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HIGH SPEED CINEMATOGRAPHY OF BLOOD DROPLET DEFORMATION IN FLIGHT - IMPLICATIONS FOR CRIME SCENE RECONSTRUCTION

Raymond MA[1,2], Liesegang J[2], Smith ER[2]

[1]Victoria Police State Forensic Science Laboratory, Macleod, Victoria, Australia 3085; and [2]La Trobe University, Bundoora, Victoria, Australia 3083

Introduction

Good homicide or major assault crime scene reconstruction has come to rely increasingly on science and technology to assist classical, thorough, patient, detective scrutiny. One of the most common types of evidence associated with crimes against a person is blood. Analysis of blood evidence offers two principal avenues of potential interest - namely reconstruction of the crime scene and/or individualisation, depending on circumstance.

The importance of immunological testing for species identification or genetic marker analysis by classification of the red cell or serum isozymes or deoxyribonucleic acid (DNA) profiling, cannot be overemphasized. There are, however, numerous occasions when the importance of the physical characteristics of blood far outweigh the biochemical. Crime scenes and those directly instrumental in their creation, reflect both the trauma and the passage of time, to a lesser or greater degree. Consequently, analysis of physical patterns like bloodstain patterns may reveal a wealth of significant information and be a major focus at a crime scene.

There are a number of scenarios where this may apply:

(i) where the suspect legitimately comes into contact with a (bloodstained) victim
(ii) where the defence of a suspect is self defence
(iii) where a police member shoots a member of the public or is shot in a 'one on one' situation and there may be allegations of impropriety
(iv) where there is a suspicious death (homicide versus suicide)
(v) where two persons or more have bled at the scene and the blood may be mingled or
(vi) where there is a combination of the above.

The geometric and trigonometric aspect of any reconstruction relies on certain physical characteristics associated with the blood droplets moving through space. Principal amongst those is the alleged spherical or spheroidal shape of the blood droplets based on the inescapable physical truth that surface tension forces at the liquid-air interface serve to minimise surface to volume ratio. Those forces, however, do not act in isolation and water droplet oscillations, collisions, break-up, coalescence, angular momentum and spin, familiar to the atmospheric scientists, Spilhaus (1948), McDonald (1954), Cotton and Gokhale (1967) and Beard and Chuang (1987), suggest caution. Although blood is highly 'viscous' relative to water, the limitations of the damping effect of that viscosity are not well known. This is despite the fact that interest in bloodstain pattern analysis appears to have been exhibited since the late 19th Century work by Gross.

Balthazard et al (1939) carried out some notable work but it was not until Kirk (1955) that this sub-discipline really came of age. MacDonell and others (1971, 1973, 1982, 1990), gave bloodstain pattern interpretation focus through the seventies and into the eighties and early nineties when finally the sub-discipline has moved towards both a more solid technology base through the research of Wilson and Schuessler (1985), Pizzola et al (1986), Podwomy and Carter (1989) and Carter (1991). A problem over the decades has simply been the fact that crime scenes are traditionally interpreted by police technicians whereas the scientific research is done in part isolation in academic institutions. It is unusual for the two to be married together by operational forensic scientists.

This paper describes the use of high speed film and cinematographic photography as a means to investigate

(i) types of oscillations inherent in, or imparted to blood drops
(ii) the extent of deformation transmitted to a blood drop by the forces associated with a drop being cast off a weapon and
(iii) the time necessary for droplet oscillations and deformation to decay to a level at which the droplet may be considered spherical.

Finally a computer program is presented to illustrate blood droplet trajectories graphically, both without air resistance and with linear (Stokes law) and linear/quadratic air resistance. The point is to emphasize the way air resistance can affect trajectories and ultimately to compare the empirical data captured by high speed photography with the theoretical analysis of a given droplet moving from a source position at a particular speed and angle.

Analysis of the empirical versus the theoretical should allow an accurate estimate of the error associated with those geometrical and trigonometrical parameters intrinsic to a crime scene reconstruction.

Apparatus and Techniques

The entire apparatus support was mounted on folded rubber tube supports to minimise vibration - particularly that caused by internal pedestrian and external motorised traffic. The floor support chosen was concrete, again to dampen vibration affects. The blood used in all cases was pig in origin, collected directly from the animal into anticoagulant (EDTA). Haematocrit measurements of the blood was found experimentally to be similar to that of human blood.

