

Experimental measurement of breath exit velocity and expired bloodstain patterns produced under different exhalation mechanisms

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Abstract

In an attempt to obtain a deeper understanding of the factors which determine the characteristics of expired bloodstain patterns, the mechanism of formation of airborne droplets was studied. Hot wire anemometry measured air velocity, 25 mm from the lips, for 31 individuals spitting, coughing and blowing. Expired stains were produced by the same mechanisms performed by one individual with different volumes of a synthetic blood substitute in their mouth. The atomization of the liquid at the lips was captured with high speed video, and the resulting stain patterns were captured on paper targets. Peak air velocities varied for blowing (6 to 64 m/s), spitting (1 to 64 m/s), and coughing (1 to 47 m/s), with mean values of 12 m/s (blowing), 7 m/s (spitting) and 4 m/s (coughing). There was a large (55-65%) variation between individuals in air velocity produced, as well as variation between trials for a single individual (25-35%). Spitting and blowing involved similar lip shapes. Blowing had a longer duration of airflow, though it is not the duration but the peak velocity at the beginning of the air motion which appears to control the atomization of blood in the mouth, and thus stain formation. Spitting could project quantities of drops at least 1600 mm. Coughing had a shorter range of near 500 mm, with a few droplets travelling further. All mechanisms could spread drops over an angle > 45°. Spitting was the most effective for projecting drops of blood from the mouth, due to its combination of chest motion and mouth shape producing strong air velocities. No unique method was found of inferring the physical action (spitting, coughing or blowing) from characteristics of the pattern, except possibly distance travelled. Diameter range in expired bloodstains varied from very small (<1 mm) in a dense formation to several mm. No unique method was found of discriminating expired patterns from gunshot or impact patterns on stain shape alone. Only 20% of the expired patterns produced in this study contained identifiable bubble rings or beaded stains.

Keywords: Bloodstain pattern analysis, Forensic Investigation, Expired Blood, Hotwire Anemometry, High Speed Imaging

1 Introduction

There is currently a lack of fundamental understanding of some of the physical processes that produce bloodstain patterns. Doubt over the identification of the mechanism causing a particular bloodstain, e.g. gunshot or expired, can lead to confusion during investigations and trials [1]. Expired blood is defined as blood forced by airflow out of the nose, mouth or a wound [2]. For example coughing up blood, or spitting blood from a cut or rupture in the airway. There are several characteristic features currently used to identify an expired bloodstain pattern including air bubbles, mucus strings linking 'beaded' stains, small droplets and a reduction in the saturation of the red colour of the blood due to mixing with saliva. However, in some cases, none of these features are present and it becomes difficult to positively identify a bloodstain as expired blood. If blood leaves the mouth, it may be possible to confirm saliva is present in the bloodstains by the presence of DNA of oral bacteria [3]. However, if saliva, mucus or air bubbles are absent, it can be difficult to discriminate expired bloodstain patterns from gunshot bloodstains or impact spatter by morphological characteristics [4,5].

There is a limited amount known about the mechanisms that are involved in the production of expired blood and how these affect the stain pattern produced. Donaldson et al. studied the formation of expired patterns using high speed video [5]. They demonstrated that in the process of coughing blood, high-velocity, very small blood droplets were ejected first. These were followed by lower velocity, larger droplets, strands and ligaments of liquid held together in part by saliva. Video images showed the formation of bubble rings and beaded stains, traditional markers for classifying expired patterns. However, the expulsion mechanism, the distance travelled by the blood droplets, and the type of surface the blood was deposited on were all factors determining whether beaded stains were generated.

Previous work [6] has also shown that the air velocity in the vicinity of the lips, when voluntarily coughing, was of the order of 12 m/s, and was the order of 4 m/s when speaking. The geometric mean diameter of saliva droplets from coughing was 13.5 μm and 16.0 μm for speaking. The estimated total number of droplets expelled ranged from 947 – 2085 per cough and 112 – 6720 for speaking. Yang et al. [7] reported the average size of coughed droplets was 0.62-15.9 μm .

Different body motions that can cause expired blood create different patterns. A sneeze can create around 40 000 blood droplets and a cough around 3000 [8], which is due to the difference in velocity in which the droplets leave the mouth and nose. The droplets can travel over 2 m, with outliers reaching 4 m [8]. Blood expired from the back of the mouth creates a pattern with irregular stains and droplet sizes that vary from 1 to 5 mm, while blood that is expired from the front of the mouth creates regular stains and smaller droplets (0.5 to 3 mm) [9]. Little is known about droplets ejected from the nose or by sneezing. Some preliminary investigations of the trajectories of drops expelled from the nose have been performed [10,11].

