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High-speed video analysis of forward and backward spattered blood droplets

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ABSTRACT

High-speed videos of blood spatter due to a gunshot taken by the Ames Laboratory Midwest Forensics Resource Center (MFRC) [1] are analyzed. The videos used in this analysis were focused on a variety of targets hit by a bullet which caused either forward, backward, or both types of blood spatter. The analysis process utilized particle image velocimetry (PIV) and particle analysis software to measure drop velocities as well as the distributions of the number of droplets and their respective side view area. The results of this analysis revealed that the maximal velocity in the forward spatter can be about 47 ± 5 m/s and for the backward spatter – about 24 ± 8 m/s. Moreover, our measurements indicate that the number of droplets produced is larger in forward spatter than it is in backward spatter. In the forward and backward spatter the droplet area in the side-view images is approximately the same. The upper angles of the close-to-cone domain in which droplets are issued in forward and backward spatter are, $27 \pm 9^\circ$ and $57 \pm 7^\circ$, respectively, whereas the lower angles of the close-to-cone domain are $28 \pm 12^\circ$ and $30 \pm 18^\circ$, respectively. The inclination angle of the bullet as it penetrates the target is seen to play a large role in the directional preference of the spattered blood. Also, muzzle gases, bullet impact angle, as well as the aerodynamic wake of the bullet are seen to greatly influence the flight of the droplets. The intent of this investigation is to provide a quantitative basis for current and future research on bloodstain pattern analysis (BPA) of either forward or backward blood spatter due to a gunshot.

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1. Introduction

Working for project No. 06-S-02 for the Midwest Forensics Resource Center (MFRC), T.L. Laber, B.P. Epstein, and M.C. Taylor took a series of over 500 high-speed videos of common bloodletting mechanisms [2]. The set of videos includes blood spatter formation due to a gunshot, blood spatter due to a blunt object such as a hammer, or blood drop formation from a single droplet and is located on the MFRC website [1]. In literature, the videos have been referred to before [3–5], and are routinely used in bloodstain pattern analysis (BPA) presentation and training classes. However, a quantitative analysis of this dataset is still unavailable, especially for the scenario of blood spatter due to a gunshot. Accordingly, the aim of the present work is in quantitative analysis of blood spatter induced by a gunshot to facilitate the BPA community tools for scientific analysis of a crime scene event.

Blood is a complex non-Newtonian fluid which is shear-thinning [6–8], exhibits viscoelastic behavior [8–11] and possesses a yield stress [12]. It is an aqueous suspension which contains plasma and particles such as white and red blood cells, and platelets. Blood starts to coagulate when it leaves the body or under conditions of increased shear stress [13]. The rheology of blood could affect the atomization process [14–16] which is of fundamental importance for BPA because it determines the distribution of drop sizes and velocities [17], thus the resulting blood spatter. The atomization is diminished by the effects of viscoelasticity [18–20], and the resulting size of the impacting droplets can be heavily influenced by viscosity and elasticity of liquid [21–26]. Therefore, an accurate crime scene reconstruction from any crime involving blood spatter must account for the rheological behavior of blood.

The uncertainties of different BPA techniques can be significant, up to a 50% overestimation of the height of the origin of a blood spatter [5]. A better understanding of the mechanisms of blood droplet formation and flight is required. The first theoretical steps in this direction are already available [27]. Such efforts would be significantly facilitated by a thorough analysis of the available

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experimental data, e.g. high-speed videos [4]. It should be emphasized that some experimental simplifications do not necessarily reflect the real crime scene situations. For example, oftentimes, human blood is substituted for swine blood for safety reasons, and because of expected similarities in size and concentration of blood cells, and in rheology [5,27], albeit it is definitely not a perfect substitute [28]. Moreover, blood spatter found in some crime scenes could be affected by the dynamic effect of muzzle gases from a firearm which are significant, especially when the gun is close to its target [29]. Crime scene reconstruction after a gunshot is often simplified by neglecting gravity and air drag, resulting in what is called a straight-line assumption, or the method of strings [30–34]. Unsurprisingly, this assumption can be quite inaccurate [5,35,36] and as a result, there is a permanent drive for more realistic models [17,27,37–39]. Accordingly, in BPA research, it is imperative to analyze all available sources of data. The MFRC videos are a treasure trove of valuable information for numerous situations. As a result of their untapped nature, they have gone relatively undetected as many groups have attempted their own high-speed video analysis for their specific problems at hand. This has the consequence of building solutions which might work only for a limited set of problems. To avoid such limitations, a general pattern must be analyzed, which is the goal of the present work.

