

The Development and Construction of a Motorized Blood Droplet Generation Device (BDGD) for Detailed Analysis of Blood Droplet Dynamics

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Abstract This work presents a motorized, mechanical blood droplet generation device (BDGD) capable of generating and projecting reproducible blood droplets at a range of sizes, velocities and directions relevant to a number of crime scene applications, particularly castoff and impact patterns. The BDGD has facilitated comprehensive, systematic, controlled experimental work including a detailed analysis of the fluid dynamics of blood drops during flight and impact. This level of control and reproducibility are impossible to achieve in experiments using human-wielded weapons. The BDGD is complemented by an LED lighting system, enabling droplet dynamics to be filmed with one or more high speed digital video cameras. It features an automated blood application pump, ensuring a controlled blood volume. The ability to generate and analyse blood drop dynamics in such a controlled manner lends itself to the development of statistical models which can aid in the presentation of objective bloodstain evidence.

Keywords: Forensic science, Bloodstain pattern analysis, BDGD, Blood drop, Dynamics.

Introduction

There is currently a dearth of controlled, systematic experimental work on blood droplet behaviour, in the bloodstain pattern analysis (BPA) literature. This means, for example, the science under-pinning the use of predictive models to calculate the impact angle and the area of origin of bloodstains is limited^[1]. Blood droplets are generally thought to travel as oscillating spheres, whose oscillations dampen after a time due to viscosity, with the spherical shape ensured by the surface tension properties of the blood^[2-4]. Recent studies have utilized high speed video to examine the dynamics of falling droplets with regard to droplet deformation on angled surfaces, the effects of gravitational and drag forces and terminal velocity^[5-7].

This level of analysis however, has not yet evolved to analysing upwardly moving droplets, relevant to cast-off and impact patterns. While the effect of gravity and drag can be modelled using equations which incorporate the physical properties of blood and air, a variety of other factors including impact surface characteristics can influence blood drop behaviour at crime scenes and thus systematic experimentation is required.

One of the challenges for research into spatter patterns is generating consistently-sized small droplets at higher velocities than a passive dropping experiment can achieve. To make this possible we have designed and built a blood droplet generation device (BDGD). The device is comprised of a motorized rotating disc, based on the concept of rotary

atomisation, to generate uniform droplet sizes. Rotary atomisation is one of many atomization techniques employed in various industrial applications such as spray cooling and ink jet printing^[8]. In this process liquid is applied to a rotating disc. During rotation the liquid migrates to the edge of the disc where it forms ligaments or sheets which disintegrate into droplets and detach from the disc's surface^[8].

The design of the circular disc BDGD enables blood droplets to be projected at any angle in the plane in which the disc is set. The direction of the device disc can be reversed, so that stains created from upward-propelled droplets can be compared with those from downward and horizontally propelled droplets.

The BDGD was primarily designed to study cast-off droplets. To determine

the relevant range of velocities for cast-off, preliminary biomechanical trials were conducted with the assistance of motivated human volunteers swinging various weapons towards ('forward swing') and away from ('back swing') a blood-soaked target. The weapon with the greatest end-point velocity was the baseball bat which measured up to 15 m/s during back swing and up to 36 m/s during forward swing^[9]. A target velocity of 40 m/sec was chosen for the maximum disc tangential velocity.

Droplet size can be controlled to an extent by controlling the volume applied. Droplets and stains can be mapped and graphed relative to a global coordinate system and a high-intensity backlighting system enables fine details of droplet dynamics to be captured with a high speed video camera. Particular attention was given in the design to the health and safety requirements of the laboratory.

Prototype Development and Preliminary Experiments

Preliminary droplet generation experiments were conducted using a prototype apparatus comprising of a 200 mm diameter Formica disc with shallow surface grooves, attached to the shaft of a 0.09 kW motor wired to a variable speed drive (VSD). The tangential velocity of the disc perimeter was set to 10 m/s and blood applied to the surface via a syringe. The droplets produced were smaller (0.2-0.4 mm in diameter) than those expected in cast-off, which was attributed to the relatively small radius of the disc and correspondingly large centripetal forces generated by the disc. A much larger disc diameter was therefore required to obtain appropriately sized drops to model cast-off.