This present work investigated three mechanisms of expired blood: blowing, coughing, and spitting. The velocity of the air exiting the lips was ascertained using hot wire anemometry. The distribution of expired droplets as they emerged from the mouth was analysed using high speed imaging. Stain patterns were then investigated, to study the range of diameters of the expired droplets and to ascertain whether it is possible to link these diameters to a specific mechanism. The distance expired droplets are projected longitudinally and how far they spread laterally was also investigated.

2 Experimental Methodology

2.1 Expired velocity

Hot wire anemometry was used to measure the velocity of expired air. A very fine wire of magnitude several microns is heated to a temperature above ambient. As air passes over it, the wire temperature reduces; a voltage is then passed to the wire to bring it back to the set temperature. A calibration is performed before the experiment to establish a relationship between probe voltage output and the flow velocity by exposing the probe to a set of known velocities and recording the output velocities.

A Dantec 55P11 single axis uni-directional hot wire probe was connected to a Dantec MiniCTA multichannel Constant Temperature Anemometry system. Calibration was performed using a Dantec 54H10 Hot-Wire Calibrator. The data was post-processed using an in-house program coded in MATLAB. Subjects were placed with their lips 25 mm in front of the probe (Fig. 1) and performed each expiration action 3 times. These actions were voluntary coughing, blowing as hard as possible and spitting. Each data set was recorded at a sample rate of 1000 Hz over a 4 second period. 31 subjects were tested, both male and female, with an age range of 25 - 60. Shouting and wheezing were not investigated as preliminary investigation showed the average velocity of these mechanisms to be too low to propel blood from the mouth. Sneezing was not investigated as it was difficult to induce on command.

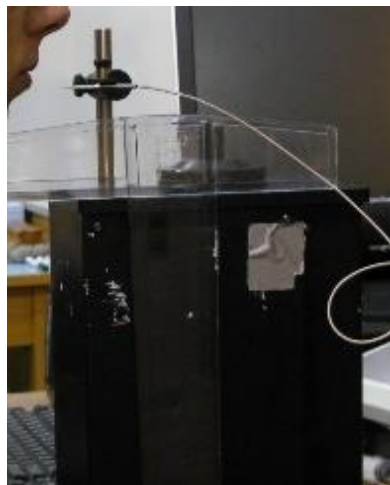


Fig. 1 Experimental set-up with the subjects' lips located 25 mm in front of the hot wire probe

2.2 Expired bloodstain pattern

A single subject performed the same expiration actions with a synthetic blood substitute (SBS) held in his/her mouth. The SBS was a mixture of 35% glycerol, 44.94% water, 20% water based dye and 0.06% xanthan gum [12]. The subject held a volume of 1.5, 3.0 or 5.0 ml in their mouth. To record the expired blood during the event, a Photron SA5 high speed camera (Fig. 2-1) was used, viewing the region external of the mouth in the sagittal plane. The frame rate was 10 000 fps and the shutter speed 1/17 000 s. The experimental set-up was illuminated with 2 LED lights of 10 000 lumen (Fig. 2-3) and 2 LED lights of 8 000 lumen (Fig. 2-5). Three of the lights provided front illumination and one light provided side illumination. Vertical and horizontal sheets of paper were placed in front of the subject to record the bloodstain patterns (Fig. 2-4). The vertical sheet position was increased from 200 mm horizontally from the subject's mouth until insufficient droplets reached it to form a pattern for analysis. The maximum horizontal distance trialled was 1700 mm, limited by the space available in the laboratory. The horizontal sheet was placed 400 mm vertically below the subject's mouth. After the patterns dried, they were photographed with a Canon PowerShot G9 camera.

