The flow field external to the human nose and the acceleration of blood drops from the nasal cavity during violent assault

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Abstract Bloodstain pattern evidence is often crucial in police investigations and in judicial trials, but is sometimes misinterpreted, with serious consequences. An important class of bloodstains, sometimes found at crime scenes, arises from expired blood, i.e. blood expelled from the nose and/or mouth as the victim breathes out. Currently, the range of initial velocities of these droplets is poorly known. The droplet size, velocity and impact angle determine the characteristics of the stain resulting from impact on a nearby surface. In this work, stereo particle image velocimetry (SPIV) is used to investigate the velocity field exiting a scale of 1.55 times life size physiologically realistic silicone model of the nasal cavity. An in-house developed computer model is used to predict the trajectory of blood drops (representative diameters of 0.5 mm and 2 mm) exiting the nasal cavity and ascertain their impact velocity and location on a ground plane 1.7 m (the average height of an adult male nose) below the nostril exit. The nostril geometry is shown to have an effect on the exit velocity with a difference of 0.49 m/s difference experienced between the maximum exit velocity of the left and right nostril. This variation in exit velocity was shown to have minimal effect on the impact velocity as the gravitational forces experienced after leaving the nasal jet dominated the droplet acceleration. The variation in velocity did however affect the resulting impact location of the drop (a difference of 46.7mm for the 0.5mm drop). Increase in drop size was shown increase the impact velocity, but reduce the distance between the impact location and the nostril exit.

1. Introduction

Bloodstain pattern evidence is often crucial in police investigations and in judicial trials, but is sometimes misinterpreted, with serious consequences: juries unable to reach the correct verdict, coroners unable to determine if a death is suicide or murder, and cases retried due in large part to confusion over bloodstain evidence (James et al. 2005; Indiana, vs. Camm 2004, 2006, 2013; California, vs. Spector 2007, 2008; California, vs. Simpson 1995, 1997; Ohio, vs. Sheppard 1954). This confusion and misinterpretation arises from a lack of fundamental understanding of the complex physical processes that generate blood stains (N. Carolina, vs. Petersen 2003) and a lack of science-based, peer-reviewed methods for interpreting bloodstain evidence (Davidson et al. 2012). In New Zealand, there are 86.1 homicides per year, with 93% resolved the same year (a suspect arrested, but not necessarily convicted). There are approximately 35,000 “Acts intended to harm” each year (84% resolved) (averages taken over 2003-2012, (Statistics New Zealand)). Only 44% of homicide prosecutions and 58% of acts intended to cause injury result in convictions (averaged over 2002-2011, (Statistics New Zealand)). There are clearly opportunities to improve detection and make better objective use of evidence in court to resolve more violent crimes and achieve timely and just outcomes for suspects, victims and their families.

An important class of bloodstain patterns, sometimes found at crime scenes, arises from expired blood, i.e. blood expelled from the nose and/or mouth as the victim breathes out or coughs. Currently, the range of initial velocities of these droplets is poorly known. The droplet size, velocity and impact angle determine the characteristics of the stain resulting from impact on a nearby surface. The present work determines the velocity field in front of the nose during exhalation using stereo particle image velocimetry (SPIV) and a refractive matched silicone flow phantom. This data provides the exit velocity a blood drop will experience as it leaves the nasal cavity. The subsequent blood drop trajectory and impact angle can be calculated using a computer model developed in-house (Kabaliuk et al. 2013b) that solves the droplet equation of motion and
uses empirical correlations to determine the drag coefficient of aerodynamically deformed (nonspherical) droplets. This information is important in understanding the information encoded in bloodstains at the crime scene, which may contribute to scene reconstruction by determining the locations of the victim and assailant when the crime was committed. An understanding of the physics of expired blood drop flight is also important in determining the limits of certainty of the information extracted from the bloodstain pattern. The certainty (or otherwise) of the inferences made from stain patterns are critical in determining whether stain evidence can contribute to a conviction. Currently there is very little experimental analysis that has been performed in this field (Donaldson et al. 2011; Denison et al. 2011) and further investigation is required to fully understand the problem.