Design and Construction of Device

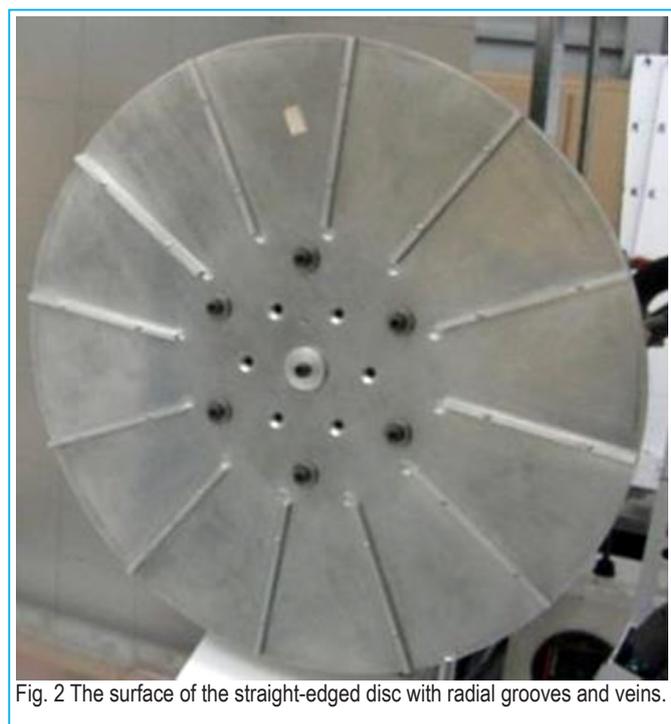
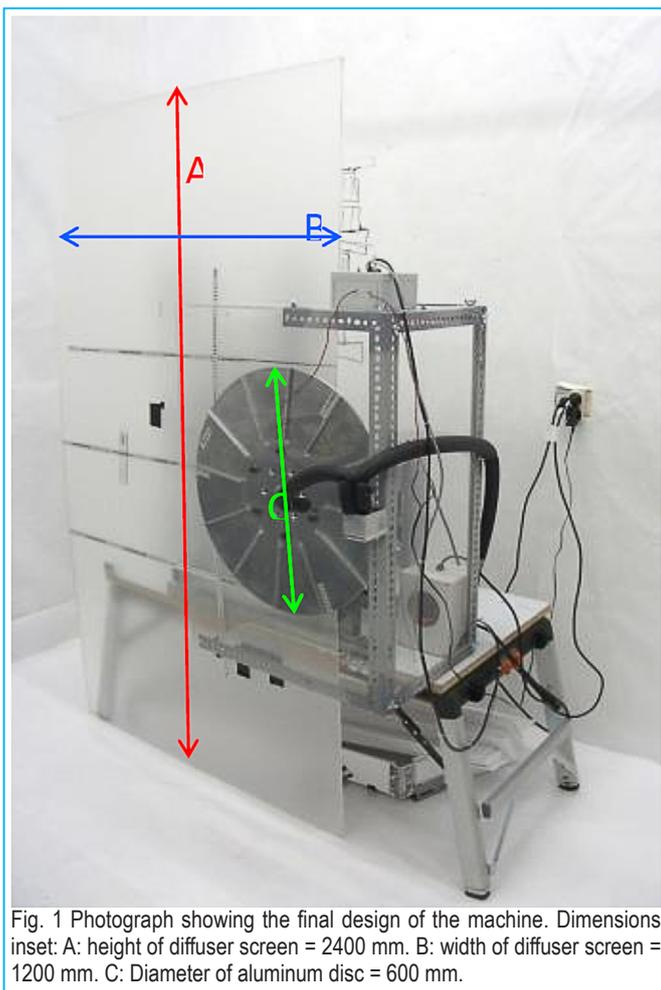
The final design, (Figure 1)

included the following features:

- A 6.0 mm thick, 600 mm diameter aluminum disc with stainless steel hub
- A 0.3 kW motor with a drive shaft and pulley system
- A variable speed drive (VSD) unit, controlled by a 10 turn potentiometer and on/off switch to control the motor
- A comprehensive framing system and weighted support base
- A medical pump to apply blood to the disc
- A safety cage
- A high intensity LED array backlighting system
- A 2.4 x 1.2 m frosted Perspex® diffuser screen, which doubled as a global coordinate system (GCS) grid

Disc Size and Features

The diameter of the disc was chosen to be 600 mm, which represented a realistic size for adequate control for tangential velocities up to 40 m/sec. The disc was cut from a sheet of 6 mm aluminium which provided a lightweight but strong structure capable of spinning without flexing



or oscillating. The disc had twelve evenly spaced, 170 mm long, 1.0 x 1.0 mm radial grooves milled into it from the disc perimeter to the centre. These were designed to encourage the fluid to pool, rather than be randomly distributed around the disc as it rotated. Aluminium radial veins were attached to the left edge of each groove (Figure 2) to increase the volume of blood being propelled from the disc at each point on its circumference and thereby produce larger droplets.

Frame and Base of Device

The circumference of the 600 mm disc is 1885 mm, so the angular velocity required to achieve a tangential velocity of 40 m/s, is 1273 revolutions per minute. Considering the mass of the disc and the torque generated by these relatively high speeds, a comprehensive framing system was constructed and the entire apparatus bolted to a solid support base to eliminate any vibration and prevent any lateral movement. An adjustable work platform, built to withstand heavy loads in the building industry, was used as the base (Figure 3). A 1.5 x 0.8 m, 20 mm Medium Density

Fibre Board (MDF®) was attached to the platform with 12 screws. Prior to mounting, 15.0 mm nuts were counter-sunk into the board, to bolt the machine frame to the MDF (Figure 3).

The frame was designed for maximum stability and to accommodate the motor and pulley system. A platform to support the motor was attached to the rear of the frame and laterally facing grooves were bored into the platform so the motor position could be adjusted to tension the drive belt (Figure 4). Multistrut® construction framing was chosen to build the frame because of its strength and versatility. Multistrut® can be pieced together using bolts and spring nuts; the positions of which can be adjusted if required. Stainless steel angle brackets were used to hold the frame together once the fixed positions were calculated.

Pulley System, Drive Shaft, Motor and Hub

The direct drive arrangement between the motor and the disc used in the prototype was inadequate for a device of larger dimensions. A larger motor was necessary for the fine

velocity control required and a pulley system with a fan belt and drive shaft was also necessary for the speed and stability required. The motor was wired up to a variable speed drive, which in turn was connected to a 10-turn potentiometer and an on / off switch, so the speed of the motor could be controlled in fine increments.

The appropriate pulley sizes and drive shaft diameter were calculated to achieve the required maximum tangential velocity of 40 m/s with increments of 0.1 m/s. A 26-5M-15 pulley was fitted to the shaft of the motor and a 60-5M-15 pulley was attached to a 30 mm diameter, 50 mm long drive shaft. The pulleys and drive shaft were stainless steel. Two 30 mm pillow block bearings were bolted to the angle brackets at the top centre of the frame, one at the motor end and one at the disc end and the shaft threaded through (Figure 4). The length of the belt to drive the pulleys was measured once these items were in place, the belt attached and the position of the motor adjusted laterally to tighten the belt.

