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**FINAL SUMMARY OVERVIEW REPORT**

**Research Performance Progress report,**
**Department of Justice, Office of Justice program,**
**Award 2014-DN-BX-K036**

Project Title:
**Finding the Region of Origin of Blood Spatters in Complex Situations: Novel Physics-Based Methods and Tools**

PD/PI Name, Title and Contact Information (e-mail address and phone number):
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Submission Date: **April 18, 2019**

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Signature of Submitting Official:

Dr. Daniel Attinger, Ames, IA

**Executive summary:** The team involved three research groups led by Profs. D. Attinger (PI), Alex Yarin and Steve Michielsen. With support from this award, 10 peer-reviewed article have been published (or in press) in leading peer-reviewed journals of fluid dynamics [1-4], forensics [5-8] or open access data [9, 10]. These research products explain the complex physics of gunshot spatters, improve the determination of the area of origin of spatters with statistics and fluid dynamics, describe the interactions of stains with carpets, and provide the forensics community with high-quality and publicly available spatter patterns for teaching and research purposes. Results have been disseminated in main forensic and fluid dynamics conferences, as well as in popular mass media.

## A) Physics-based Modeling of gunshot blood spatter

**A1. Introduction:** Gunshots are often involved in bloody crimes, but the physics of the related spatter patterns is complex and poorly understood. With this award, a physical model describing blood backspatter patterns resulting from a blunt bullet gunshot has been proposed in [4]. The predictions are compared to experimental data acquired in [10]. Back spatter pattern were predicted numerically and compared to the experimental data in terms of number of stains, stain areas, and the final impact angle as function of location on a cardstock target. Comparisons of the predicted results with the experimental data revealed satisfactory agreement.

**A2. Design and methods:** Experiments with back spatter resulting from a blunt bullet impact were performed at an indoor shooting range, and described in details in [10]. A high-density fiberboard pierced with a hole twice the diameter of that bullet's was placed between the gun and the cardstock, to minimize the interference of the muzzle gases (a topic of future research) with the back spatter process. The information on stain location, number of drops, and area, was determined with a purpose-developed in-house program. The in-house program lumped the stain characteristics into a set of bins corresponding to 11 concentric disk-shaped areas.

Atomization modeling was done as follows. The blunt (hollow point) bullet has a front edge which resembles a disk. The impact duration $\tau \sim 1$ µs, and the impact velocity $V_0 \approx 1000$ m/s, is at least of the order of the speed of sound in blood and is supersonic relative to air. Such situation is characteristic of impact-driven fluid mechanics, where the fluid flow is potential and satisfy the axisymmetric Laplace equation. Using potential flow theory and the boundary conditions imposed by the bullet motion, the velocities impacted to the blood by the bullet impact are determined. The breakup of the blood upon impact is then described in the framework of the Rayleigh-Taylor instability, where a dense fluid (blood) breaks into drops when accelerated into a lighter fluid (air). Results of the model show that the size of the drops produced depends on their distance from the bullet path, on the bullet velocity and shape. Smaller, faster drops originate close to the impacting blunt bullet while the larger and slower ones are formed further from it.

Calculation of the drop trajectories was done as follows. The continuous spectrum of droplets issued as a result of the Rayleigh-Taylor instability were grouped into discrete bins. These bins were considered as inter-penetrating continua with air which was entrained into motion by viscous suction due to the eddy viscosity. Individual blood droplets from each bin experience air drag and gravity. The chosen value of the impact spatter jet angle is based on its suction of a significant mass of air, which happens at the periphery of the spattered two-phase jet. Accordingly, the ejected drop blob essentially forms an axisymmetric two-phase submerged turbulent jet. In a dense spray, like those in gunshot blood spatter, air entrainment can be dominated by the fastest moving droplets "leading" the spray (the two-phase jet), whereas the other droplets are moving in the aerodynamic wake of the leading ones and experience a diminished drag, as was previously shown for sprinkler jets [11]. The locations reached by drops on a vertical sampling cardstock located at a known distance from the target were determined.

Scanned images of the cardstock sheets, which were located vertically at a distance of 50 cm from the blood source and perforated by a blunt bullet, were discretized radially from the penetration location to the furthest drop into 10 concentric disk-shaped areas of equal width. In each ring-shaped segment, the number of stains was counted and summed to find the number of stains per segment. Other measurements were made of the area of stains as a function of the location on the cardstock target.