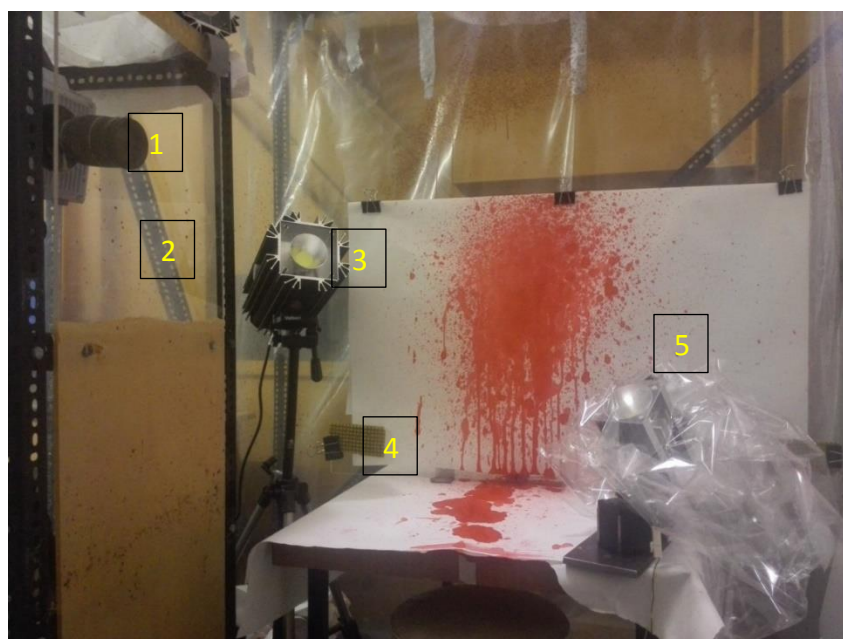


Fig. 2 Set-up for high speed image recording and collection of bloodstain patterns; 1-Photron SA-5 camera, 2-camera protection booth, 3-10 000 lm LED light, 4-paper for collection (horizontal and vertical), 5-8000 lm LED light

3 Results

Expired Velocity Tab. 1 provides the expired air velocity results for blowing, coughing and spitting. The mean and 85th percentile velocities are computed for the entire exhalation mechanism over all subjects (31) and the maximum and minimum peak velocities seen for individuals are also reported. This maximum occurred near the beginning of the air motion for mechanisms over all subjects (Figures 4 to 6). Of the three expired mechanisms tested, the largest maximum air velocity was recorded during blowing and spitting and the largest

mean was for blowing only. The smallest maximum velocity was observed in spitting and the lowest mean velocity was during coughing. Tab. 2 provides the standard deviation in the mean velocity with the average intra-personal deviation and inter-personal deviation. It can be seen that the inter-personal deviation (55-65% of the mean) is around twice that of the intra-personal deviation (25-35% of the mean).

Tab. 1 Velocity measurements obtained using hot wire anemometry. All velocities in m/s

Mechanism	Mean Velocity	85th Percentile	Largest Observed Maximum Velocity	Smallest Observed Maximum Velocity
Blowing	12.14	21.37	64.55	6.00
Spitting	7.46	13.81	64.49	0.74
Coughing	4.10	6.77	46.93	1.24

Tab. 2 Standard deviation on mean velocity measurements. All velocities in m/s

Mechanism	Mean Velocity Intra-personal Standard Deviation	Mean Velocity Inter-personal Standard Deviation
Blowing	3.82	6.54
Spitting	2.03	4.35
Coughing	1.03	2.61

Along with the variation in velocity magnitude, there was also a variation in the velocity temporally between the 3 mechanisms. This is important as acceleration of the air in the mouth affects the atomization of blood into airborne droplets. Fig. 3 to Fig. 5 present representative example plots of velocity against time for all mechanisms, taken from the same subject. For all three mechanisms there was a rapid increase to peak velocity. For spitting (Fig. 4) this was followed by an equally rapid deceleration. For blowing and coughing (Fig. 3 and Fig. 5) the deceleration was more gradual, with a secondary peak in the velocity profile for blowing evident for most subjects.