A two-piece circular stainless steel hub was machined to securely attach the disc to the drive shaft and to prevent any torsion or oscillation of the disc. A bolt-hole matching that on the disc (Figure 3) was drilled into the 20.0 mm thick, 255.0 mm diameter outer portion of the hub and planed to sit flush with the rear surface of the disc (Figure 4). Half of the 40 mm thick inner portion was bolted in a similar fashion to the outer portion, with the innermost 20 mm machined to a 60 mm diameter, with three grub screws securing it to the drive shaft (Figure 4).

Velocity Control

The 0.3 kW, 3-phase, 4 pole motor was wired in delta configuration (240 V, AC, 3 phase) and connected to a SEW Eurodrive Movitrac® variable speed drive (VSD) controller (Figure 5).

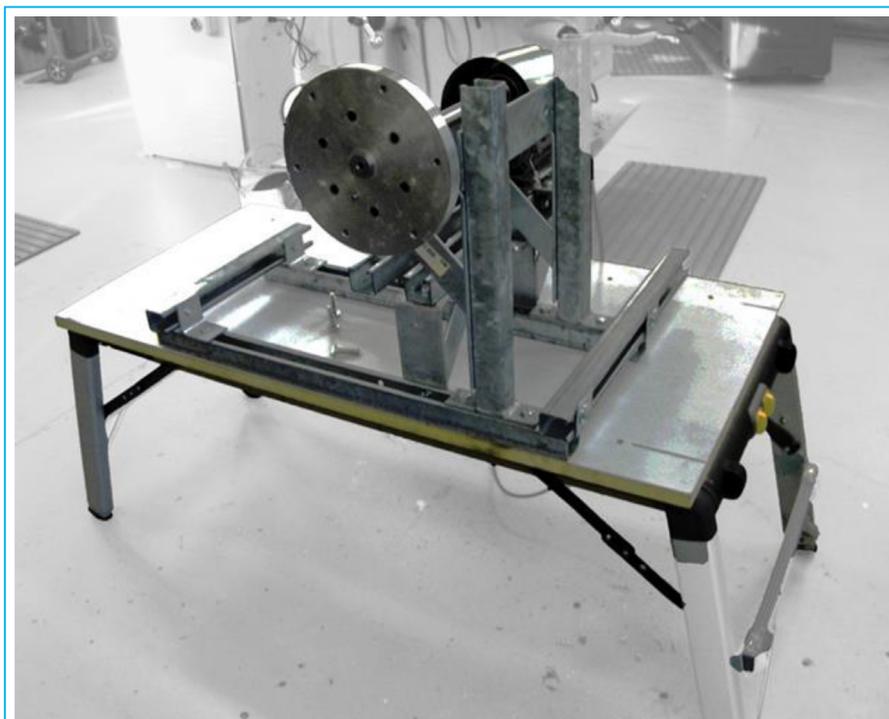


Fig. 3 The work platform and MDF board, with the Multistrut® frame bolted in place.

The VSD controller was wired to a 10 turn potentiometer, via a 1.5 m cable, allowing the operator to stand away from the machine. The potentiometer was mounted in a plastic box with a

rotary dial allowing fine control over the velocity and an on/off switch (Figure 6). The VSD had a digital display in Hz, so a calibration table was written correlating frequency with the

tangential speed of the disc perimeter. The VSD settings could be changed so that the rotational direction of the disc could be reversed; this facilitated the generation of upward and downward moving droplets. Velocity could be controlled to 0.1 m/s.

Blood Application Pump

A KNF Neuberger® micro-diaphragm pump was used to apply blood to the disc in controlled amounts. The flow rate of the pump was 3.8 ml/sec and it was approximately 150 x 50 x 50 mm in size (Figure 6a). The pump was wired up to a rotary switch (Figure 6b), with eight time settings; 0.25 sec to 2 sec in 0.25 sec increments and an activation button (Figure 6a).

At the press of the button, the pump activates for the amount of time set by the rotary switch; 0.95 ml in 0.25 sec, 1.9 ml in 0.5 sec, up to 7.6 ml in 2 sec. The pump was mounted onto the device in an aluminum box, screwed to the frame of the safety cage (Figure 10), at the right side of the disc (Figure 7b).

The fluid, which is usually pig blood, was placed on a heating plate behind the disc (Figure 7a), with the temperature of the blood set to whatever value was required for any given experiment. A 5 mm plastic tube, insulated with Centurylon® pipe insulation, ran from the blood source to the pump, where a second tube ran from the pump to the disc, held in place by a bracket (Figure 7b). The pipe insulation ensured that the blood temperature remained constant from the beaker to the disc. The pump was 'bled' (blood was pumped through the tube into a waste beaker for 4 seconds) immediately prior to each test to ensure that any effects of blood sitting in the tube for a time; such as a temperature decrease, settling of cells or coagulation, were eliminated. A small plastic hose fitting was placed in the end of the tube facing the disc, to