2. Experimental Methodology

In the present paper, a rigid transparent silicone flow phantom (Fig. 1) representing a nasal cavity (Spence et al. 2011) was cast at a scale of 1.55 times life size using an investment casting technique (Geoghegan et al. 2012). The geometry was constructed from computed tomography (CT) data imaged from a 44-year-old male with 452 axially acquired slices at a resolution of 512x512 pix² with 0.6 mm slice spacing. Physiological features such as nostril hairs and mucous membranes inside the nasal cavity were not resolved because the main interest of this paper was the large flow features external of the nasal cavity, which were assumed independent of these details.

![Fig. 1 Silicone nasal cavity flow phantom viewed sagittally from the right](image)

The phantom was connected to a flow circuit with a schematic shown in Fig. 2. To minimise optical distortion due to refraction at the fluid-silicone interface, the working fluid was refractive index matched to the silicone phantom. A 39% water and 61% glycerine mixture by weight was found to be the optimal mixture to match the silicone refractive index of 1.43 (Geoghegan et al. 2012). The liquid temperature was maintained constant at 25°C with a cooling and heating system. The phantom was placed in a reservoir tank (b) containing the same water/glycerol mixture used in the flow circuit. The reservoir surface area and phantom depth were such that at the required flow rate there was minimal movement in the free surface providing a constant exit pressure from the nose. Steady flow was provided by a header tank with weir (f), giving a constant head of pressure. Flow rate control was provided by a ball valve (e2) and was measured with an electromagnetic flow meter (c) (Sparling Tigermag FM626). Return flow was pumped (d) back up to the header tank with return and overflow controlled by two ball valves (e1 and 3) to ensure flow over the weir provided a constant head. An in vivo steady expiration flow rate of 32 l/min (realistic expiratory air flow rate when naturally exhaling air from the nasal cavity) was applied in vitro using Reynolds number matching (Tab. 1). The fluid system was seeded with near neutrally buoyant 10 µm hollow silver coated spheres.
SPIV measurements were obtained using a system comprising a 15Hz dual-head 120 mJ Nd:YAG laser (New Wave Solo XT), two digital 2 megapixel CCD cameras (Dantec Flowsense) and collimated optics producing a light sheet approximately 2 mm thick. Laser and camera timings were synchronised using a BNC 565 pulse delay generator. To take advantage of the Lorenz-Mie scatter pattern the left camera was positioned at a small stereo angle of -2.3° and the right camera positioned at 30.4° in forward scatter. A minimum background subtraction technique was applied to remove background noise. The images were then processed with a dynamic histogram filter and Gaussian smoothing with a 3×3 kernel which resulted in a wider correlation peak, improving the sub-pixel fitting and peak locking that is normally associated with under sampled images. The Gaussian filter also acted as a low pass filter and removed high frequency noise such as CCD noise. A zero flow condition was applied to the non-flow regions by way of a masking technique. Mask geometries were obtained from the CT scan of the flow phantom and by extracting the cross-sections at measurement planes analysed using an open source software package (Paraview) (Geoghegan et al. 2012).

Camera calibrations were made at each measurement plane with a self-calibration routine applied to correct for misalignments of the laser sheet and the calibration target plate. Correlation was performed on an initial window size of 64x64pix² using an iterative window refinement technique to 32×32pix². An average overlap factor of 74% was obtained using a grid spacing of 1.2mm. Window deformation and displacement were also applied. The light sheet and CCD cameras were fixed and the reservoir traversed in increments of 2mm to obtain 22 sagittal slices per phantom. Mean flow fields and a reconstructed volume were produced from ensemble correlation averaging 245 image pairs. Time delays ranged from 650-1500 μs through the planes to ensure a maximum particle displacement of about 8 pixels in any one plane.

### 3. Results

Fig. 3 presents the in vivo absolute velocities in the central plane of the two jets exiting the nostrils of the nasal cavity. Velocities below 0.6m/s have been removed from the image as these lay outside the exiting jet
streams. The peak exit velocity varies between the two nostrils with the left and right nostril having a peak exit velocity of 3.47 and 3.96 m/s, respectively.