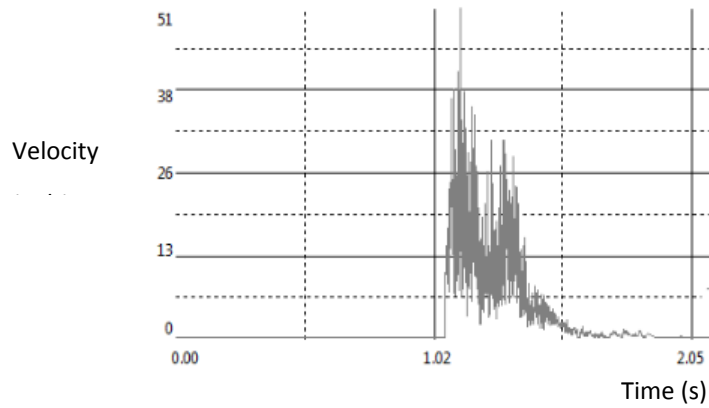


Fig. 3 Typical velocity plot for blowing

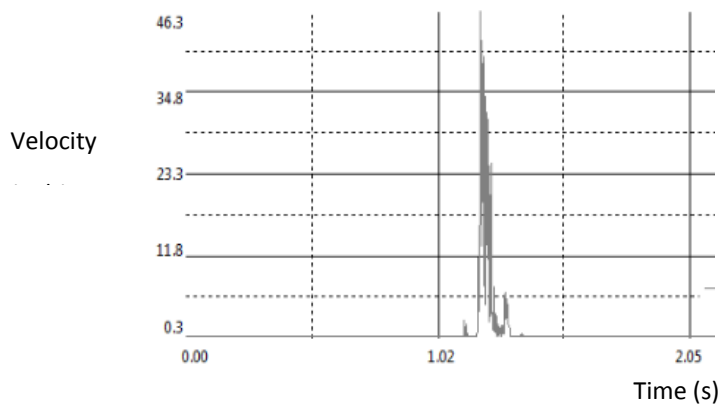


Fig. 4 Typical velocity plot for spitting

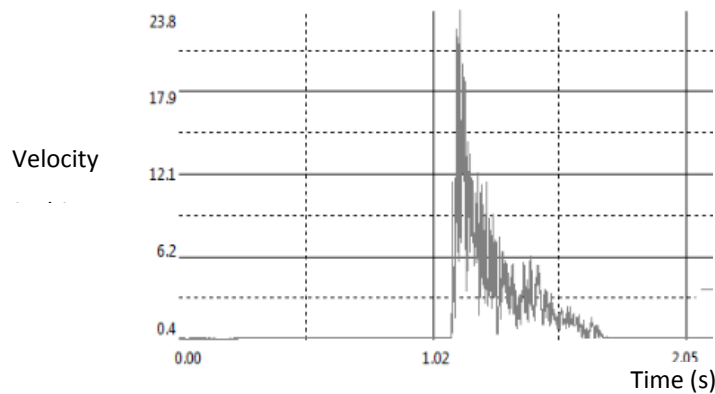


Fig. 5 Typical velocity plot for coughing

3.1 Blood drop formation and projection

Fig. 6 shows sequential images of projected fluid from the mouth when spitting 1 ml of SBS. Initially a jet of fluid was formed which progressed to the formation of a sheet, which in turn broke up into ligaments and from there into droplets. Spitting 3 ml of SBS produced the same sequence as with 1 ml, but more ligaments were created at the lips. Spitting 5 ml of SBS also resulted in the same droplet formation process, but there was a greater variation in droplet size, with many larger droplets. The lateral spread of droplets also increased.