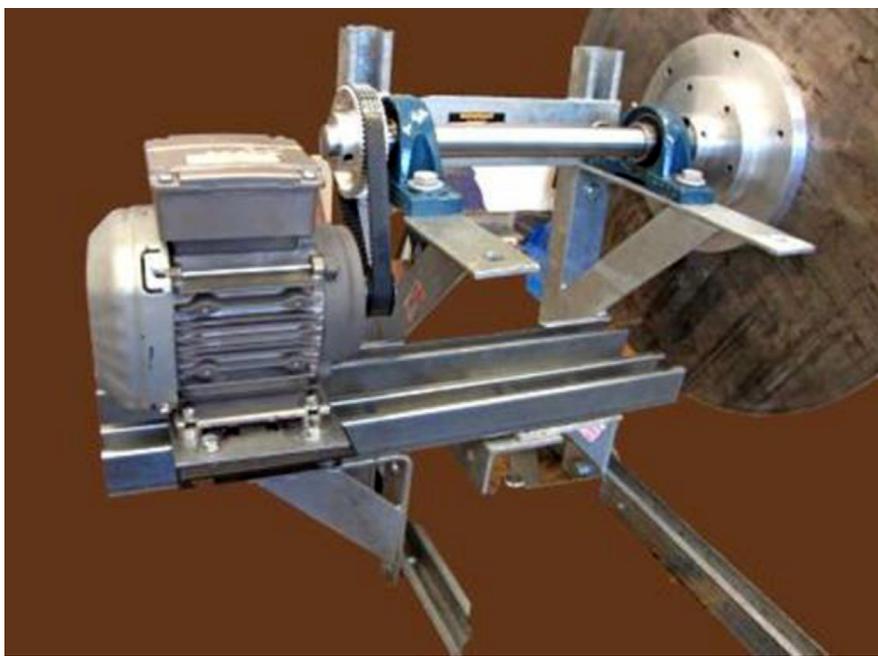


Fig. 4 Multistrut® frame, with 0.3 kW motor, two pulleys and belt drive (left). Two pillow boxes hold the 30 mm shaft, which attaches to the boss on the rear surface of the disc (right)..



Fig. 5 The VSD, cable and potentiometer with rotary dial and on/off switch.

control the direction of expelled blood.

Diffuser Screen and Global/Local Coordinate Systems

A diffuser, 2400 mm high and 1200 mm wide, was securely positioned 80 mm behind the front surface of the disc, in the same plane as the disc. The screen was comprised of 6 mm thick frosted Perspex®.

The diffuser screen served four functions; to diffuse the backlighting to create an even level of illumination, to provide a surface for a global coordinate system (GCS) grid to be marked on, to provide a surface to attach impact targets and to provide additional stability to the machine.

The GCS was designed so that the positions of each droplet and resulting bloodstain could be correctly plotted relative to each other and to the position of the disc. The grid coordinates 0,0 in the x and y axes were located at the bottom left corner of the diffuser screen, with the x coordinates increasing to the right and the y coordinates increasing in an upward direction. The centre of the disc was located at x,y coordinates 1100, 990 mm. The flight paths of blood droplets propelled from the disc were plotted according to their GCS coordinates. The device can propel blood drops onto any surface to create test bloodstains. Initial tests utilized

Foamcore® strips cut in 2000 mm and 1200 mm lengths, 150 mm wide, marked with the GCS coordinates and attached to the diffuser screen at 90 degrees (Figure 9).

The device and coordinate system were set up for droplet flight to be filmed with a high speed video camera, positioned perpendicular to the diffuser screen. Image dimensions are measured in pixels so a calibration scale, called a local coordinate system (LCS), was constructed in order to plot droplet position relative to the GCS. A transparent Perspex® box with a millimetre grid was placed in the same plane as the disc in front of the diffuser



Fig. 6a KNF Neuberger® pump, rotary switch dial and activation button.

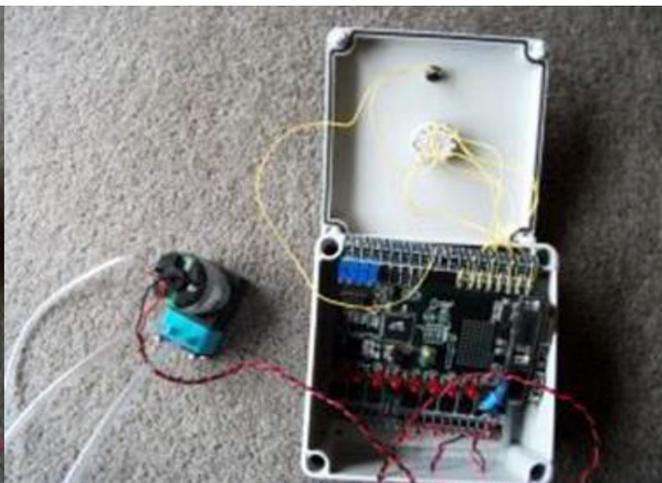


Fig. 6b KNF Neuberger® pump and circuit board with rotary switch.

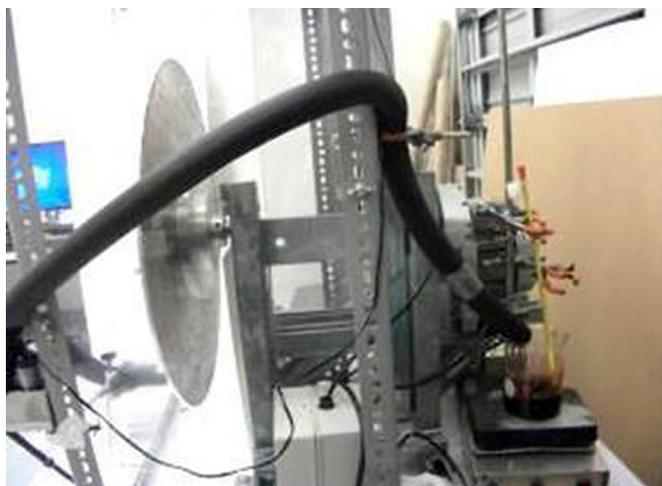


Fig. 7a Blood in a beaker on an element at the rear of the device with an insulated 5 mm tube running from the beaker to the pump.



Fig. 7b The position of the insulated application hose and pump for upward-moving trials: 20 mm from the perimeter of the disc, 55 degrees from the horizontal, 15 mm from the surface of the disc and the pump (far right).

screen and the camera focused in this plane (Figure 9).