Photographic Recording Equipment

Data collection, that is, photographic recording of all images was either by two 35mm cameras synchronized to simultaneously photograph a volume in space from two different angles or by using a high speed 16mm cine camera to show droplet movement through space.

(a) Two Olympus OM2 35mm cameras were mounted on a fixed board to minimise vibration and prevent accidental camera lens repositioning at every manual frame change; (Appendix A). The angle subtended from the centre of the volume by the horizontal, optical axes of the cameras was 90 degrees. Thus, the only common dimension of the images captured by the cameras was the vertical. The cameras were mounted exactly the same distance from the image (assuming vertical drop descent).

The photographs were taken in darkness with both camera shutters in the open position. The aperture settings were f11 and the film used was Ilford FP4+ ISO 125, which was found to give the best compromise between speed and definition. White opaque reflectors were positioned behind the target space, directly opposite each camera lens; that is, the reflectors too, were at approximately 90 degrees to one another.

(b) The twin Stroboscopes used were modified beat-triggered strobes of the variety marketed in kit form by 'Altronics' of Western Australia. The "beat" electronics were short circuited and the strobe circuitry redesigned with a 5.6 volt threshold positive edge trigger.

(c) A Droplet Delivery Mechanism Apparatus was designed which allowed the throughput of droplets of liquid of a predetermined constant mass (or radius), at a pre-set constant temperature; (Appendix B). The apparatus consisted of a reservoir which fed into a thermostatically controlled, constant-head tank,(to insure uniform drop-mass delivery). Droplet size, temperature and delivery rate were fixed for a given investigation. The aperture which modified drop size was an interchangeable brass funnel connected via an O ring to an internal needle valve.

(d) The Timing Mechanism was designed such that it was activated by the passage of a liquid droplet through an aperture situated in a sensor unit housing. The droplet passage interrupted the photon track from a light emitting diode (LED) to a photoelectric cell. The interruption in turn, produced the pulse of sufficient voltage (greater or equal to the 5.6 volt trigger threshold) necessary to simultaneously discharge the xenon tubes of the stroboscopes after a specific time delay. This delay was controlled by a combination of fine and coarse potentiometer controls giving a 20 millisecond (ms) to 1 second (s) time delay range.

Thus, the image of the droplets could be easily captured by the cameras positioned at 90 degrees to one another. In addition, it could be ensured, within experimental error, that the drops were photographed when situated at the centre of the camera view finders to minimise any parallax error.

Consequently, two photographs, set 90 degrees to one another, were obtained for each target subject. This allowed close observation of the droplet oscillations, the period of oscillation and the decay time.

(e) The Fastax High Speed (rotating prism) 16mm Cine Camera was used in conjunction with a Wollensak WF358 Goose Control Unit which meant that the camera could be synchronized with the event being photographed. In addition, the Control Unit provided a means for altering the camera speed and varying the acceleration phase of camera run. The droplets were photographed at approximately 2000-3000 frames per second using Ektachrome 400 Daylight film. These film speeds necessitated a 100-180 volt camera voltage Goose setting. The light necessary for the photography was provided by twin quartz halogen lamps outputting 1000 Watts each mounted directly behind the falling droplets. The lighting was diffused using a white opaque screen located between the light sources and the droplet apparatus. The camera lens mounted on the Fastax camera was a 50 or 60mm Nikon lens. The optimal camera shutter speed was dictated by the Goose voltage setting and the optimal aperture setting for the light and film conditions was calculated at 5.6. The film length used in each case was 100 feet giving an exposure period of approximately 1.5 seconds for each run.

(f) The blood droplets were ejected off the weapon of choice (for instance a brass, steel or hardened steel rod), secured firmly to a springloaded catapult construction or "flicker apparatus"; (Appendix C). The blood, preheated to approximately 38 degrees C, was applied with a syringe to the end of the bar, just prior to release. The catapult had both a maximum tension limit and a 'stop' limit to regulate the speed of delivery of the droplets. The image of the droplets leaving the bar was captured on both 35mm film and high speed film. This was carried out in both a flicker mode and a contact mode using a bloodied reconstructed head as the target. The droplets impinged on a surface pre-set exactly perpendicular to the blood source.