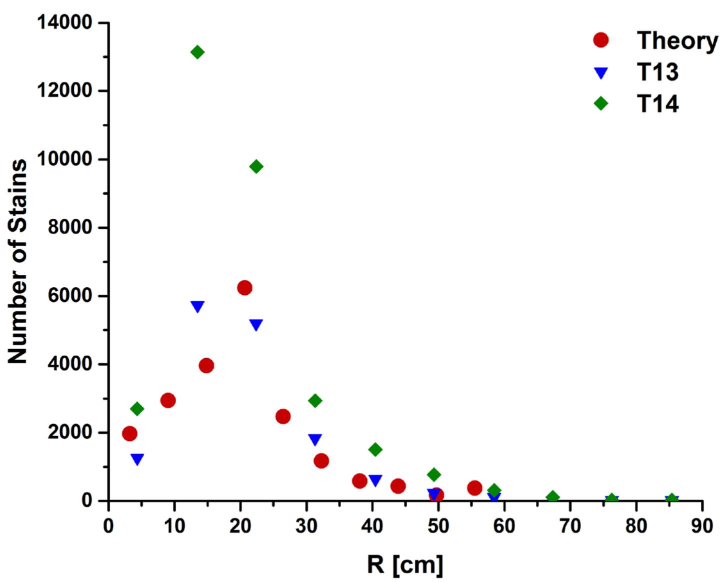


**Figure 1: Predicted and measured number of stains in back spatter patterns at different radial locations R relative to the bullet path at a vertical cardstock collector at 50 cm before the blood source. Red circles show the theoretical prediction, blue triangles show the data of experiment T13, and green diamonds show the data of experiment T14, from** [4]**.**

**A3. Data analysis and results:** In Figure 1, the experimental trends are similar between the two experiments, and the theoretical predictions closely follow the data of the experiment. The results reveal a steep rise in the number of drops which peak for a characteristic maximum around a distance of about 15-20 cm from the location where the cardstock was penetrated by the bullet followed by a gradual decrease in the number of drops deposited further on.

**A4. Implications for criminal justice and practice:** While the above work is the first physical description of the generation of a back spatter pattern due to gunshot, the implications are not immediate for criminal justice, because it is a forward study (where results are obtained from known initial conditions) not suitable for reconstruction (where initial conditions are sought from inspection of the final conditions – the spatter pattern). Another publication sponsored by this award modelled the forward blood spatter atomization with percolation theory, and results have been found in good agreement with experiments [1].

## B) Area of origin reconstruction with probabilities and fluid dynamics

**B1. Introduction:** For spatter patterns, the determination of the 3D location of the spatter producing event −*the area of origin*− is relevant to criminal cases. Trajectory reconstruction in bloodstain pattern analysis is currently performed by assuming that blood drop trajectories are straight along directions inferred from stain inspection [12]. With this award, we have proposed a method to reconstruct the area of origin of impact blood spatter patterns that considers the curved trajectories caused by fluid dynamics, as well as the statistical uncertainties [5]. Eight spatter patterns from a publicly available data set of impact spatter patterns [9] on a vertical wall with various impactor velocities and distances to target has been used to test the model and evaluate its robustness, precision, and accuracy. The proposed method provides an estimate of the uncertainty specific to the spatter pattern of interest, and the error of the method is assessed by comparisons with patterns generated under known conditions.

**B2. Design and methods:** Here, we focus on the common situation where the spatter pattern is found on a vertical wall. The principle of the method is depicted in Figure 2. The proposed method extends a probabilistic approach by Camana [13], aimed at finding the region of convergence of a blood spatter pattern in a 2D space, to the determination of the area of origin in a 3D space. The core idea of the proposed method is as follows: for each stain of interest, impact angles are estimated from the orientation and ellipticity of the stain. Then, fluid dynamics arguments based on the shape of the stain determine a finite range of possible impact conditions (as proposed in [14]) in terms of pairs of drop diameters and velocities, which correspond to a finite range of possible backward trajectories. These fluid dynamics arguments consider drop deformation and breakup during flight and impact, the latter being visible by inspection of the periphery of the stain (symmetrical, wavy or with splash features).

