dynamic mechanisms of blood atomization
Award:	2017-DN-BX-0171
Sponsor:	National Institute of Justice Office of Justice Programs U.S. Department of Justice
PI:	Dr. James Michael Assistant Professor Department of Mechanical Engineering Iowa State University Ames, IA 50011 e: jmichael@iastate.edu ph: 515-294-0723
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I. Summary of the project

Major goals of the project

The major goals of the project were to incorporate experimental and numerical simulations to capture blood fluid atomization, bloodstain patterns, and in-flight droplet behavior. Experimental methods included high-speed and laser-based holographic imaging to provide three-dimensional information about the trajectories and mechanisms of blood droplets and blood atomization processes relevant to forensic analysis of bloodstain patterns. A series of studies provided relevant blood-letting events ranging from blunt impact to high velocity bullet impact. The project also resulted in experimental results available for continued use by both the forensics and fluid dynamics communities for test and comparison of models.

The specific goals of the project included:

1. The development of faster techniques for high-speed visualization.
2. The development of a holographic imaging system for three-dimensional, time-resolved measurements of blood atomization processes.
3. The creation of a database of highly-detailed measurements of blood atomization processes for jetting, blunt impact, and projectile impact events.
4. The validation of a predictive fluid dynamics model, including the incorporation of muzzle blast effects.

Research questions

Over the course of the past decade, increased attention has been focused on a number pattern-based forensic analysis techniques with the goal of quantifying the uncertainties. Pattern-based

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techniques including *bloodstain pattern analysis* (BPA), received significant attention in the 2009 report by the US National Research Council "Strengthening Forensic Science in the United States: A Path Forward." The report points out that uncertainties associated with BPA are complicated by the interaction between multiple physical domains[1]. These include the complex role of fluid mechanics in BPA, which was examined in a critical review (Attinger et al. 2013)[2]. BPA is inherently complex: fluid mechanics are involved in the generation, flight, and collision of blood droplets with surfaces; complex tissue mechanics are involved with wounding and blood-letting events; and variations in the environment and in the character of blood outside the body can lead to a wide range of bloodstain patterns from seemingly similar events.

The project targeted research questions related to the generation and propagation of blood, which ultimately results in bloodstain patterns. Specific research questions include:

- What are the droplet size distributions in-flight resulting from different blood-generating mechanisms?
- How do the size and velocity distributions of the generated droplets alter bloodstain patterns?
- What are the effects of muzzles gases on the resulting bloodstain distribution and the behavior of generated droplets?

[1] National Research Council. Strengthening forensic science in the United States: a path forward. National Academies Press, 2009.
[2] Attinger, Daniel, Craig Moore, Adam Donaldson, Arian Jafari, and Howard A. Stone. "Fluid dynamics topics in bloodstain pattern analysis: comparative review and research opportunities." Forensic science international 231, no. 1-3 (2013): 375-396.

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Research design, methods, analytical, and data analysis techniques

To address these questions, an approach combining experiments and numerical modeling of the fluid physics was used to examine situations relevant to blunt impact trauma, bullet impact, and gun muzzle gas influence.

Expected applicability of the research

The results of this project are expected to have significant implications for criminal forensics applications of BPA. In particular, the major contributions have provided detailed physics-based mechanisms for the atomization (production of blood droplets), propagation (flight of blood droplets), and interaction with muzzle gases.

The generated fluid dynamics models and experimental datasets are also available through the published work and additional datasets. Use of these models in forensics applications is expected to aid in quantifying the uncertainty associated with bloodstain pattern analysis (BPA). The identification of detailed blood atomization mechanisms is expected to lead to improvements in BPA by linking the fundamental fluid mechanic mechanisms, droplet trajectories, and blood spatter to the observed blood spatter patterns in forensic investigation.

Participants and collaborating organizations

At Iowa State University, the PI and Co-PI were Dr. James Michael and Dr. Daniel Attinger. They supervised two graduate students and two professional/scientific staff during the course of the project.

Dr. Alexander Yarin at the University of Illinois Chicago served as a subawardee during the project, and supervised two graduate students.