Computer Programs

The programs, which allow comparison of theoretical parabolic trajectories, trajectories influenced (ideally) by linear resistance and those influenced by linear/quadratic resistance as described by Lock (1982) were written on a Quattro Pro Spreadsheet.

The programs allow input of initial velocity, droplet diameter, initial z coordinate and angle of trajectory and plots the corresponding trajectories to give the theoretical position of a droplet at a given instant. This allows a marriage of the theoretical with the actual droplet position as captured on film.

Preliminary Results

Droplets Falling Under Gravity

The combination of still and high speed photography showed conclusively that a droplet (water or blood), falling from the reservoir source, oscillated strongly (+/- 10%) between an oblate and prolate shape over the first few centimetres fall (the drop being oblate when its major axis is horizontal to the plane of the earth and prolate when its plane is vertical). The period of oscillation was not surprisingly, shown to be quicker the smaller the droplet. A large (approximately 4.5mm) droplet was found to have a period of oscillation of approximately 0.06 seconds (s) with smaller droplets having a shorter period.

In addition, falling water droplets, particularly those with diameters in excess of 3 mm, displayed significant flattening to give the classic assymetric oblate spheroid or almost doughnut shape with a flattened bottom and rounded top.

Preliminary analysis of falling blood drops indicate, however, that the forces associated with that medium dictated a near-spherical shape with little oscillation or distortion within a 250mm fall, whereas a 500mm drop or more caused obvious flattening of the droplet. This appears to be valid for droplets as large as 4.5mm which is very significant for those analysing very much smaller droplets and where the shape is dominated by surface tension forces.

The question as to whether the oscillations would be naturally damped or would be reinforced by eddy curent shedding is not yet fully resolved; although high speed photography showed no detectable oscillation after blood drops had fallen 1.4 metres(m). The time taken for the oscillations to decay to a negligible level has yet to be fully quantified, either theoretically or practically.

Droplets Leaving the "Flicker" Apparatus

The very significant forces associated with a bar moving through space cause blood drops to leave the bar at the top of its arc and again when the bar was "halted" by the apparatus stop-mechanism
or upon striking its target, giving rise to two spray patterns. Initial experimentation shows that for at least 15 cm of drop travel, there are indications of droplet break-up, some spinning particularly where the drop has a dumbbell-like shape - and considerable deformation of shape in some instances.

It is not known at this time

(i) how long the forces intrinsic to the blood droplet itself would take to impose a near-spherical shape on the drops or

(ii) what the effect of the spin is, if significant.

Quattro Pro Program

The influence of air resistance on particle movement, even under linear resistance may be significant. This is particularly true of the tiny droplets resulting from gunshot injuries. What this program also shows however, is the sometimes dramatic influence of the turbulence associated with the wake of a drop moving through space. The resultant additional drag on the drop imposes significant limitations on its movement; (Appendices D1..D6).

Discussion

Flow over a body is termed external flow and with a blood droplet moving through an air 'fluid' stream, the fluid may be considered to be infinite in extent. The authors' primary interest is focused on the forces that the fluid places on the drop, the details of the flow pattern near the drop and the resulting influence of those forces on the movement of the droplet through space.

A blood droplet moving through a fluid, in this case air, experiences fluid contact forces. Bodies may be three dimensional and axisymmetric, that is, have circular cross sections like a sphere.

The aerodynamic force on an axisymmetric body is defined by the body axis and the approaching flow velocity vector. The force component in the direction of the approaching flow is called drag and the component perpendicular to it is termed lift. The drag force vector always points downstream. Lift forces are not necessarily present in all flows; they occur only if there is lack of symmetry. Asymmetry may be caused by the asymmetry of the body or by the misalignment between the body and the fluid flow.

If one considers a 3-dimensional body, the approach flow vector may be parallel to the symmetry plane (if indeed one exists), in which case the resultant force also lies in the symmetry plane and can be split into its two force components, lift and drag. If completely asymmetric, however, the resultant force can be split into three components, drag, lift and side force.

Consequently, it can be seen that for a blood droplet moving in a windless environment, only drag (the extent of which would alter with any droplet shape change during flight) need be a consideration. If the droplet is not spheroid, however, or is spheroid, but in a fluid field which is not constant (gusts of wind for instance), not only will the droplet impinge on a surface in a fashion that precludes the use of simple trigonometric interpretation, but it will have arrived there via a flight path which may involve a significant lift component and perhaps a side force component as well. Consequently, predictions as to position of blood droplet origin may involve significant error.

