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Experimental validation of a numerical model for predicting the trajectory of blood drops in typical crime scene conditions, including droplet deformation and breakup, with a study of the effect of indoor air currents and wind on typical spatter drop trajectories

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ABSTRACT

Bloodstain Pattern Analysis (BPA) provides information about events during an assault, e.g. location of participants, weapon type and number of blows. To extract the maximum information from spatter stains, the size, velocity and direction of the drop that produces each stain, and forces acting during flight, must be known.

A numerical scheme for accurate modeling of blood drop flight, in typical crime scene conditions, including droplet oscillation, deformation and in-flight disintegration, was developed and validated against analytical and experimental data including passive blood drop oscillations, deformation at terminal velocity, cast-off and impact drop deformation and breakup features. 4th order Runge–Kutta timestepping was used with the Taylor Analogy Breakup (TAB) model and Pilch and Erdman's (1987) expression for breakup time. Experimental data for terminal velocities, oscillations, and deformation was obtained via digital high-speed imaging. A single model was found to describe drop behavior accurately in passive, cast off and impact scenarios.

Terminal velocities of typical passive drops falling up to 8 m, distances and times required to reach them were predicted within 5%. Initial oscillations of passive blood drops with diameters of 1 mm $< d <$ 6 mm falling up to 1.5 m were studied. Predictions of oscillating passive drop aspect ratio were within 1.6% of experiment. Under typical crime scene conditions, the velocity of the drop within the first 1.5 m of fall is affected little by drag, oscillation or deformation.

Blood drops with diameter 0.4–4 mm and velocity 1–15 m/s cast-off from a rotating disk showed low deformation levels (Weber number $<$ 3). Drops formed by blunt impact 0.1–2 mm in diameter at velocities of 14–25 m/s were highly deformed (aspect ratios down to 0.4) and the larger impact blood drops ($\sim$1–1.5 mm in diameter) broke up at critical Weber numbers of 12–14. Most break-ups occurred within 10–20 cm of the impact point. The model predicted deformation levels of cast-off and impact blood drops within 5% of experiment. Under typical crime scene conditions, few cast-off drops will break up in flight. However some impact-generated drops were seen to break up, some by the vibration, others by bag breakup.

The validated model can be used to gain deep understanding of the processes leading to spatter stains, and can be used to answer questions about proposed scenarios, e.g. how far blood drops may travel, or how stain patterns are affected by winds and draughts.

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1. Introduction

Violent crimes involving bloodshed may result in the formation of a number of blood drops that move through air and eventually impact onto a surface producing a group of bloodstains (or bloodstain pattern). This is termed blood spatter [2].

It has been shown that stain shape can be correlated with the drop impact angle on a target surface (the Sine law: [3–5]). The 'sine law' is routinely used in the analysis of crime scene bloodstain patterns. A number of attempts have been made to correlate stain characteristics (size and morphology) to the volume and impact velocity of the blood drop. These studies have all focused on stains formed as a result of blood dripping from a wound or bloodied object (weapon) under the action of gravity ([6–9]; [63]). These approaches have important limitations: the reproducibility in counting of spines and the limited number (or absence) of spines for low velocity impacts on some surfaces. Interpretation of the stain morphology is sometimes difficult, for example due to impact surface irregularities or porosity. Further research is needed for other types of bloodstains and target surfaces.

A common analysis done at a crime scene is the estimation of the position of the blood source in an impact spatter event. If two or more drop trajectories can be determined, the point at which they intersect is the probable location of the victim at the time the wound was inflicted. To determine the trajectory of an individual drop from analyzing stain characteristics certain assumptions need to be made.

The stringing method [10] assumes the drop trajectory is a straight line. Gravitational and drag forces are assumed to have a negligible effect on the direction of flight while the droplet is airborne. The Backtrak® (http://people.physics.carleton.ca/~carter/) and Hemospat® (http://hemospat.com/research.php) software programs are based on the straight line trajectory approximation. Straight line blood drop trajectory approximation also underlies the tangent method [11]. These approaches, however, were shown to produce considerable errors in area of origin determination, unless the trajectories are very short and the velocities relatively high [12–14].

Another method of blood source determination proposed by Podworny and Carter [15] assumes parabolic trajectories of spherical drops. Buck et al. [16] and Buck and Kneubuehl [17] argued that this method is adequate for reconstructive purposes.