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In the use of the digital inline holography code, Dr. James Michael collaborated with Dr. Daniel Guildenbecher at Sandia National Laboratories in the use of the HoloSand v1.0 code[3].

Changes in approach from original design

No changes in approach from original design.

II. Outcomes

Accomplishments

The major accomplishments of this project have been contributions to the fluid mechanics and forensic pattern analysis associated with bloodstain patterns.

The theoretical modeling developments have contributed to dealing with arbitrary bullet shapes, predicted the distribution of backspatter droplets, and examined the influence of muzzle gases from a self-similar vortex theory. These contributions have significantly advanced the fluid mechanics associated with backspatter events with consideration of the formation of droplets, their propagation, and the potential for interaction with oncoming muzzle gases. Coupled with experimental observations, these advances will allow for further refinement of fluid mechanic models.

Two recent companion papers reporting the full reversal of backspatter blood droplet trajectories and the muzzle-gas ‘wind-driven’ breakup of droplets have pointed to additional fluid mechanic mechanisms which should be accounted for in predictive models (Li et al. and Sliefert

[3] Guildenbecher, Daniel. Sandia Particle Holography Processor v. 1.0. Computer software. USDOE. 9 Dec. 2015. Web.

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et al., 2021). In addition, these articles received significant attention from several popular science write-ups.[4]

The project has also resulted in datasets of blood droplet size and velocities in situ, using high-speed imaging and holography techniques. Comparison of such results with resulting bloodstain patterns will permit analysis of drag-based models and allow assessment of other potential uncertainties in the analysis of bloodstain patterns.

The paper published by Attinger et al. in Forensic Science International (2019) incorporates drag-based fluid models and statistical uncertainties to obtain an estimate for the originating location of the droplets. Comparison with results shows success for instances where the distance between the bloodletting event and observed blood spatter patterns exceeds 1 m, which is a conclusion directly applicable to BPA in crime scene reconstruction.

For each goal, the specific accomplishments are summarized below:

1. High-speed visualization and measurement of droplets resulting from various blood splashing phenomena
    a. Large field of view shadowgraphy to capture events
    b. High-speed holography to allow capture of events
    c. Identification of phenomena during blunt impact
    d. Identification of phenomena during projectile impact
2. Application of 3D holography technique to blood spatter droplet formation
    a. Measurement of size and velocity distributions following a blunt impact event
    b. Measurement of size and velocity distributions following a bullet impact

[4] https://www.science.org/news/2021/04/who-pulled-trigger-gun-muzzle-exhaust-may-complicate-analysis-crime-scenes; and https://cosmosmagazine.com/science/blood-droplets-travel-in-all-directions-in-crime-scenes/

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3. Generation of experimental databases of blood atomization from jetting, blunt impact, and projectile impact events
    a. High-speed imaging sequences
    b. Velocity and size distributions in flight
    c. Size and position from resulting blood spatter
4. Validation of predictive fluid dynamics models
    a. Validation of drag coefficient for intact liquid jets
    b. Development and comparison with experiment of a model for forward spatter generated by bullets of arbitrary shape
    c. Development and comparison with experiment for the interaction of muzzle gases with blood backspatter

Results and findings

Highlights from these accomplishments are detailed in the subsequent discussion.

- Advanced, high-speed techniques were used to capture blood spatter events. These include time-resolved capture of blunt impact and gunshot blood spatter phenomena using high-speed imaging and high-speed holography methods. An exemplar set of data is shown in Figure 1, where shadowgraphy is used to capture the evolving backspatter blood spray and breakup after impact by a 22-caliber rifle bullet. In these series, the standoff distance of the muzzle was varied, showing a range of conditions where significant impact from the muzzle gases are observed. These in situ measurements captured the mechanisms of secondary droplet formation and flow reversal at sufficient time resolution to allow for further comparison with fluid-mechanical models as presented in Li et al. (2021) and Sliefert et al. (2021).