2. Experimental video analysis

The MFRC videos were produced from experiments performed primarily at the Minnesota Bureau of Criminal Apprehension Forensic Science Laboratory, in Minnesota, USA, with some performed at the Christchurch Laboratory of the Institute of Environmental Science and Research, in Christchurch, New Zealand [2]. The camera used to record the experiments was a Photron Fastcam-SA1 High-Speed Digital Video camera with most videos using either a Tamron 90 mm macro lens, Micro Nikkor 55 mm, or Micro Nikkor 105 mm lens. Proper lighting was specific to each experiment which resulted in a variety of apertures and shutter speeds used to produce the highest quality videos possible. Room temperature human blood with an anti-coagulant was used within 72 h of the draw date for every experiment.

Of the series of over 500 videos, over 200 are posted on the MFRC Blood Pattern Analysis Videos webpage, 19 of them are directly related to blood spatter due to a gunshot, and four of those show different muzzle discharges [1]. The targets consisted of a blood soaked sponge, fabric covering the sponge, tape encompassing the entire sponge, and a silicone-encased sponge. The targets were placed at distances in the 1–182 cm range from the muzzle of the gun. Of the 19 videos available for blood spatter induced by a gunshot, five were chosen for a quantitative analysis with particle image velocimetry (PIV) in the present work because they either contained both forward and backward spatter, or, their spatter pattern was resolved enough (in time and space) for an accurate analysis. The five experiments used in this analysis are described in Table 1.

Each frame of the high-speed videos were taken at time intervals of 0.1 ms. In the present work, PIV analysis was conducted to characterize the motion of the blood droplets. The PIV method relies on recording the positions of fluid particles (here droplets) for two time instances in quick succession of the order of a millisecond. Statistical correlation of the two images with the position of the particles allows for the determination of the velocity field that is the spatial distribution of velocities. Here, PIV is conducted from approximately the time the bullet impacted the sponge to two milliseconds in each experiment. The program used for PIV was PIVlab 1.41 which is an application built for the numerical computing language MATLAB [40]. The analysis was done with a Fast Fourier Transform (FFT) algorithm with four interrogation passes from 64, 32, 16, and finally 8 square pixels. A linear interpolator was used with a Gauss 2×3-point sub-pixel estimator and the contrast of each image was automatically locally enhanced before processing. A region of interest mask of 100×200 pixels was drawn about a centimeter from the target for back spatter, and half a centimeter from the target for forward spatter. The dimensions for the region of interest were chosen so that it would be sufficiently large enough to capture the created spray of blood droplets, yet not too large as to increase the likelihood of a false reading by including phantom vectors. The location of the region of interest away from the target was dictated by the distance at which droplets became recognizable, as it was centered about the splash of blood droplets. Post-processing vector validation was performed, in which physically impossible vectors were deleted as outliers.

Each experiment was also analyzed for the area of each droplet, measured as the area of the droplet in flight as seen directly from frames of the high-speed videos, and the number of droplets located within a region of interest. This was done using ImageJ [41], utilizing the particle analysis toolset. A rectangular region of interest, 100×200 pixels large, was placed at approximately the same respective location as done in the PIV tests. Each experiment was analyzed at approximately 2 ms, a time which was chosen because the droplets became very easily distinguishable from the background. Automatic local thresholding was performed on each image following the method of Phansalkar et al. [42] with a thresholding radius of 15 pixels, $k = 0.25$, and $r = 0.5$. This converted each image into a binary image which was then analyzed with the particles toolset. There were no pixel-size limiting or circularity-based restrictions imposed on the analysis.

3. Results and discussion

The PIV technique described in Section 2 was employed to find the velocity magnitude at the midplane of the region of interest, parallel to the target face. For each time interval between the frames of interest, the velocity magnitude along this midplane was averaged and then these velocities were plotted against the time reckoned from the bullet impact on the target. For the bare sponge experiments number 7Aa1 and 7Ab1 from Table 1, this process results in Fig. 1. These two experiments are directly comparable with one another because they differ only in the caliber of bullet used and both experiments resulted in forward and backward spatter.

Fig. 1 shows that the larger caliber bullet used in experiment 7Ab1 results in an overall larger average velocity for both

Table 1
Experiments from the MFRC used in this analysis. The experiment number corresponds to a part of the title of a particular video on the MFRC website.

Experiment number	Bullet caliber	Target type	Target distance [cm]
7Aa1	.22	Bare sponge	182
7Ab1	.44	Bare sponge	182
7Cb3	.44	Tape-covered sponge	182
7Db1	.44	Silicone-covered sponge	182
7Db2	.44	Silicone-covered sponge	182