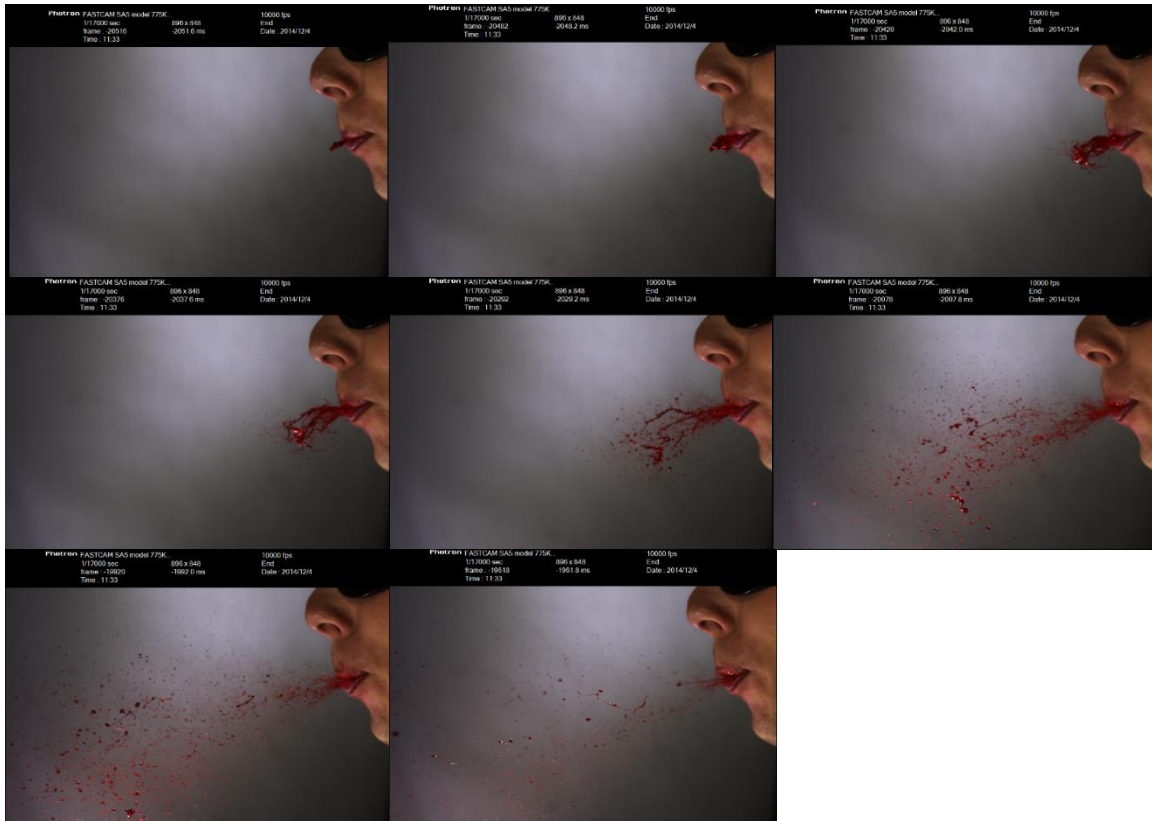


Fig. 6 Sequential high speed images of spitting using 1.5 ml of SBS. The first picture is displayed in the left upper corner and the last in the lower right corner

When expiration of SBS fluid was effected by blowing, the sequence of stages was characterised by the initial formation of an air bubble which gave rise to a sheet of fluid, which then broke up into ligaments and droplets (Fig. 7) in a similar progression observed for spitting. Droplet size was generally consistent and smaller (< 1 mm) than that observed for spitting. For larger volumes of fluid (i.e. 3 and 5 ml) further air bubbles were produced. These broke down into droplets as before. During their flight, droplets dispersed laterally, evenly in both the horizontal and vertical planes.

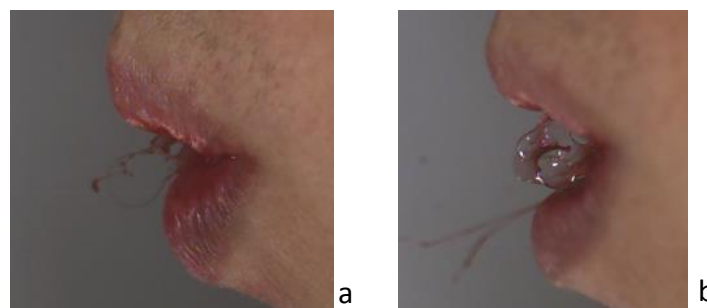


Fig. 7 (a) Bag breakup when blowing 1 ml of SBS with cheeks inflated. (b) Air bubble breaking up into ligaments and droplets when blowing 3 ml of SBS with cheeks inflated

When coughing 1 ml of SBS, initially there were some droplets and small ligaments, which broke up quickly relative to blowing. This was followed by a variety of droplet sizes and long ligaments, which were projected predominantly in a downward direction (Fig. 8). The direction was likely affected by the angle of the head to the vertical. There was minimal spread in the horizontal direction with a short travel distance from the mouth exit to ground impact. When coughing 3 and 5 ml of SBS, some air bubbles were evident. These broke up in the same manner observed for blowing. Coughing produced fewer droplets overall compared with the other mechanisms investigated.



Fig. 8 Coughing 1.5 ml of SBS with an open mouth produced long ligaments which were projected downwards

3.2 Bloodstain Patterns

Fig. 9 shows an example of bloodstain patterns in the vertical and horizontal planes, produced by spitting 1 ml SBS. Most of the large stains on the horizontal sheet had a predominately oval shape in comparison to the large stains on the vertical paper, as expected since to reach the horizontal sheet they had arced downwards under the influence of gravity. There were few elongated stains on the vertical sheet but several in the middle of the horizontal sheet. These differences are likely to be a function of differences in trajectory and impact angle for different drops. A characteristic feature of expired bloodstains was observed on some of the sheets; this feature is known as a beaded stain or mucous strand [4] (Fig. 10). This occurs when blood droplets are linked by a strand of saliva or mucus. However these were found in only 20% of the patterns. If the horizontal and vertical patterns are considered together, 85 % of the stains created by the spitting mechanism were near circular in shape.