Safety Features

For safe practice while using the device, several features were added to the design. A safety cage around the disc prevents any projectile accidentally released from the rotating disc to be flung toward any personnel or equipment. The cage also catches any blood being released from the edge of the disc, preventing lab contamination and providing stability for the diffuser screen. Lengths of stainless steel slotted angle iron were cut to appropriate lengths and welded in the configuration seen in Figure 11 and bolted to the MDF board. Clear Perspex® windows

were cut to size to form a front cover, left side cover, top and bottom as labeled in Figure 10.

In addition to the cage, the belt drive also required a cover to minimise the risk of injury from fast moving, rotating parts. An aluminum sheet was screwed to a wooden semi-circular plate and fastened over the belt and pulleys and clear Perspex® sheets were fastened to the cover at right angles, preventing any contact with the belt while the device is in use (Figure 11).

Backlighting System

A high intensity backlighting system was required for the high speed camera to capture the flight dynamics of small blood droplets travelling at high

velocities at a sufficiently high shutter speed to prevent motion blur and a small enough aperture for sufficient depth of field. A four LED array system was assembled for this purpose and will be detailed in a separate publication. An adjustable frame to hold the system was constructed from Multistrut®, which enabled the positions of the LED arrays to be moved according to the area being filmed. Figure 12a provides an illustration of the position of the backlighting frame relative to the diffuser screen and the proximity of the LED arrays to each other; a configuration which was shown to provide the most even illumination at the right intensity to film the blood droplets being propelled from the disc (Figure 12b).

Performance Experiments

Experiments were conducted to determine whether the droplets generated by the device were in the size and velocity ranges of those generated by human-wielded assault weapons (Figure 13). In these initial validation experiments, the tangential velocity of the disc was set to each of the four different velocities in Table 1. The volume of blood applied to the disc was initially 0.98 ml and this was increased if it was found that the blood droplets were smaller than those generated by the human-wielded weapons, until the volume made no difference to the droplet size.

Results

Figure 14 shows five consecutive images of droplets being propelled at 6 m/s, with 0.98 ml of blood applied to the disc. It was observed that as the disc rotated, blood travelled to the disc perimeter and formed a ligament as it travels away from the disc. The



Fig. 8 The Perspex® diffuser screen with the global coordinate system (GCS) grid; in 100 mm squares.

ligament started to break up when surface tension forces were no longer sufficient to provide the necessary centripetal force to keep the blood on the disc. At this point individual droplets continued to travel in the direction they were travelling at the instant of release from the ligament; on a flight path tangential to the perimeter of the disc. Figure 15, an overlay of the images in Figure 14, shows that initially this is a straight line trajectory; however it is assumed that this trajectory will start to curve due to the forces of air resistance and gravity some time later. During ligament breakup very small droplets can be observed between the larger droplets in figures 15 and 16, while the average size of the larger droplets is similar; a standard deviation of 0.16 was calculated for 200 droplets released at 6 m/s, recorded within 200

mm of the disc perimeter.

Figure 16 provides a visual comparison of the droplet sizes summarized in Table 1, projected at disc tangential velocities of 6, 10, 20 and 30 m/s with approximately the same global coordinates. It is evident from these results that the device generates droplets smaller than a human wielded baseball bat at 20 and 30 m/s. However it is unlikely to see shorter weapons with tangential velocities in this range in practice, so this remains an acknowledged limitation of the device.

Conclusions

The BDGD has proved to be capable of generating large numbers of reproducible droplets in any planar direction, within the size and velocity ranges of cast-off from common

humanwielded assault weapons relevant to blunt and sharp force trauma, with the exception of a baseball bat being swung at greater than 20 m/s.

In controlled laboratory conditions, each independent variable in the system can be defined, set at a predetermined value, and large numbers of droplets generated, stains created, and results observed. The experimenter can then change one independent variable in that system, keeping all others constant, test again under the new conditions and observe any changes in the outcome variables and the frequency of those changes under the new conditions. An example would be to compare the number of spines and scallops observed in stains created at a given location under condition A, then increasing the tangential velocity of the disc by 3 m/s, and repeating the experiment. The