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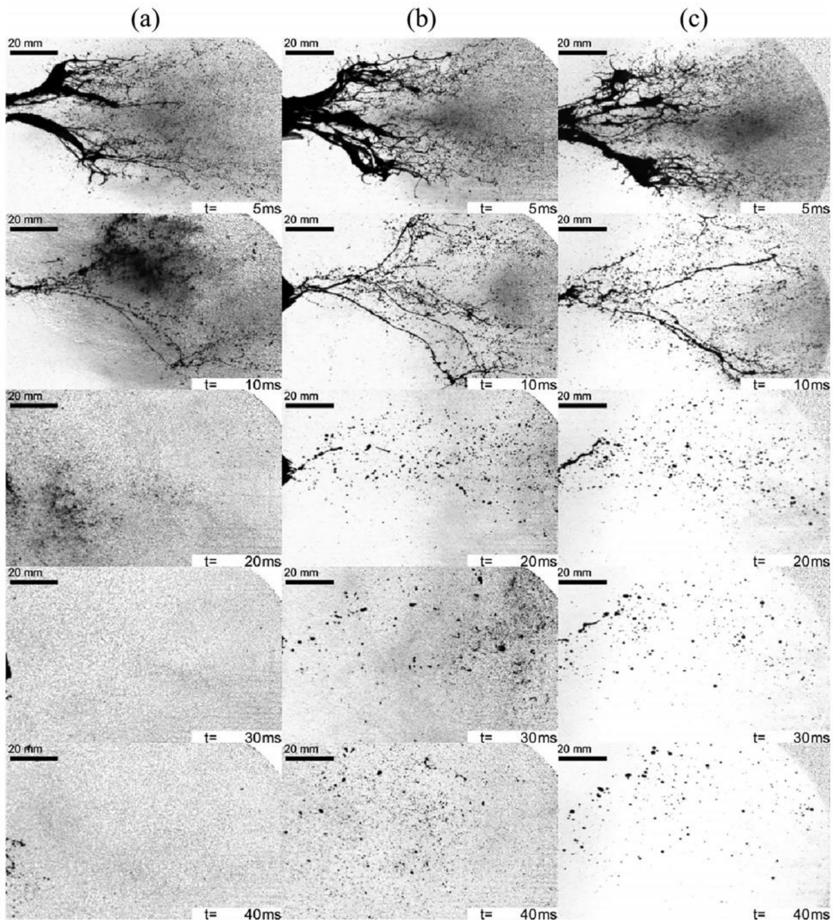

Figure 1: Muzzle gas interaction cases over increasing muzzle gas distances. Distance from muzzle to blood source is (a) 65 cm, (b) 125 cm, and (c) 300 cm. Reproduced from Sliefert et al. (2021).

- In situ measurements were made using digital inline holography for the droplet size and velocity distributions of both blood (shear-thinning) and water (non shear-thinning) for blunt impact scenarios. The median values of velocity and diameter were similar for both fluids, as shown in Figure 2. However, significant differences are noted when examining diameter-velocity scatter plots, as shown in Figure 3. These in situ measurement point to differences in the breakup mechanism in blood, as suggested by the percolation breakup of Comiskey and

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Yarin. These measurements represent detailed in situ characterization of blood droplet sizes, rather than inferred information from individual bloodstains.

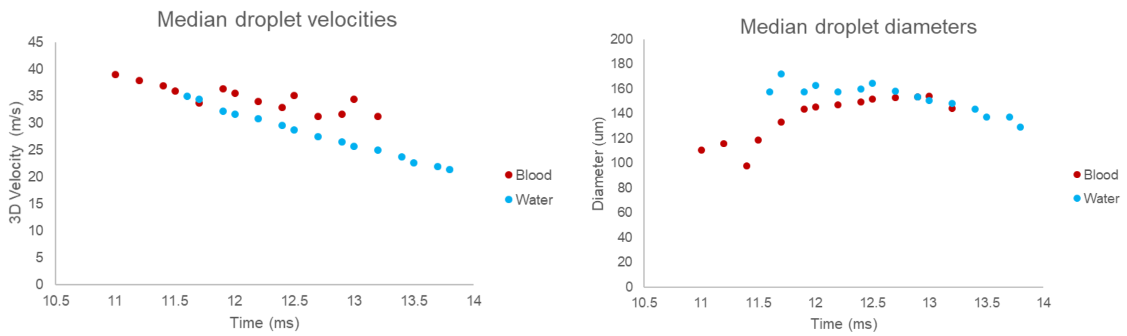

Figure 2: Median droplet velocities and diameters resulting from a blunt impact on a thin liquid film of blood and water. Reproduced from (Das Diss.2019).