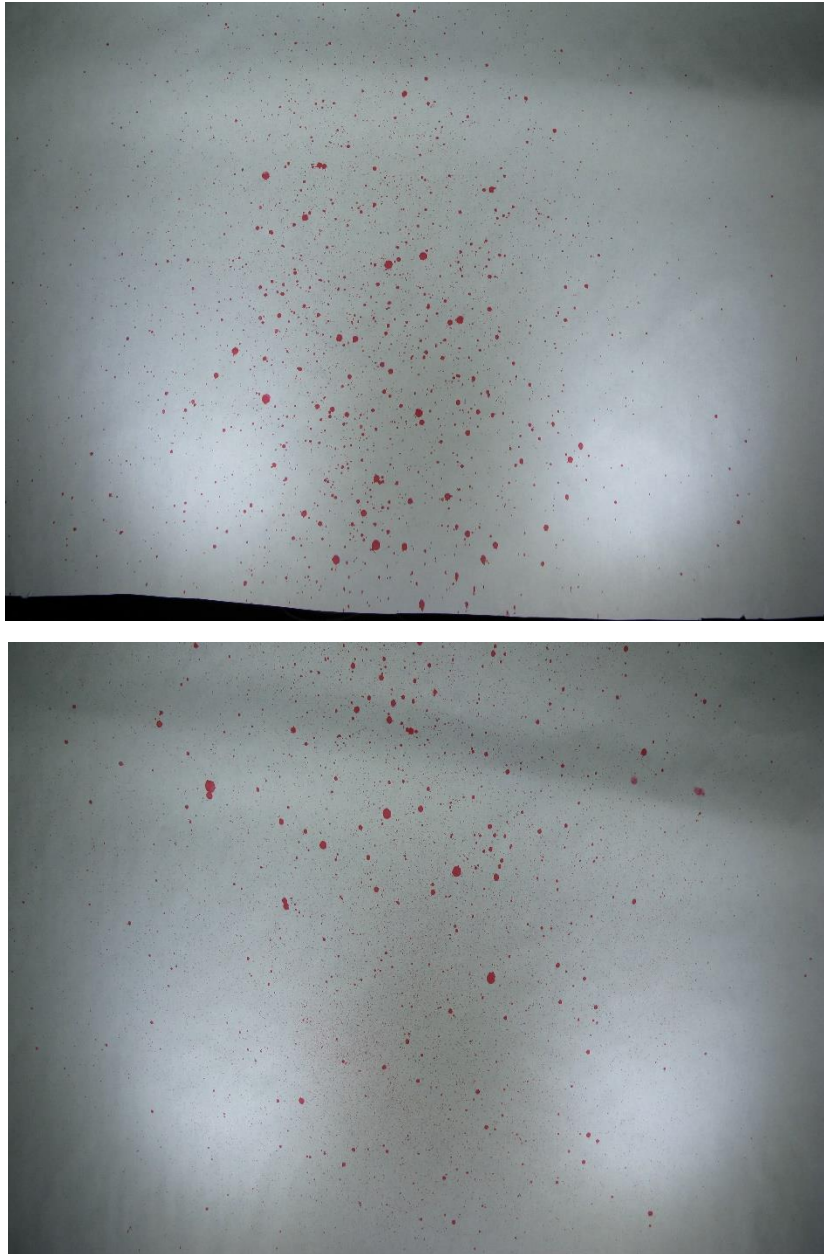


Fig. 9 The pattern that is created by spitting 1 ml of SBS. The patterns shown were captured on a vertical sheet, 1000 mm from the subject (top photo) and a horizontal sheet 1600 mm below the subject's mouth (bottom)



Fig. 10 Example of a “beaded” stain (within red oval) that was observed on a vertical sheet. Three droplets are linked together with a mucous strand

Further example patterns with 3 ml of SBS on a vertical sheet 500 mm from the mouth exit are shown in Fig. 11 to Fig. 13 for blowing, coughing and spitting. Criteria were developed to characterise the patterns produced based on the density of the bloodstains (Tab. 3). A comparison of all three mechanisms for a distance of 500 mm with 1 and 3 ml of SMS is shown in Tab. 4. An investigation of projected distance for 3 ml SBS is shown in Tab. 5. The experimental set up had a geometric constriction where the maximum allowable distance of the vertical sheet was restricted to 1600 mm. For spitting, droplets were observed on both the vertical and horizontal sheets up to this distance, therefore the maximum extent of the pattern could not be determined. For coughing, the maximum distance that the bulk of the droplets were observed to travel was 500 mm, but a few were observed to go further, with 1 observed at 1300 mm. Blowing was similar, with the bulk of the droplets travelling 500 mm. A few small droplets were observed at 1600 mm.