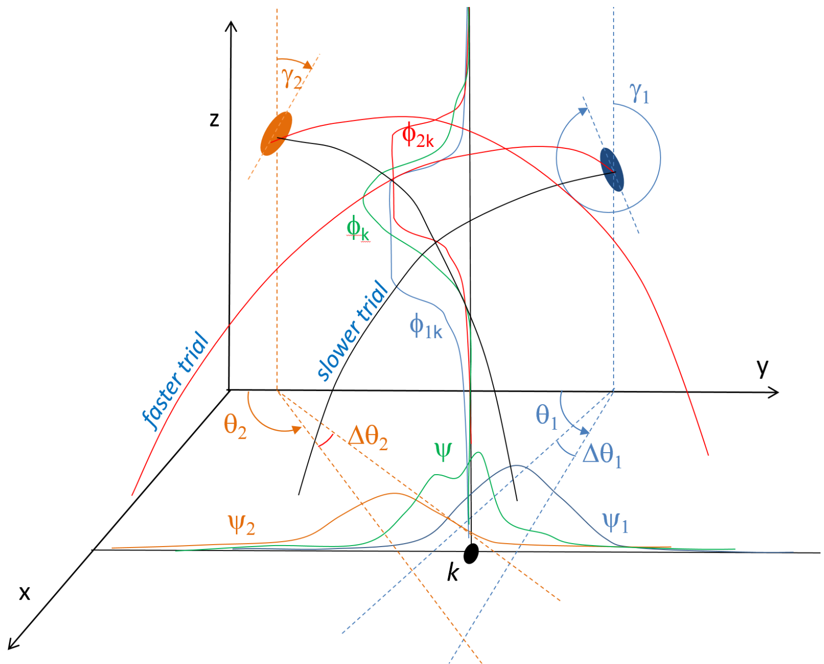


**Figure 2: A probabilistic method to evaluate the region of origin of a blood spatter pattern was developed in [5]. Here, two stains *i=1,2* are illustrated in blue and orange, respectively, and the method is compatible with large numbers of stains. From each stain, a range of trial trajectories are reconstructed. Fluid dynamic principles guide the reconstruction and the range of trial trajectories (the faster trajectory in red, and the slower, in black). The directional angle $\gamma$ is measured by stain inspection, and $\theta$ is the direction of the drop trajectories projected on a horizontal plane. On the horizontal plane, the likelihood $\psi$ determines the location of the horizontal projection of the area of origin, and is obtained as a product of the probability density functions (PDFs) of each stain. On the vertical axis, the likelihood $\phi$ determines the height of the origin above point *k* of the region of convergence, and is obtained as a product of the PDFs of each stain. The area of origin is then constructed as a product of $\psi$ and $\phi$.**

Then, we statistically identify a 3D region from which the physically sound trajectories most probably originate. This probabilistic determination is based on the principle of maximum likelihood [15]. That region is called the area of origin, and defined not as a point but as a series of nested volumes. These volumes can be represented as a set of Russian dolls, as in in Figure 3, with the smaller internal ones corresponding to an area of origin determined with a lower probability than the larger ones – we considered probabilities of 90, 99 and 99.9%. The uncertainty on the trajectories is determined using the propagation of uncertainties on the following measured quantities: the width and length of an ellipse fitted on the stain, the direction of its main axis. The proposed method propagates measurement uncertainties and determines the volume of the area of origin based on fluid dynamics and statistics, for the spatter pattern of interest.

The reconstruction model is implemented in the scientific computing language MATLAB [16]. Stains are automatically segmented (extracted as a geometrical entity from their background), and ellipses are automatically fitted. The equations of motion including drag and gravity are integrated with the ordinary differential equation solver 'ode 45'.

For each spatter pattern, a set of about 40 stains were automatically and randomly selected for reconstruction purposes. Criteria for stain selection were: (1) stains located at least at a given horizontal distance (8% of the horizontal distance between blood source and target) from the centroid of the spatter pattern; (2) stains with ellipticity corresponding to an impact angle between 40 and 75 degrees; (3) stains that minimize the uncertainty on the angle $\theta_i$ defined in Figure 2; and (4) half the stains with splashing features, and half without, in an attempt to use information from a variety of stain shapes.

**B3. Data analysis and results:** Eight available digital spatter patterns scanned at high resolution, and publicly available [9] are used as input for the simulations. Distances from the wall varied between 30cm and 190 cm, and the velocity of the impactor on the blood varied from 2 to 8 m/s. Reconstruction results for a slow impact and origin 120cm away from the wall are in Figure 3.