In most flows of practical interest, the drag and lift coefficients for a given shape in a steady flow are functions of angle of alignment and the Reynolds number, the latter being an indication of turbulence associated with particle movement. Assuming incompressible flow, gravity wave and surface tension effects are considered negligible. The fluid flow status can be considered to be primarily laminar. Where blood droplets of varying dimensions are concerned, however, the larger of which clearly alter shape during flight and do not conform to the sphere or spheroid model, effect of surface tension cannot be discounted. Literature abounds with data reflecting the overriding influence of surface tension on the shape of tiny water droplets. The net result of that is a spherical shape seemingly little altered by the influences of an airstream. The literature maintains, however, the same cannot be said for water droplets greater than 0.3 - 0.4mm in diameter. Nonetheless, experimentation thus far indicates strongly that the problems are not nearly as significant with blood, although the forces which predominate immediately after droplet generation may introduce early flight path deviation. This may help explain some of the surprising width/length ratios as described by White (1986) where the width of a bloodstain, impacting on certain fabrics, occasionally exceeded its length.

Finally, it is well known that any circulating body in an otherwise uniform stream experiences lift; (ask any soccer, baseball or cricket player Mehta (1980), Mehta et al (1983) and De Mestre (1990). For instance, if we imagine an air flow from left to right across a spheroidal blood droplet and one spins the sphere in a clockwise direction and one assumes no slippage at the surface, then a small distance away from the surface, the fluid near the top surface speeds up but slows down near the bottom surface due to the respective additive or subtractive effects. Obviously this effect diminishes as one moves away; however what we have is a net lifting of the sphere - the so called Magnus effect. This too would introduce path deviation making trigonometric reconstruction slightly flawed. Although it has been shown that there is some rotation of the dumbbell-like droplets and therefore there may be spinning of the drops themselves, it appears unlikely at this time, that the speed of rotation at the time the droplets are asymmetrical would be sufficiently significant to cause flight path deviation.

The high speed photography has shown that the viscous nature of the blood does (in the short term at least) produce a range of blood droplet shapes, many of which are spheroidal and some that are not. It is not yet known accurately how long it will take for those droplets which are significantly distorted to assume a spherical shape. In addition, the crime scene analyst should note that for bloodied low friction weapons at least, two spray patterns may result from each contact blow.

Even if one considers the forces active on a perfect sphere, that is, where there is no lift force, the resistance to the droplet, the drag force, is rarely linear except where the fluid is very viscous, the sphere very small or its velocity very slow. In essence, to a good approximation, the airresistance force does not depend on the mass of a spherical object, be it solid or hollow, but only on its speed v and radius r in the combination vr (Lock 1982).

There are two competing effects, linear and quadratic air resistance - the latter a direct result of the wake caused by the passing droplet where the air molecules within the wake region swirl around in little whirlpools or eddies behind the object after it passes. The retarding effect of the frictional forces and the adverse pressure gradient along the rear of the sphere together slow down the air so much that relative to the sphere, the air reaches zero speed and then small pockets of reverse flow develop giving rise to currents in the wake. The wake extracts the energy from the knetic energy of the droplet and hence it slows down due to the increased drag.

This overall effect may best be described by the formula

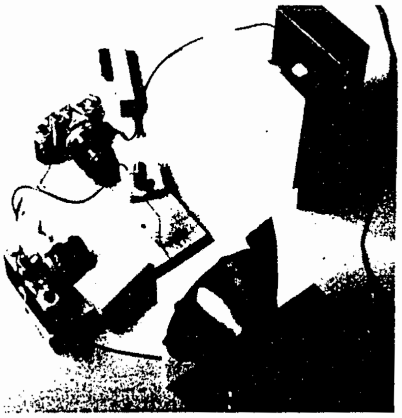
Force (air) = $A\ vr + B\ v2\ r2$

where A & B are constants and v and r represent the velocity and radius respectively.