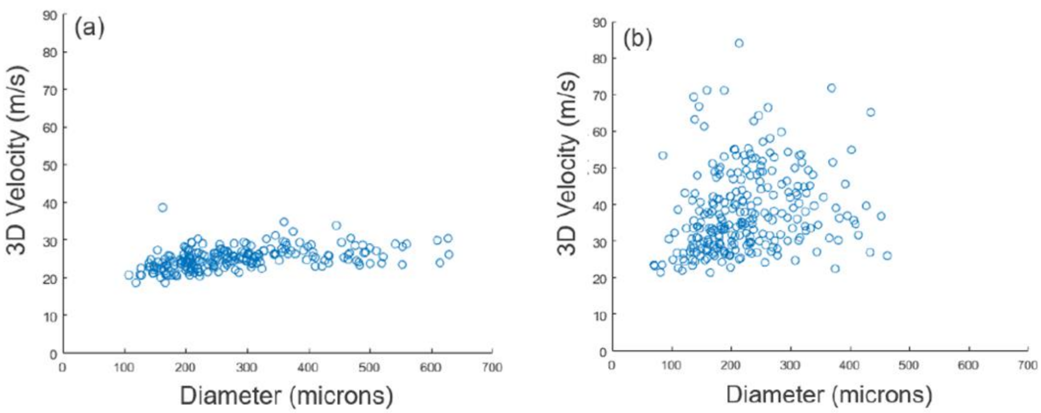

Figure 3: Droplet size-velocity scatter plots showing the distribution resulting from blunt impact on a (a) thin film of water and (b) a thin film of blood. Reproduced from (Das Diss. 2019).

- For bullet impact, 3D velocities were measured for backspatter droplets resulting from a bullet impact. Measurements were made approximately 0.6 m from the impact location, which was necessary due to the density of droplets at locations near the target. Thus, the initial atomization process was not captured via the holography technique. Quantitative data shown for an exemplar set of droplet distributions (Sliefert diss. 2020) is shown in the right panel of Figure

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4. Errors in individual measurements are indicated, based on the variation in object position across a single particle track.