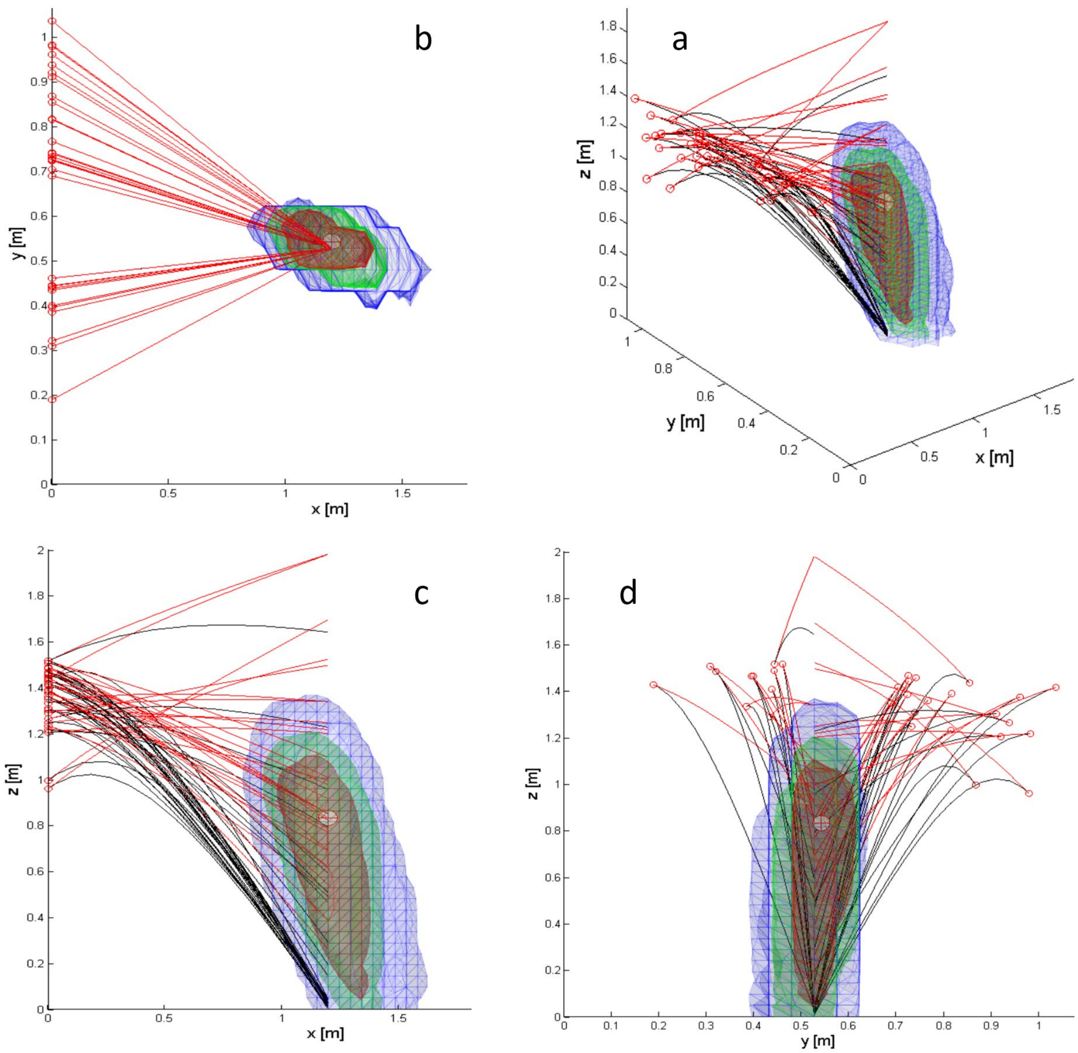


**Figure 3: Results for spatter pattern C9, corresponding to a slow impact, far from the wall ($x_o$=120cm). 3D view (a), top view (b), side view (c), and view from the stained wall (d) of the trajectories and the region of origin. The region of origin is represented as concentric volumes, where red, green and blue colors corresponding to probability values P of 90%, 99% and 99.9%, respectively. Trajectories with the highest energy are in red, and trajectories with the lowest energy are in black. The known origin is shown by a white disk with a red cross. From [5], with joint support from this award and from the Center for Statistics and Applications in Forensic Evidence (CSAFE) through Cooperative Agreement No. 70NANB15H176 577 between NIST and Iowa State University**

In Figure 3, the area of origin has a volume of 95 L, which correspond to about 93 grapefruits or 13 basketballs –proposed estimate of the volume of the area of origin [17]. Interestingly, the major uncertainty is along the vertical axis. Stains pointing downwards, which are typically excluded from the determination of the height of the origin, are also considered in the reconstruction.