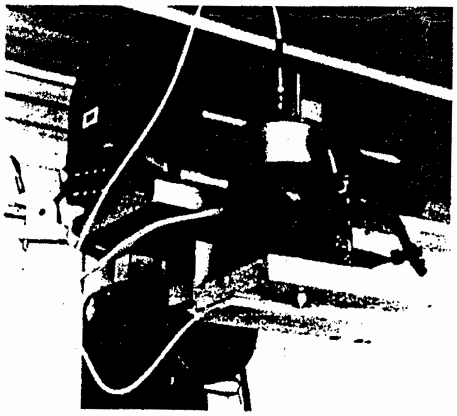
Finally, the program built from this formula demonstrates quite clearly that there may be a significant difference between the distance travelled by a spherical droplet influenced solely by Stokes Law and one merely describing a parabola, particularly where the droplet radius is small. More importantly, there may be a significant difference in the distance travelled by a droplet which is influenced only by Linear Resistance and one that is influenced by both Linear and Quadratic Resistance which more accurately describes the norm. The program has a number of uses other than as a basic teaching tool. Firstly, it can be useful in making predictions as to how far different size droplets would travel, which can be useful in a shooting scenario. More importantly, it will allow the authors to predict the flight path of a given droplet 'manufactured' at source, which may then be cross-checked against the empirical data which is to be generated by high speed photography of individual droplets from source to target.

Conclusion

What has been established to date is that there may be significant distortion associated with the production of a blood droplet. This may strongly influence the initial flight path. It is our intention to try and marry the empirical with the theoretical and to analyse the forces acting on the droplets to give further scientific basis for what may be a very useful crime-scene reconstruction tool. This analysis should also enable error margins to be estimated where appropriate. The bottom line indicated by the present report suggests caution when interpreting blood patterns from limited information and limited numbers of droplets. It reinforces the need for crime scene analysts to choose their droplets for analysis carefully, with due consideration given to size, directionality and distance from the target surface.

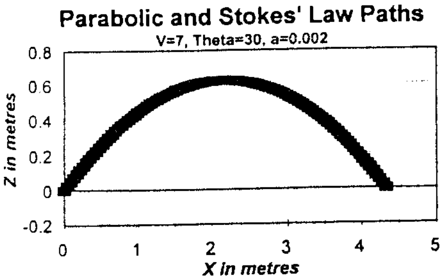


Appendix A

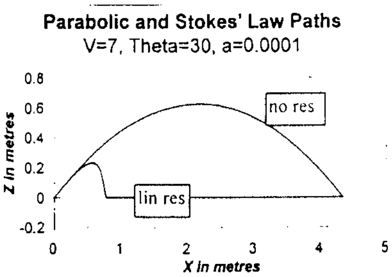


Appendix B

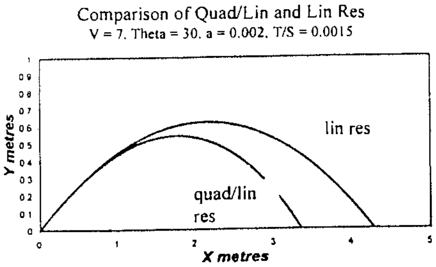
Appendic C



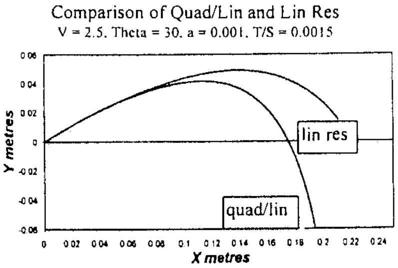
Appendix D1



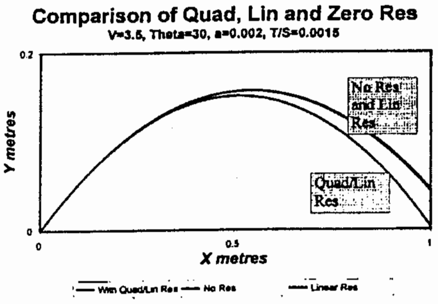
Appendix D2



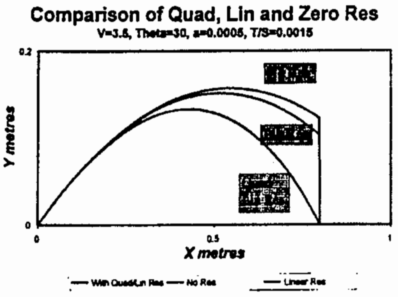
Appendix D3



Appendix D4



Appendix D5



Appendix D6

Acknowledgments

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