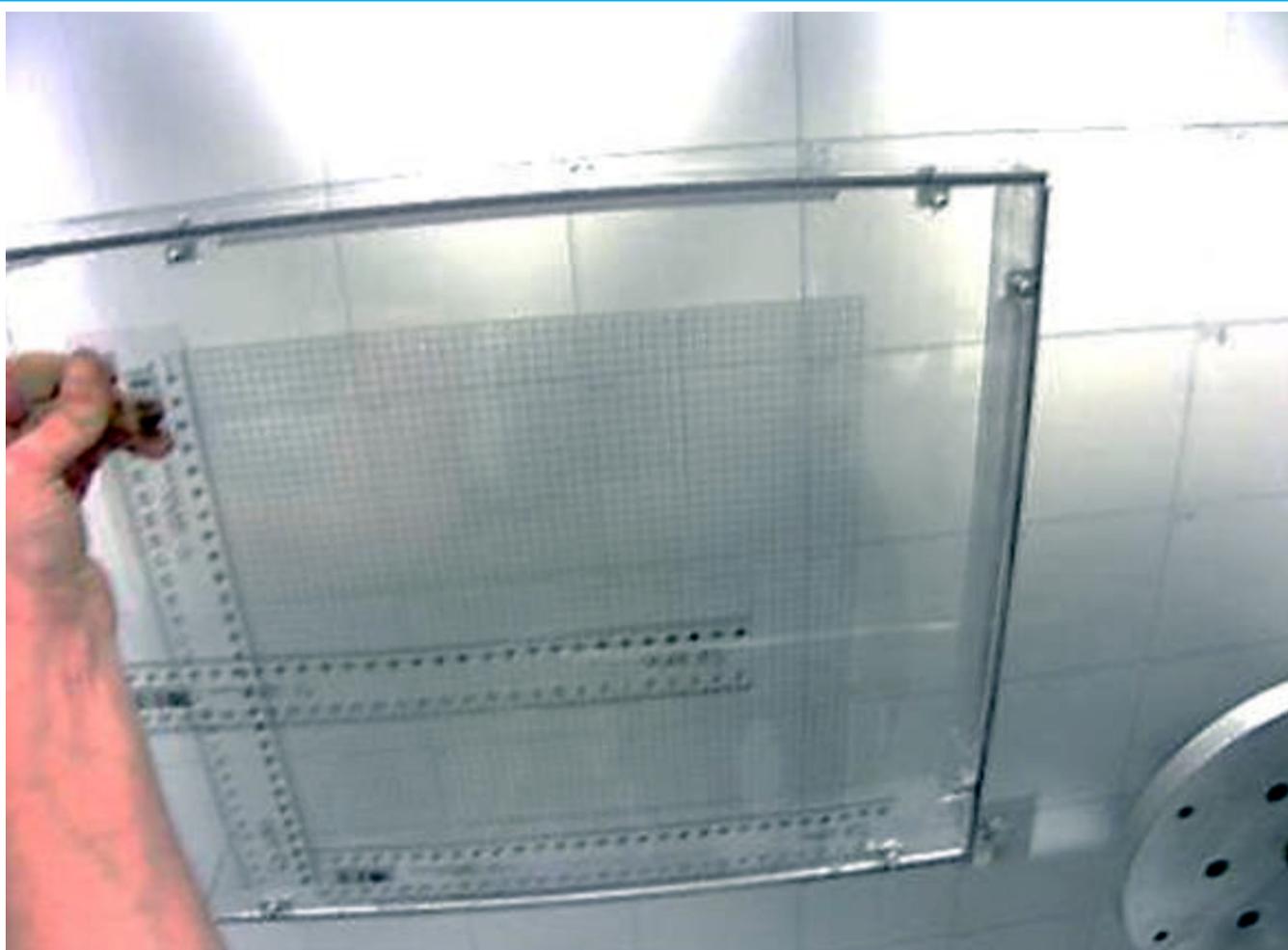


Fig. 9 The local coordinate system (LCS) calibration grid being held against the surface of the diffuser screen.

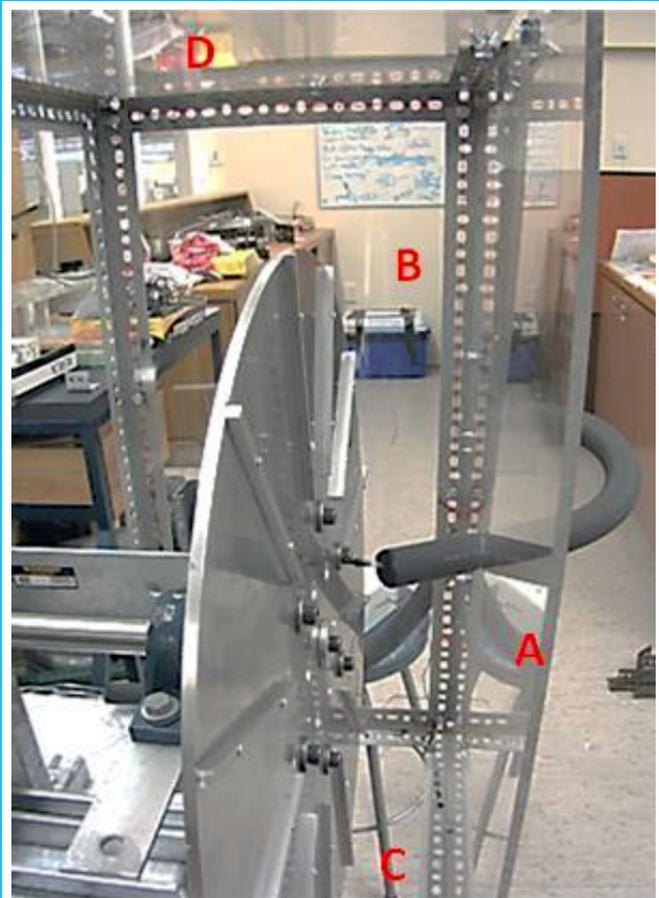


Fig. 10 Safety cage surrounding the disc, attached to the MDF board. A: Perspex front cover, B: right side cover, C: bottom cover, D: Top cover with slit for diffuser screen.



Fig. 11 The belt drive cover with the clear Perspex® walls.



Fig. 12a LED array backlighting system on the adjustable Multistrut® frame, bolted to the MDF board.

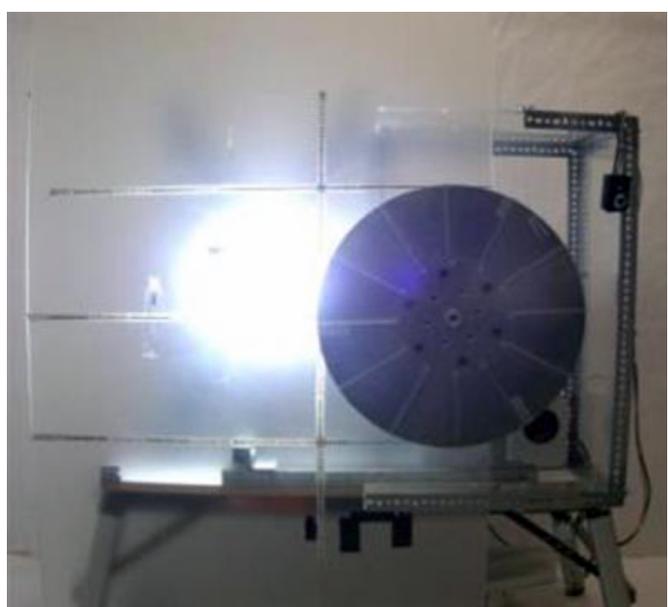


Fig. 12b The illumination provided by the backlighting system.