Similar reconstruction efforts have been undertaken with seven other spatter patterns. The volume of the area of origin $V_{RO}$ was found proportional to the distance $x_0$ between source and wall at a power of about five,

$$V_{RO} \sim x_O^{\,n} \text{, with } 5.2 \le n \le 5.5 . \qquad (1)$$

The above estimate confirms that the volume of the area of origin has a strong dependence on the distance from the wall.

Besides the uncertainty on the determination of the area of origin, the method can also determine its error. The error in the determination of the area of origin is defined in the classical manner [18] as the difference between the estimated and the known area of origin of a spatter pattern. Assuming a probability $P$=99%, the error of the present method, at least with the eight spatter patterns studied, is always smaller than 10cm, and does not grow with the distance from the wall. In comparison, the method of strings shows a systematic error in the determination of the height: the determined height is higher than the known height. This bias is well known by BPA researchers and practitioners [19, 20], and two of them stated to us that the pattern C9 in Figure 3 was not suitable for reconstruction with the method of strings. Another contribution of the present method to estimate the uncertainty associated with the reconstruction of a specific spatter pattern.

**B4. Implications for criminal justice and practice:** We plan to test this reconstruction method with more spatters, such as those produced in datasets [9, 10]. Two recommendations for crime scene documentation can be made. Since the novel reconstruction method in Figure 3 relies on inspection of the stain boundaries, it is important to photograph stains with the highest possible resolution. In this study, a resolution of 600 dots per inch was used. Using a macro-lens and a state-of-the-art digital camera, resolutions of the same order can been reached by stitching [21] multiple images of small areas (O(10cmx10cm)). Protocols for reliable stitching and for quality illumination in the macro-photography process –where the camera objective is close to the object- would have to be designed. Also, the transitions between stain shapes depend on the blood and target material on which stains are found, which has implications in documentation and preservation of evidence. We recommend that investigators collect samples of the target surface of interest and hematocrit measurements.

## C) Publicly available data for the forensic community

**C1. Introduction:** We produced two data sets of blood spatter patterns scanned at high resolution, simulating impact (beatings) and gunshot backspatter events, under conditions in Table 1.

**General specifications:**

| | |
|---|---|
| Subject area | *Legal Medicine, Engineering* |
| More specific subject area | *Forensics – Bloodstain Pattern Analysis (BPA)* |
| Data format | *images scanned at 600 dot per inch (about 42.3 μm per pixel) and saved as .jpg with minimum compression (10% compression max)* |
| Experimental factors | *Spatter images with dimensions of max 1.36m x1.1 m, scanned in a piecewise manner and reassembled with image processing software* |
| Data source location | *Ames, IA. Physical Targets have been preserved* |
| Data accessibility | *Electronic data set is with this article, in several zip files of supplementary material* |

**Specifications of impact spatter data:**

| | |
|---|---|
| Type of data | *Images of 61 blood impact beating spatters, with text file describing the experimental conditions* |
| How data was acquired | *Blood atomized with custom test rigs, as described in the manuscript. Spatters collected on poster board or butcher paper, and scanned with flatbed scanner A3 Epson Expression 11000XL* |
| Experimental factors | *Spatter images with dimensions of max 1.36m x1.1 m, scanned in a piecewise manner and reassembled with image processing software* |
| Experimental features | *Blood pool of ~1mL volume on flat immobile surface impacted by either a cylindrical rod or a flat surface; impact velocities between 2m/s and 8m/s; horizontal distances between target and blood source from 30cm and about 2m; few data items involve multiple impacts on same target, and impact on soaked foam rather than pool* |

**Specifications of gunshot backspatter data:**

| | |
|---|---|
| How data was acquired | *Blood spattered backward from a bullet impact, as described in the manuscript. Spatters were collected on cardstock poster board, and scanned with a flatbed scanner* |
| Experimental factors | *Spatter images with dimensions of maximum 1.36m x1.1 m, scanned in a piecewise manner and reassembled with image processing software* |
| Experimental features | *Blood volume of 2.5-175 mL was either contained in a closed cavity or soaking a porous foam (sponge). Blood source was impacted normally by a bullet travelling horizontally; bullet velocities between 285 and 987m/s. Horizontal distances between the vertical target and blood source ranged from 10 cm to about 120 cm; fewer spatters on horizontal targets. Muzzle gases have been screened out with a diffuser plate for most spatters, to minimize their interaction with the backspatter;* |