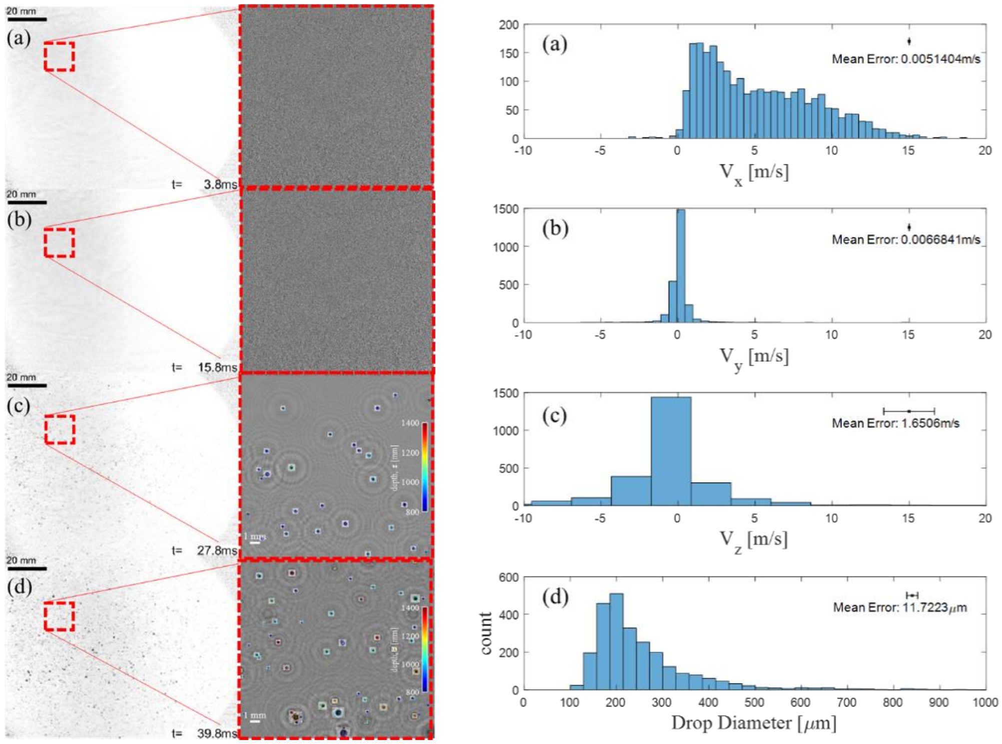

Figure 4: (Left) Location for monitoring backspatter from a .22-caliber rifle bullet approximately 0.6 m from the target. Insets show refocused holograms with identified droplets. Using particle-linking approaches in Sandia's HoloSand v1.0 code, individual droplet parameters are determined. A total of 2500 particles are identified, with 3D velocities and diameters shown in the histograms of the right panel (Sliefert Diss. 2020, Michael et al. in preparation).

- In situ measurements and observations of the blood spray breakup were coupled with measurements of blood patterns and ultimate travel distances. These developments include determination of the maximum distance at which backspatter stains can be found on fabrics (Faflak and Attinger, 2021) and the development of simplified charts incorporating fluid mechanic trajectory (drag-based modeling) to provide estimates of horizontal distance based on the ellipticity and equivalent diameter of stains (Attinger 2019). In addition, bloodstain

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patterns were recorded for cases under the influence of muzzle gases. Three exemplar bloodstain patterns are depicted in Figure 5, showing the distribution of stains (left panel) and the distribution of stains at various horizontal distances measured along the floor. The blood source was located at 1 m height and the muzzle standoff for a suppressed 22-caliber rifle was varied from 0.3 to 3 m. At near distances, the droplets are deflected, the number is reduced, and fully reversed (some do not even fall to the floor). At 3 m standoff, there is no evidence of droplet deflection or breakup from the oncoming muzzle gases.