Table 1. Showing the range of droplet sizes for each velocity and blood volume.

Disc Velocity (m/s)	Blood Volume (ml)	Average Droplet Diameter (mm)
6	0.98	0.9
10	0.98	0.6
20	1.9	0.26
30	2.85	0.18

device can generate a sufficient number of results to quantitatively assess the effect of the manipulated independent variable (e.g. initial velocity) on the dependent variables such as measurable stain characteristics. This approach enables, for example, the systematic assessment of the relationship between the trajectory of a constantly accelerating assault weapon swung in an arc, and the resulting cast-off pattern.

Utilizing the backlighting system and global coordinate system, the device can be used as a vehicle to study and understand parabolic blood droplet trajectories and the limitations of the straight line trajectory calculation

methods. Blood droplet trajectories can be mapped and plotted and databases of the dynamics of different sized droplets can be developed over time.

In case specific experimentation, the device can be used in hypothesis testing in a systematic fashion, incorporating factors such as the effect of the impact surface on stain formation, and subsequent impact angle calculation.

The enhanced back-lighting system provides the means to analyse the oscillation amplitude of individual droplets, and the time to dampening for droplets created under a range of conditions; velocities, drop sizes and

viscosity values, so that the effect of oscillation on stain formation and the accuracy of the subsequent impact angle calculation can be evaluated experimentally.

While a simple concept and a relatively straightforward design, the BDGD provides an effective vehicle to improve the scientific rigour behind bloodstain impact angle reconstruction and can quantitatively test some of the fundamental principles of bloodstain pattern analysis.

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This project would not have

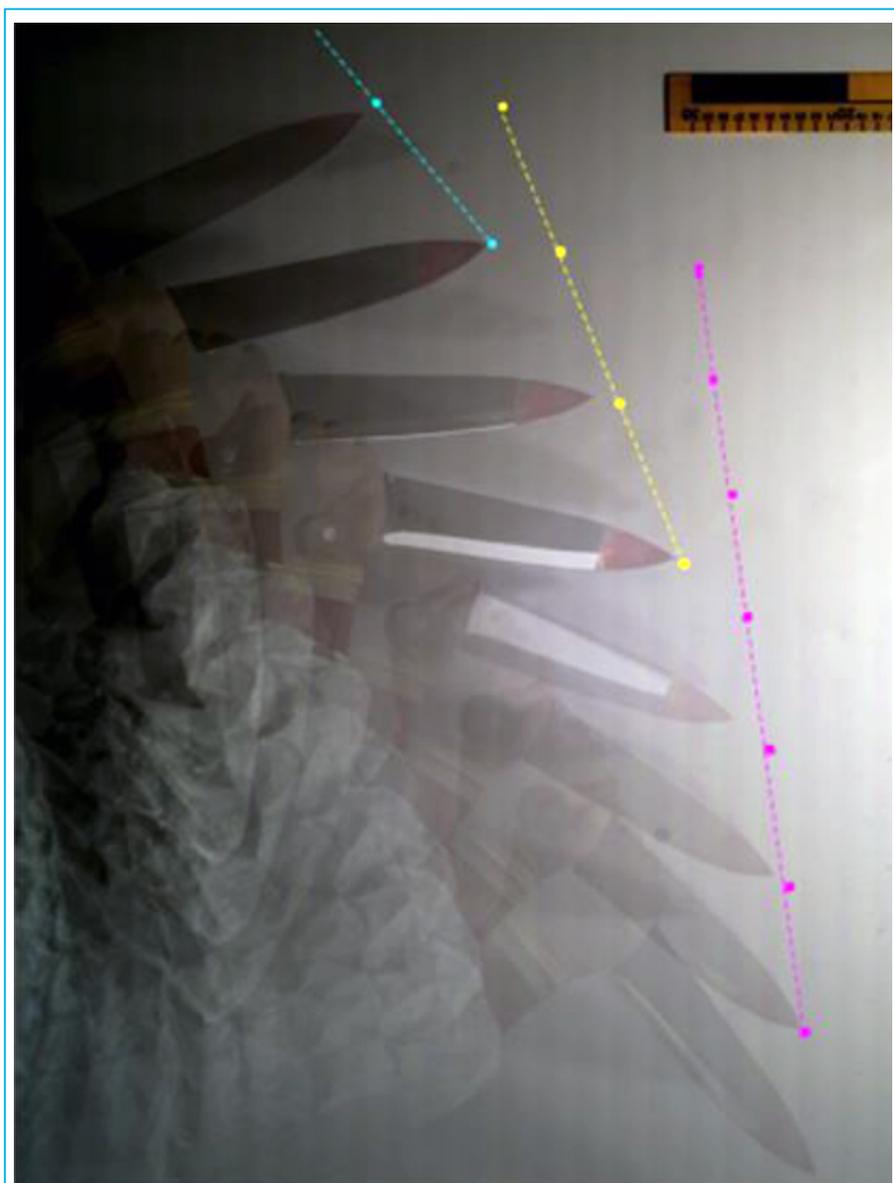


Fig. 13 Overlaid images of a kitchen knife being swung forcefully backwards by a human volunteer, after being dipped in pig blood. Overlaid graphics illustrate the blood droplet trajectories.