**Table 1: Specifications of the spatter pattern data published in open access articles [9, 10].**

**C2. Design and Methods:** A first set of 61 blood spatter patterns scanned at high resolution, generated by controlled impact events corresponding to forensic beating situations was published in [9]. Fresh swine blood was used; its hematocrit and temperature were measured. Main parameters of the study were the impact velocity and the distance between blood source and target sheet, and several other parameters were explored in a less systematic way, as per Table 1. The conditions of each experiment are documented in a text file located in the same directory as the spatter image. Impact spatter patterns were generated with either two flat surfaces squeezing a pool of blood, or a cylindrical rod hitting a pool of blood on a flat surface. Gunshot backspatter patterns (**Figure 4** and [10]) were made with a handgun or a rifle, bullets of different shapes. Impact velocities and horizontal distance from blood source to target were the parameters that were systematically varied. Muzzle gases were screened for some experiments, but not for all.

**C3. Data Analysis and results:** No data analysis was provided in [9, 10], because the purpose of the publication venue is to provide public data that everybody can use for their models. Other publications from this award have analyzed the data [3-5, 22].

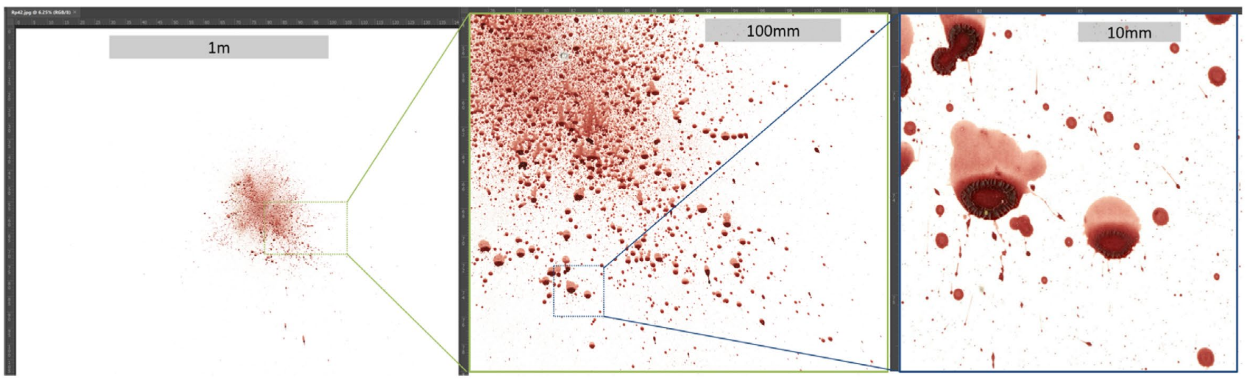


**Figure 4: One gunshot backspatter pattern from the 68 patterns publicly available in [10]**

**C4. Implications for criminal justice and practice:** Data sets [9, 10] can be used by researchers to test crime scene reconstruction models for classification with respect to their generation mechanism (e.g. impact vs. gunshot), or to test models to determine the area of origin of the blood spatter. Accessibility to large amounts of bloodstain patterns produced under controlled conditions is important for the development of the needed science base. The data in this manuscript addresses the above issues by systematically documenting the experimental conditions. We hope to have started a trend where research advances in BPA are published together with the bloodstain patterns of interest.

Generation and transport of bloodstain patterns are cumbersome. This database provides BPA instructors with a safe set of spatters ready to be printed at high resolution for their classes.

The experimental design and methods described in [9, 10] can be readily reproduced and used to generate additional blood spatters. For instance, there is no consensus on which experimental setup is best to simulate the complexity of gunshot spatters in realistic conditions, where blood is located within a complex structure involving body tissues and blood vessels, covered by skin. Experiments reported in [10] used both soaked foams and cavities filled with blood as the blood source, and the information on which blood source was used is specified.

## D) Area of origin on porous and absorbing surfaces (carpets)

**D1. Introduction and purpose:** Most published work related to BPA only deals with hard, non-porous surfaces and no study has carefully characterized carpets. Soft and porous carpets are often encountered at crime scenes since they are common in American homes accounting for 51% of total U.S. flooring market; this has motivated the research described herein. To assess fluid penetration into tufted carpets, a new method for determining porosity and pore size distribution in tufted carpets has been developed for bloodstains on carpet. The work has been published in a peer-review journal [8].