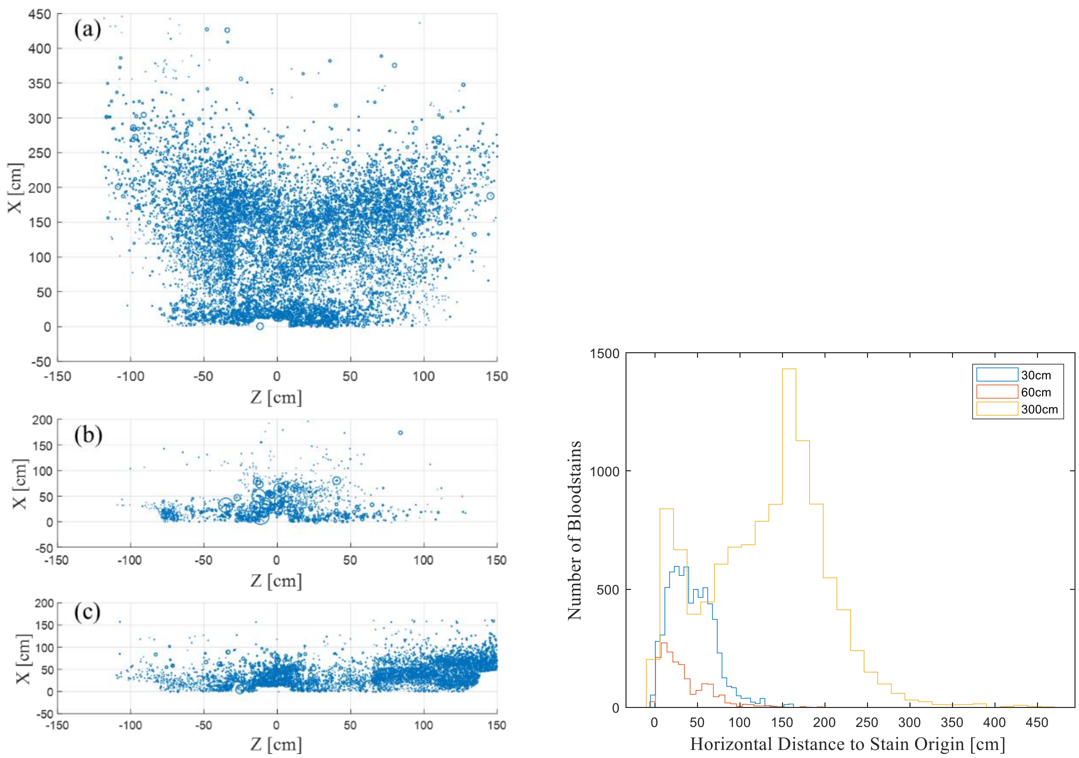

Figure 5: (Left) Bloodstain pattern collected on butcher paper on the floor in a backspatter configuration. Three cases are shown for muzzle gas standoff distances of 30, 60, and 300 cm corresponding the shadowgraphy images shown in Figure 1. (Right) The number of bloodstains presented as a histogram with the horizontal distance from the stain to the origin. (Sliefert Diss. 2020, Michael et al. in preparation).

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A number of theoretical developments were also made, and allowed for comparison between theoretical model and experiment. Highlights include:

- Verification of the friction coefficient of free liquid jets for a Reynolds number range of 621-1289. For this range, the theoretical development presented by Comiskey and Yarin (2018) predicts the trajectory of free jets, with a dependence of $C_{fd} = 5\, Re_d^{-1/2}$ (Comiskey and Yarin, Exp. Fluids, 2018).
- A generalized model was developed to predict the forward-directed blood spatter for bullets of arbitrary shapes. The velocity field within the experimental target is a direct result of the geometry and velocity of the bullet. The theory captured experimental observations from the Kansas City Police Department Crime Lab, with reasonable predictions of the average stain area and number of stains. The comparison between experimental data and the model is shown in Figure 6 (Comiskey, Yarin & Attinger, Phys. Fluids, 2019). Two different backward spatter models were also examined and showed favorable comparisons with experimental observations (Comiskey, Yarin & Attinger, FSI, 2019).

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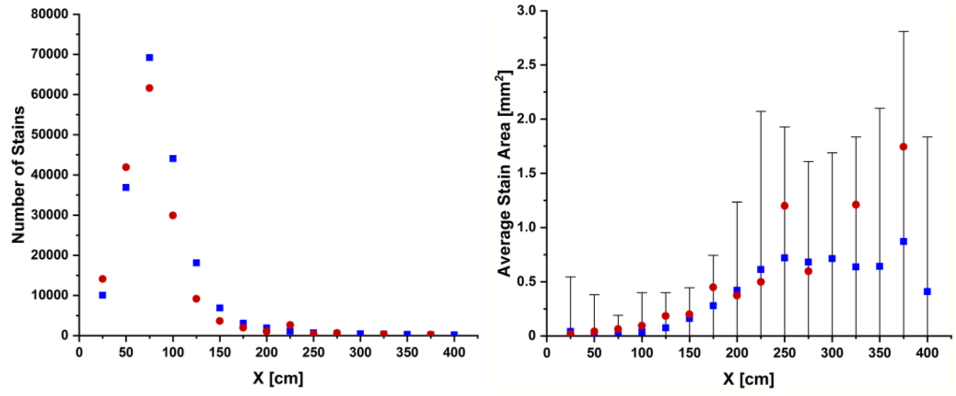

Figure 6: Comparison of model and experimental bloodstain analysis reproduced from Comiskey, Yarin, and Attinger (2019) where the model uses percolation theory to predict drop number, size, and velocity from liquid disintegration. The left panel shows the number of stains from a forward spattering event with blue squares showing experimental measurements and red circles showing the model prediction. The right panel shows average stain area.