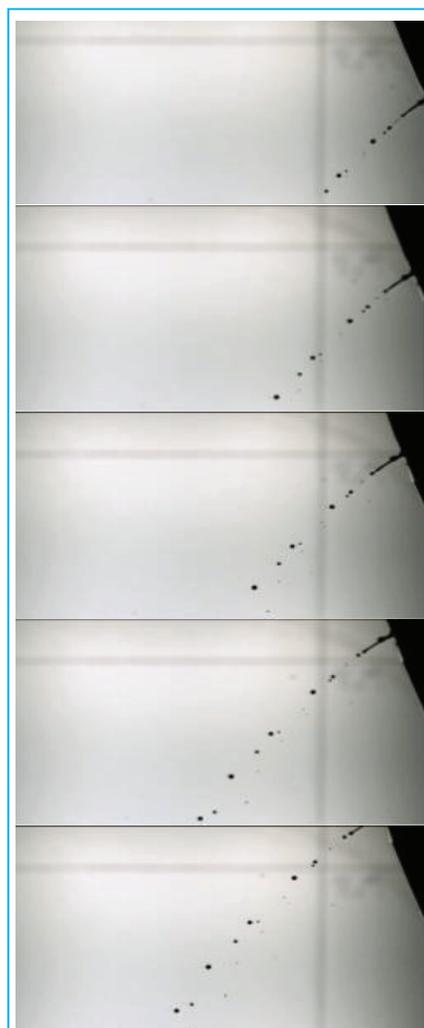


Fig. 14 Five still images taken every 0.000926 sec, of blood being propelled off the disc at 6 m/s, filmed at 5400 frames per second at a shutter speed of 1/178000th of a second..

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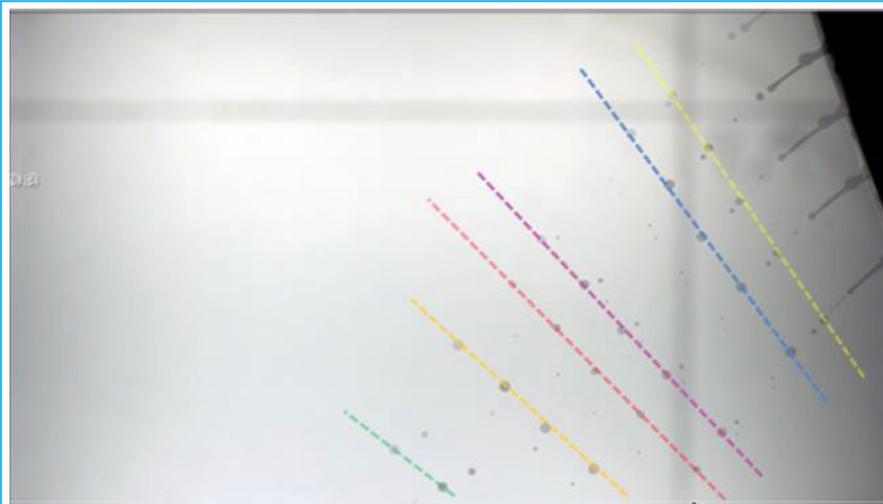


Fig. 15 The five still images from Figure 14 overlaid, with inserted graphics illustrating the flight path of each droplet, which in the initial flight phase, is tangential to the perimeter of the disc.

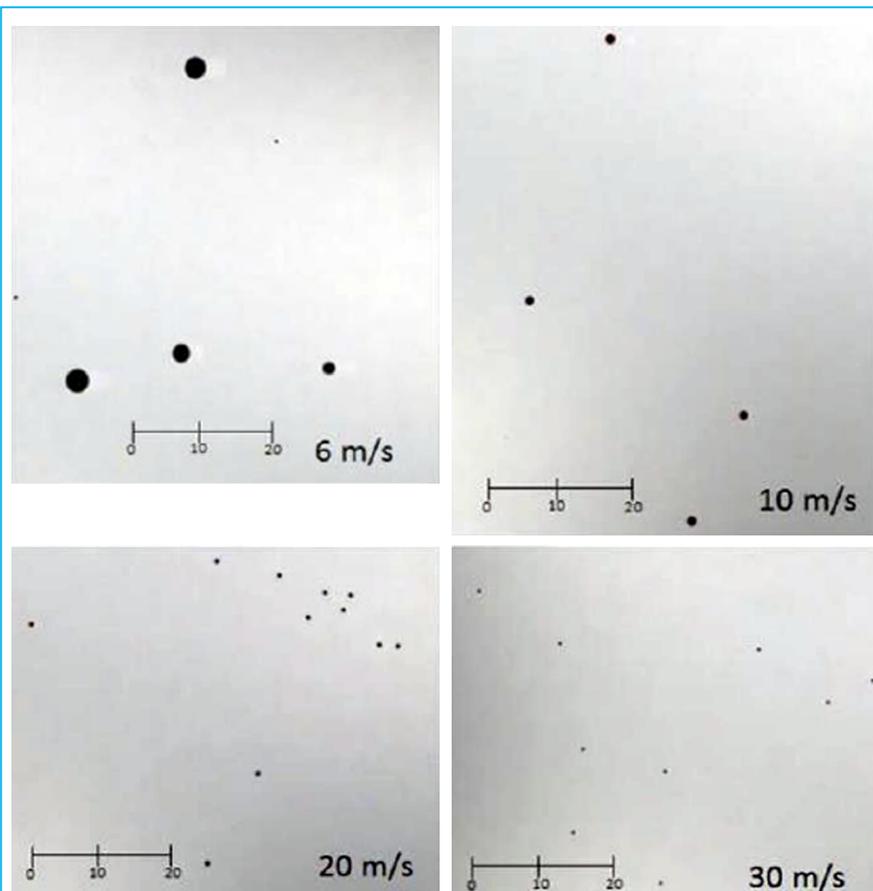


Fig. 16 Still photographs of in-flight droplets generated by the device at 6, 10, 20 and 30 m/s.