Fig. 11 Pattern on the vertical surface caused by blowing 3 ml of SBS at a 500 mm distance



Fig. 12 Pattern on the vertical surface caused by coughing 3 ml of SBS at a 500 mm distance



Fig. 13 Pattern on the vertical surface caused by spitting 3 ml of SBS at a 500 mm distance

Tab. 3 Criteria for bloodstain pattern classification

	Criteria	Meaning
Lateral spread (breadth) of pattern	Narrow	< 400 mm
	Intermediate	400 to 800 mm
	Wide	> 800 mm
Stain size	Small	< 0.5 mm
	Intermediate	0.5 to 1 mm
	Large	> 1 mm
Stain Count	Low	few droplets
	Intermediate	no mist*, many droplets
	High	mist plus many droplets

*"mist" here means a dense distribution of stains of <1 mm diameter

Tab. 4 Comparison of 1 and 3 ml of SBS for each mechanism on a vertical sheet at 500 mm distance

Mechanism	Volume (ml)	Spread	Size	Count
blowing	1	Intermediate	Small	Low
	3	Intermediate	Small/Intermediate	low
coughing	1	Intermediate	Small/Intermediate	Low
	3	Intermediate	Intermediate/Large	Intermediate
spitting	1	Wide	Small to Large	High
	3	intermediate	All ranges	High

Tab. 5 Investigation of projected distance of 3 ml of SBS for each mechanism

Mechanism	Distance of vertical sheet (mm)	Spread	Size	Count
blowing	1600	wide	small	low
coughing	1100	small	small	3-4 drops
	1300	small	small	1 drop
spitting	1600	wide	Intermediate/large	Low

In the lateral spread of the patterns, there is no clear trend between different mechanisms. All patterns showed a range of sizes of stains and the mechanisms could not be discriminated on stain size, at least with the qualitative assessment of the whole-pattern stain sizes used here. The smaller droplets tended not to appear at longer distances, in coughing and blowing as expected. Due to their higher drag to mass ratio, these drops lose horizontal speed earlier than their larger counterparts. This was not the case for spitting.

The only criteria which clearly discriminated between the mechanisms was the density of the patterns, i.e. the number of stains per unit area, which is clearly greater for spitting than for the other mechanisms at a range of 500 mm.

4 Discussion

Coughing is a reflex action to eject liquids or solids below the soft palate. Broadly, it consists of a rapid motion of the chest wall and diaphragm to compress the lungs, accompanied with a wide open mouth to provide an easy route for the projected material (Fig. 14a). Voluntary and involuntary coughs are similar in mechanism, though may differ in strength.

Spitting is a voluntary action to clear liquid from the mouth (i.e. to the front of the soft palate). It consists of chest movement similar to a cough, with the lips and tongue forming a straight, narrow passage along which the liquid is ejected (Fig. 14b). The tongue is used to close the mouth to build air pressure, then opened to allow the air to accelerate, taking liquid from the mouth with it.

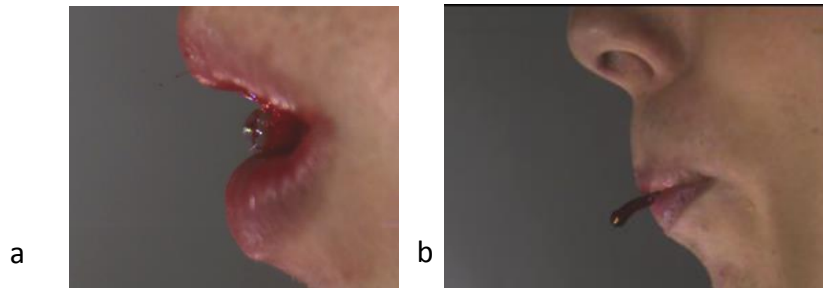


Fig. 14 (a) Position of the mouth and lips when coughing demonstrating the open mouth (b) Position of the mouth and lips when spitting demonstrating their pursed position

Coughing and spitting are instinctive behaviours to be expected of a person with bleeding in their airway. Blowing is a voluntary action included here for comparison. Our test subject showed a lip position in blowing similar to spitting. The functional differences were (1) that the air motion is sustained over a longer period in blowing, with a greater mean velocity (though similar maximum velocity), and (2) the tongue motion is absent in blowing. The soft palate is expected to be closed in all three mechanisms as none of them require air to pass through the nasal cavity. The narrowness of the oral passage in spitting has the role of increasing the velocity of the air as it passes through the mouth, relative to the speed attained in coughing.

Blood, mucus or saliva can be broken into drops by one of three mechanisms:

- Air pressure behind a bolus of liquid which obstructs the airway
- Viscous shear forces as the air passes over liquid lining the airway
- Viscous shear forces as the air passes over liquid adhering to the teeth and lips

A further mechanism is the formation of bubbles on the lips due to the opposing forces of surface tension and air pressure. Such bubbles break up, creating drops (the bag-burst mechanism). This was observed in blowing, but not in the other mechanisms.

While in or near the mouth, the air is moving faster than the drops, and aerodynamic drag accelerates them away from the subject. As the stream of air widens and slows outside the mouth, the drops continue their motion, pulled downwards by gravity and slowed by drag from the relatively still air around them. The smaller the droplet, the greater the ratio of drag force to mass, so the smaller droplets stop and fall vertically earlier than larger drops.