- A theoretical framework was developed to model the propellant gases issuing from a firearm. This self-similar turbulent vortex theory was used to predict the trajectories of muzzle gas residue (Comiskey and Yarin, JFM, 2019) and of backward propagating blood drops resulting from gunshot backspatter. Validation of self-similar turbulent vortex theory with muzzle gas expansion was improved with longer time record and larger field of view experiments (Comiskey and Yarin, JFM, 2019; Li et al., Phys. Fluids, 2021; Sliefert et al., Phys. Fluids, 2021), as shown in Figure 7.

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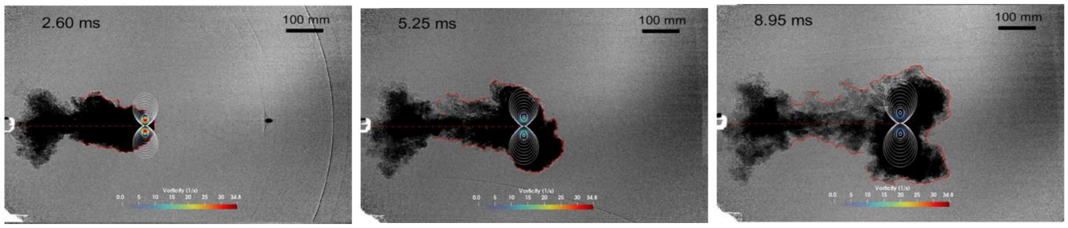

Figure 7: Comparison of experimental muzzle gas plume propagation and comparison with the self-similar turbulent vortex theory using empirically determined parameters for the impulse, spreading, and initial time. Reproduced from Sliefert et al. (2021).

Limitations

The research products resulting from this project are fundamental contributions, and great care should be taken extending these results to criminal forensics applications. The theoretical, numerical modeling, and experimental results provided key ideas into additional physics which must be incorporated, but a great deal of variability may occur in the initial conditions or environmental conditions in field work or in forensic crime scenes.

As an example, muzzle gas distances and the interaction between the backspatter muzzle gas were measured experimentally and compared favorably with fluid simulations. However, characterization of an individual firearm and ammunition may be required to make definitive predictions about the role of oncoming muzzle gases.

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III. Artifacts

Publications, conference papers, presentations, and databases

Archival Publications:

1. Comiskey, P. M., and A. L. Yarin. "Friction coefficient of an intact free liquid jet moving in air." *Experiments in Fluids* 59.4 (2018): 1-7. *Federal support acknowledged.* https://doi.org/10.1007/s00348-018-2519-y
2. Comiskey, P. M., A. L. Yarin, and Daniel Attinger. "Implications of two backward blood spatter models based on fluid dynamics for bloodstain pattern analysis." *Forensic science international* 301 (2019): 299-305. *Federal support acknowledged.* https://doi.org/10.1016/j.forsciint.2019.05.026
3. Attinger, Daniel. "Charts based on millions of fluid dynamics simulations provide a simple tool to estimate how far from its source a specific blood stain can be found." *Forensic science international* 298 (2019): 97-105. *Federal support acknowledged.* https://doi.org/10.1016/j.forsciint.2019.02.052
4. Comiskey, P. M., and A. L. Yarin. "Self-similar turbulent vortex rings: interaction of propellant gases with blood backspatter and the transport of gunshot residue." *Journal of Fluid Mechanics* 876 (2019): 859-880. *Federal support acknowledged.* https://doi.org/10.1017/jfm.2019.564
5. Comiskey, P. M., A. L. Yarin, and D. Attinger. "Hydrodynamics of forward blood spattering caused by a bullet of general shape." *Physics of Fluids* 31.8 (2019): 084103. *Federal support acknowledged.* https://doi.org/10.1063/1.5111835
6. Li, Gen, et al. "Blood backspatter interaction with propellant gases." *Physics of Fluids* 33.4 (2021): 043318. *Federal support acknowledged.* https://doi.org/10.1063/5.0045214

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7. Sliefert, Nathaniel, et al. "Experimental and numerical study of blood backspatter interaction with firearm propellant gases." *Physics of Fluids* 33.4 (2021): 043319. *Federal support acknowledged.* https://doi.org/10.1063/5.0045219
8. Faflak, Richard, and Daniel Attinger. "Experimental study of how far blood spatter stains on fabrics can be found from the blood source, and relevance to crime scene reconstruction." *Experiments in Fluids* 62.4 (2021): 1-17. *Federal support acknowledged.* https://doi.org/10.1007/s00348-021-03187-7
9. J. Michael, N. Sliefert, R. Faflak, S. McCleary, D. Attinger, "Comparison of blood spatter distributions with in situ drop trajectory measurements," in preparation. *Federal support acknowledged.*