**D2. Design and methods:** In this study, three kinds of nylon carpets were used: a low, a medium and a high face-weight carpet. Each carpet had an antistain treatment, which was removed from half of each carpet by steam-cleaning with a pH 12 NaOH solution. This resulted in six carpet samples. Yarn twist, carpet weight, pile height, water contact angles on carpets, water contact angles on individual fibers, and fiber cross-sectional shapes were characterized. Porosity and pore size distribution were analyzed using confocal laser scanning microscopy (CLSM). Porcine blood was used as a human blood substitute at three liquid volumes (30 mL, 10 mL, and 2 mL). Analysis showed that porous carpet construction and antistain finishing both affected penetration. The depth of blood penetration decreased with the increase of carpet face-weight but increased with increased drop height. The removal of antistain treatment increased blood penetration into the carpets and changed the pore size distribution. Effects of antistain treatment, porosity and pore size distribution of tufted carpet, and blood wicking behaviors on carpets were found to strongly affect blood penetration into the carpets.

**D3. Data analysis and results:**

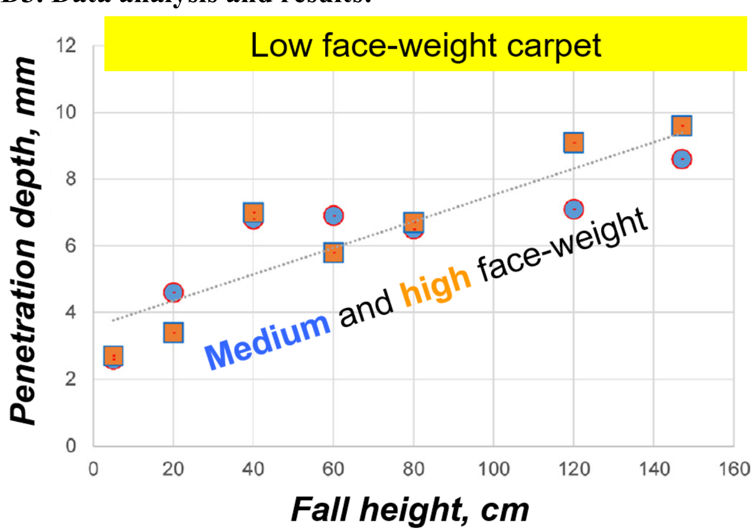


**Figure 5: Penetration depth of 30 µL blood drops released from different heights for as-received medium face-weight, high face-weight carpets and low face-weight carpets. Dashed line is a linear fit provided only to guide the eye. From [8].**

Findings of the work show that small drip stains on carpet do not spread, but wick along single yarns or tufts. Figure 5 shows that blood penetration increases as drip height increases and may reach primary backing. Blood collects behind primary backing and may provide good source of DNA.

**D4. Implications for criminal justice and practice:** The finding that blood collects behind the primary backing might provide forensic evidence even for washed carpet. In particular, for low face-weight carpets, blood was found to penetrate along a single yarn or tuft through the primary backing where it will be particularly difficult to remove. This may provide a good source of DNA evidence. In addition, it may also help localize the location of the bloodstain.

**E. Dissemination of research findings**

The work on gunshot spatter has been presented at the 2016, 2017 and 2018 Fluid Dynamics Conference of the American Society of Physics [23-25]. The popular science venues that have reported about this are The New Scientist, Gizmodo, and a press conference at the 2016 Fluid Dynamics Conference of the American Society of Physics (see press release). In each of those communications, the PIs acknowledged the award from NIJ.

Propublica has interviewed Dr. Attinger on his vision for BPA research in a piece critical of BPA. Results of research sponsored with this award have been presented at the IABPA Training Conferences (2016 Salt Lake City, 2017 Long Beach, 2018 Buenos Aires and 2010 Paris). IABPA is the International Association of Bloodstain Pattern Analysts. The data sets of publicly available spatter patterns have been presented at the 2018 IAI conference in San Antonio.

Dr. Attinger is now adjunct Professor of Medical Sciences at the University of the West Indies, in Kingston, Jamaica. He teaches in the forensic MS program a 1-week class on bloodstain pattern analysis. Jamaica is one of the world countries most affected by violent crime. Attinger was invited as a guest to OSAC general meeting in late 2018.

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