![Fig. 3 Absolute velocities through the central planes of the jets exiting through the nostrils (orange iso-surface represents the external surface of the nose and upper lip)](image)

This data was used to predict drop trajectory using an in-house computational model (Kabaliuk et al. 2013b). Drop sizes of 0.5 mm and 2 mm were investigated as these are representative of the minimum and maximum diameters expected. Drops are tracked from the nostril exit to a ground plane set 1.7 m below (representative of the average nose height of an adult male). Fig. 4 shows the results for a blood drop with diameter 2 mm exiting the right (a) and left (b) nostril and the trajectory it follows through the jet. The blood density and surface tension was 1056 kg/m$^3$ and 0.062 N/m (at 37°C) respectively. Inertial, gravitational and drag forces (with drop drag coefficient as a function of Re number) acting on a drop in flight were considered. Blood drops were treated as non-distorted spheres. Blood drops were assumed to have zero initial velocity as they left the skin surface and were then in turn carried and accelerated by the stream of air. The trajectory tracking model took the initial conditions from the velocity magnitude and direction at the nostril exit. The droplet displacement was then calculated at time steps of 0.001 s through the flow field accounting for velocity magnitude and direction changes as it moved. After the drop exits the jet boundary depicted in Fig. 3 the computer model tracks the drop until it impacts with the ground. The main forces acting from here are gravitational acceleration and drag. Ambient conditions such as draughts, cross winds etc. have not been incorporated in this current analysis.
Fig. 4 Predicted blood drop trajectory of a 2mm blood drop within the jet exiting from (a) the right nostril and (b) the left nostril

Tab. 2 provides the main results for the 0.5 and 2 mm droplets exiting the left and right nostrils. The absolute velocity at point of impact with the ground from an initial height of 1.7 m for both droplets from both nostrils is comparable to velocities experienced from blood drops formed by passive dripping (<7 m/s), but lower than the drop velocities typical of cast-off (1.5-20 m/s), impact (1.5-30 m/s) and gunshot (15-45 m/s) (Kabaliuk et al. 2013a; Kabaliuk et al. 2013b). The effect of initial velocity difference between the nostrils is shown to have minimal effect on the final impact velocity with the ground plane for both droplet sizes. This implies that the gravitational acceleration after the drops leave the jet has the most influence on impact velocity. The difference in exit velocity does however affect the impact location of the droplet in the ground plane (1.7 m below the nostril) especially for the 0.5 mm drop as shown in Fig. 5. Distance traversed in the ground plane is shown to increase with increased velocity. Increase in drop size from 0.5 mm to 2 mm is shown to decrease the distance traversed in the ground plane. It can also be seen that the drops exiting the nostril actually cross paths. This happens after the drops exit the boundary of the nasal jet (nasal jet boundary ceases 60 mm below the nostril exit) at a distance ~200 mm below the nostril exit.

<table>
<thead>
<tr>
<th>Drop Size (mm)</th>
<th>Left</th>
<th>Right</th>
</tr>
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<tbody>
<tr>
<td>0.5</td>
<td>3.47</td>
<td>3.96</td>
</tr>
<tr>
<td>2.0</td>
<td>4.85</td>
<td>3.96</td>
</tr>
</tbody>
</table>

Tab. 2 0.5mm and 2mm droplet results from the left and right nostrils. The ground plane is located 1.7m below the nostril.
4. Conclusions

This study has shown that for an expiration flow rate of 32 l/min in vivo there is a maximum exit velocity from the nostril of 3.96 m/s. It is shown that exit velocity is geometry dependent with a difference in maximum exit velocity of 0.49 m/s between the left and right nostril. This difference in exit velocity has minimal effect on the impact velocity with the ground plane 1.7 m below the nose. It does however influence impact location. Drop size affects both impact location and impact velocity. Compared to the 2 mm drop, the 0.5 mm drop had a reduced impact velocity, but its impact location in the ground plane was further from the nostril exit. This data can be used in conjunction with bloodstain impact diameters to help ascertain the location of the victim when the crime was committed. Future work following from this will look at stronger expiration velocities that are representative of someone forcing air through their nasal cavity to remove blood. Increasing the number of slices used for PIV investigation will also produce a higher resolution velocity volume increasing the accuracy of the droplet tracking.

5. References

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