Dissertations:

1. Comiskey, Patrick. *Fluid mechanics of blood motion resulting from common bloodletting events*. Diss. University of Illinois at Chicago, 2019.
2. Das, Reetam. *Digital In-line Holography of blood atomization*. Diss. Iowa State University, 2019.
3. Sliefert, Nathaniel D. *Influence of muzzle gases on blood droplet backspatter*. Diss. Iowa State University, 2020.

Conference Papers and Presentations:

1. P.M. Comiskey, D. Attinger, and A.L. Yarin, "Investigation of Blood Spatter Resulting from a Gunshot," PITTCON 2018 Expo in Orlando, FL (February 2018).

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2. P.M. Comiskey, D. Attinger, and A.L. Yarin, “Atomization of Blood Spatter Resulting from a Gunshot,” 14th International Conference on Liquid Atomization and Spray Systems, Chicago, IL (July 22-26, 2018).
3. R. Das, R. Faflak, D. Attinger, and J. B. Michael, “Blood atomization from blunt impact on a liquid film using high-speed digital inline holography,” ILASS-Americas 30th Annual Conference on Liquid Atomizaiton and Spray Systems, Tempe, AZ, May 2019.
4. D. Attinger, “Can a chart based on millions of trajectory simulations provide a simple tool to estimate how far a blood drop can fly?”, ILASS-Americas 30th Annual Conference on Liquid Atomizaiton and Spray Systems, Tempe, AZ, May 2019.
5. D. Attinger and R. Faflak, “Impact and imbibition of blood drops with textiles: Where does this stain come from?” 72nd Annual Meeting of the APS Division of Fluid Dynamics, November, 2019.
6. A. Yarin and P. Comiskey, “Self-similar Turbulent Vortex Rings: Interaction of Propellant Gases with Blood Backspatter and the Transport of Gunshot Residue,” 72nd Annual Meeting of the APS Division of Fluid Dynamics, November, 2019.
7. D. Attinger, A method to determine area of origin of blood spatter patterns with curved trajectories and statistical uncertainties, Presentation at IABPA 2019 European Conference, Paris, June 18, 2019.
8. J.B. Michael, D. Attinger, Nathaniel Sliefert, Ricky Faflak, Scott McCleary, Reetam Das, “Blood atomization: connecting in-flight drop measurements to blood spatter,” PITTCON 2020, Chicago, IL, March 3, 2020.

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9. Li, Gen, et al. "Blood backspatter drops moving toward the shooter can land behind the victim due to interaction with propellant gases." *Bulletin of the American Physical Society* (2021).

Databases

1. J. Michael, N. Sliefert, D. Attinger, R. Faflak, S. McCleary, “High speed imaging sequences of muzzle gas and muzzle gas/blood interactions,” Iowa State University, Dataset, https://doi.org/10.25380/iastate.16862209.v1
2. J. Michael, D. Attinger, N. Sliefert, R. Das, R. Faflak, S. McCleary, “Blood stain pattern and fluid dynamics datasets,” Iowa State University, Collection, https://doi.org/10.25380/iastate.c.5672977

Data sets generated

The project has resulted in data sets corresponding to several scenarios. These include blood spatter patterns and in situ droplet measurements and imaging resulting from both blunt impact upon a film of liquid blood and bullet impact into a pool of liquid blood. In addition, the fluid dynamic models are described in detail in the publications which have appeared as a result of this project.

Dissemination activities

Results have been published in 8 peer-reviewed publications in both fluid mechanics and forensics science journals, along with additional conference papers.

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The results have also been presented in 9 meetings including at the APS, the Institute for Liquid Atomization and Spray Studies, and during PITTCON meetings. In addition, work has been presented to BPA experts at the 2019 IABPA European forensics meeting.

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