Spitting and blowing have a similar lip shape, though blowing perhaps has a wider open mouth. There is a similar chest movement (subjective) and both have breakup near the lips. They have similar peak air velocities, and similar pattern characteristics, to each other, but these differ from coughing. Coughing has a lower maximum range over which it can project drops. Mouth shape is the key parameter here: spitting and blowing share a similar pursed-lip mouth shape, but the wide mouth in a cough results in lower air velocities at the mouth, hence ejects slower drops which travel shorter distances.

Spitting, being a physical action optimised to eject liquid from the mouth at high speed, produced the densest patterns, and the greatest distances (max. observed 1600 mm,

compared to 500 mm for blowing with minimal outliers at 1600 mm and 500 mm for coughing with minimal outliers at 1100 mm). The air motion in spitting has a shorter duration than blowing, but this has little effect on the results. It is the initial air motion which atomizes the blood and carries it off, and thus controls the stain characteristics. Any of the three mechanisms can result in droplets fanning out laterally over an angle of more than 45°.

In spitting, with sufficient volume of liquid in the mouth, it is possible to eject a jet of liquid and no air. This jet will break up due to shear with surrounding air. No such jet was observed in this study, probably due to small volumes of liquid in the mouth used here. Although spitting is of shorter duration than blowing, it produced as many, or more droplets than blowing, therefore initial velocity is more important than duration.

Long ligaments were observed clinging to the lips in coughing. These did not form, or were shorter, in the other mechanisms, which is probably due to their breaking up into droplets in the higher air velocities. Bubbles were observed forming and breaking on the lips during blowing.

Despite these differences, there was no clear way to determine which mechanism produced which pattern from pattern characteristics alone. All mechanisms investigated produced a similar range of sizes. Only 20% of the patterns contained identifiable bubble rings or beaded stains.

Expired patterns share characteristics with impact or gunshot spatter patterns: dense collections of small stains, with sometimes weak or no indications of directionality. It is of interest to find ways of discriminating between expired patterns and these other types. However the patterns produced in the present work suggest no such technique, at least with the qualitative analyses used. Detailed study of the stain size probability distribution should be investigated to see if there is some way of definitively discriminating between these types of patterns.

There are a number of limitations to this study. The physical processes are inherently variable, even from test to test with the same person: the standard deviation of inter-personal variations was twice that of the intra-personal, but the intra-personal deviation was far from negligible. Physical attributes must be considered when investigating exit velocity. The age, weight, gender or degree of fitness of the participants were not considered in this study. The present data for coughing velocity of a mean of 4.6 m/s differs from that of Chao et al. [6] who measured 11.9 m/s. However, Chao et al.'s result lies with the range we observed, and may have been measured closer to the mouth. The quantity of saliva mixed with the SBS was not controlled. Lastly, the SBS may behave differently to human blood in the mouth, and this may affect the overall pattern with regard to beaded stains and air bubbles in the pattern.

5 Conclusion

Peak air velocities 25 mm from the lips varied from 6 to 64 m/s for blowing, 1 - 64 m/s for spitting, and 1 - 47 m/s for coughing, with mean values of 12 m/s (blowing), 7 m/s (spitting) and 4 m/s (coughing). Spitting and blowing involve similar lip shapes. Blowing has a longer duration of airflow, though the peak velocity at the beginning of the air motion appears to control the atomization of blood in the mouth, and thus stain formation. Spitting can project quantities of drops at least 1600 mm. Coughing generally has a shorter range of near 500 mm, although it may be possible for a few droplets to travel farther. It is noted that Donaldson et al reported the projection of coughed blood drops up to 1750 mm from the mouth of the prone individual [5]. Any of the mechanisms investigated can spread drops over an angle > 45 degrees. Spitting is the most effective for projecting drops of blood from the mouth, due to its combination of chest motion and mouth shape leading to strong air velocities.

No unique method was found of determining the physical action (spitting, coughing or blowing) from characteristics of the pattern, except possibly distance. The range of diameters in expired bloodstains vary from very small drops (< 1 mm) to several millimetres in diameter. No unique method was found of discriminating expired patterns from gunshot or impact patterns on stain shape alone. Only 20% of the expired patterns produced in this study contained identifiable bubble rings or beaded stains.

There is a large (55-65%) variation between individuals in air velocity produced, as well as variation between trials for a single individual (25-35%). Studies with deeper quantitative analysis of the stain pattern characteristics (size and shape probability distribution) are recommended.

6 Acknowledgements

We would like to thank Margaret Dodds for her patient help with the experimental setup and obtaining materials.

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