To assess the accuracy of trajectory reconstruction methods, it is necessary to have an in-depth understanding of the physics of blood droplet flight and impact. This paper deals with predictions of the flight of droplets, for which the initial conditions are known.

In order to accurately predict the trajectory (flight path) of a blood drop to calculate its origin, the initial state of the drop (size, shape and velocity) must be known and the forces acting during flight should be considered.

Depending on the mechanism of formation, a fluid drop may be non-spherical and experience shape oscillations under the influence of surface tension. Drop oscillations are damped exponentially in time by the drop fluid viscosity [18,19].

As the drop travels through air it experiences inertial, gravitational and aerodynamic drag forces. The latter is proportional to drop projected area (the area facing the incident flow), the drag coefficient and the dynamic pressure exerted by the external fluid (air) flow.

Surface tension forces at the free surface act to minimize the drop's surface energy and shape it into the smallest possible surface area, a sphere. When subject to external fluid flow however, a drop deforms to balance normal and shear stresses on its surface [20]. The level of drop deformation depends on the intensity of the deforming aerodynamic force.

Alteration of drop shape changes its drag properties. Distortion toward an oblate shape increases the projected area and drag coefficient (relative to the case of a spherical drop of the same volume). This may lead to a significant alteration in drop trajectory [21], which is of importance to the point of origin determination.

Under certain critical conditions a drop may reach a severe state of deformation, a so-called 'liquid disc'. The drop may further deform into a hollow sphere or bag, a hollow sphere with a jet or exhibit more irregular deformation and finally disintegrates (or breaks up) into smaller 'child' drops [22,23].

This raises two questions: (i) Under typical crime scene conditions, do the deformation and oscillation of blood drops appreciably affect their trajectory? (ii) Is mid-air breakup into smaller drops possible in typical crime scene conditions?

This paper aims to address these issues by developing and validating a numerical code for accurate and detailed blood drop flight modeling. Special attention is given to blood drops produced as a result of passive dripping, cast-off and impact. The numerical simulation described here provides a reliable and non-laborious method for understanding and predicting the flight characteristics of spatter drops.

2. Mechanisms of spatter drop generation

The external force which causes the victim's blood to break up into airborne drops may be gravity (drip or passive stains), blunt force impact (impact patterns), centripetal acceleration (cast-off) or bullet impact (gunshot spatter patterns).

The characteristics of typical blood drop formation and flight in the fluid dynamics framework are described below. Further discussion of the physics of drop formation is given in Jermy and Taylor [24] and Attinger et al. [25]. Further to the material in those sources, an estimate of the range of drop sizes, velocities and key non-dimensional parameters is given below.

Table 1
Blood drop characteristics in BPA, where $\rho_{air} = 1.2$ kg/m^3, $\nu_{air} = 1.51 \times 10^{-5}$ m^2/s are air density and kinematic viscosity at 20 °C; $\rho = 1056$ kg/m^3, $\mu = 4$ mN s/m^2, $\sigma = 56$ mN/m are blood density, high-shear-rate viscosity and surface tension, respectively, at 37 °C.

Mechanism	d, mm	V, m/s	Re	We	We_{avg}	Bo	Oh
Passive dripping [6,55]	3–7	<7	<3200	<7	~1	<9	~0.01
Cast-off [8,11,56]	0.5–4	1.5–20	50–5300	0.02–34	~6	0.05–3	0.01–0.02
Impact [8,56,57]	0.2–2	1.5–30	20–4000	0.01–39	~6	0.01–0.7	0.01–0.04
Gunshot [4,6]	0.05–1[a]	15–45[b]	50–2000	0.24–43	~10	<0.2	0.02–0.07

[a] Because of the lack of experimental data on gunshot related spatter, the size and velocity of the gunshot-induced drops have been estimated. Drop volume (and hence diameter) was based on the reported gunshot spatter stain sizes (areas) and estimated stain thickness (calculated as a constant, ~10^2–10^3, times erythrocyte dimensions).

[b] In some instances gunshot spatter may be affected by firearm muzzle gases [58]. In this case the relative velocity between the gases in fast movement and the drop should be used for Weber number calculation. This would depend on the proximity to the firearm to the blood source and firearm used. The reported data on the range of magnitudes of relative velocities associated with gunshot is lacking in BPA literature however. To avoid speculation the data from [6] was used instead to provide a reference drop velocity range for gunshot spatter of around 30.5 m/s. The relative velocity may considerably exceed this value.