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Forensic implications of respiratory derived blood spatter distributions

David Denison [a], Alice Porter [b], Matthew Mills [c], Robert C. Schroter [d,*]

[a] Royal Brompton Hospital and National Heart & Lung Institute, Sidney Street, London SW3 6NT, United Kingdom
[b] Cody Technology Park, Ively Park, Farnborough, Hants GU51 4QS, United Kingdom
[c] Nottingham University Hospitals NHS Trust, Queen's Medical Centre, Nottingham NO47 2UH, United Kingdom
[d] Department of Bioengineering, Imperial College London, Exhibition Road, London SW7 2AZ, United Kingdom

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ABSTRACT

The nature of blood aerosols produced in physiological studies of an upright subject expiring small volumes through straws, spitting and mouthing sounds, and a semi-prone subject spitting through a bloody mouth or snorting through a single nasal orifice and by a simplified physical model of the respiratory system were investigated. Each manoeuvre produced many hundreds of droplets of a range of size, the vast majority being less than 1 mm diameter. Droplets under 1 mm dia. travelled over 1 m – much further than could be expected if their flight was ballistic, like that of impact spatter. Respired blood aerosol properties are explained in terms of established mechanics of airflow shear induced aerosol production and the fluid mechanics of exhaled air movement.

1. Introduction

Scenes of violent crime are frequently associated with blood spatter. The patterns of spatter are often attributed to impact spatter, movements of the victim or assailant or cast off from a weapon. However, some blood may have originated from the respiratory system and been distributed by mechanisms that follow different physical processes and the observed distributions may require to be interpreted in a different way. Furthermore, it is possible for such aerosols to be produced some time after death when liquid blood is still present. Founding fathers of pathology, such as Morgagni, Hunter and Virchow knew that, after violent death, often blood did not clot and acted as if it contained a fibrinolysin, although these facts are sometimes overlooked in modern times. This paper analyses these phenomena and discusses their implications.

The objective was to develop a scientifically based understanding of the probable behaviour of airborne respired blood aerosols and whether, or not, the observed amount and distribution of blood spots on clothing of a murder suspect could possibly be the result of respired blood as opposed to impact spattered blood [1–6]. We have been unable to find any clear explanations in the forensic science literature or textbooks which provided a reliable scientifically based description of the processes involved in creating respired blood aerosols from the nose or mouth, or indeed puncture wounds to the chest, of the physical mechanisms underlying their flight characteristics, or how spots of respired blood captured on clothing might be distinguished from, or confused with, spots originating from other sources, particularly impact spatter.

A number of simple human and physical model experiments were undertaken that could be considered to be a reasonable representation of real situations. Studies were performed that could relate to the expulsion of blood from the nose or mouth by the conscious action of a subject, or be caused to occur involuntarily by a subject, alive or dead. It is appreciated that the studies reported here may be of relevance, not only to respired aerosols via the nose or mouth, but, to the production and fate of blood aerosols derived from expiration of air via puncture wounds to the upper airway, trachea or chest [7,8].

In this paper, we consider first the experimental studies we undertook and then relate these to the known physical processes relating to airflow generated aerosols. Whilst the experimental studies demonstrate that exhaled aerosols can potentially travel distances in excess of 1 m, the general question of their motion over greater distances was not explored; this was because the flight characteristics are strongly dependent on the exhalation airflow properties and these are can vary greatly. A definitive study of the motion to greater distances would involve a considerable research project in its own right, beyond the scope of the principal focus of the present work.

* Corresponding author. Tel.: +44 20 7594 5175.
E-mail addresses: d.denison@rbht.nhs.uk (D. Denison), vaporter@qinetiq.com (A. Porter), m.mills@nuh.nhs.uk (M. Mills), r.schroter@imperial.ac.uk (R.C. Schroter).

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2. Experimental studies of respiratory generated blood aerosols

Environmental airflow patterns are a matter to be considered when designing experiments such as those undertaken. The room used was without any form of artificial ventilation and there was no detectable airflow through gaps around the edge of the door, which itself was well removed from the experiment. Thermally induced movement of air up or down walls and the like – though it can never be totally eliminated – was minimal. The air movement speeds of the experiment were very considerably greater than any such perturbing air flows. We were completely satisfied that there were no significant extraneous air movements within the room and any very slow motions had no detectable influence on the experiments. Whilst conducting the experiments, the investigators took great care not to move their arms or legs as additional precaution against the introduction of unwanted air movement. The experiments involved the transport of droplets larger than somewhat smaller than 0.1 mm diameter – that is with settling velocities greater than around 0.25 m s^{-1}.

2.1. Study 1: puffing through short, blood coated straws in an upright posture

Whilst in a seated position, a fully conscious normal human subject (author DD) gently puffed a brief exhalation through a hand-held, short, lightly blood-stained, drinking straw oriented horizontally. The straws were either 5.3 cm or 3.3 cm in length and 6 mm internal diameter.

Before each exhalation, the inner surface of the straw was lightly coated in the subject's own freshly drawn venous blood by dipping, tapping the straw free of all but a thin film of blood on the inside and wiping the straw clean on the outside. The retained volume of blood was estimated, but not measured, to be approx. 0.15 ml or 10 standard drops of blood.

The typical puff volume, of approx. 50 ml, was estimated as follows. The subject inhaled maximally to total lung capacity and then performed the puff repeatedly until he reached residual lung volume; both these standard lung volumes are known for the subject. Dividing this total exhaled volume by the number of puffs gave the average individual puff volume.

The exhaled blood aerosol was captured on a vertical, A1 (841 mm × 594 mm) sized, paper target placed 1 m from the mouth; the paper readily absorbed ink pen writing and also impinging blood droplets. The target provided an interception cone of approx. 30° × 45° from the source. Inspection of the deposition patterns of incident droplets always indicated a focus of spots towards the centre of the target, with virtually none near its edges – strongly suggesting that, in essence, all droplets travelling the notional target distance were captured on it. The spot counts were then determined as described for Study 2.

The experiment was performed 10 times for each size of straw. Each manoeuvre was performed making a quiet effort whilst producing a peak mouth pressure, on average, of less than approx. 25 mm Hg. Mouth pressure measurements were made as explained in Study 2 below.

2.2. Study 2: mouthing sounds and words in the upright seated posture through a bloody mouth

The principal object of this study was to determine whether or not an upright seated subject, when expressing a voiceless 'P' or 'S' with a blood stained mouth, would generate blood spatters on a vertical target placed in front of the face.

The subject introduced 1 ml of his own freshly drawn venous blood into his mouth to coat the mucosal surfaces both in front of, and behind, the teeth, for subsequent exhalation via the mouth. The resulting aerosolised droplets were partially captured by an upright A1 size paper target placed approx. 1 m from the face – as described for Study 1. The exhalation protocol was to voicelessly expel a 'P' (or 'per') causing the lips to part transiently or an 'S' (or 'esse') through pursed lips and closely opposed teeth with the tongue forward close to the palate. Only a small volume of air (approx. 50 ml) was required to produce each sound. The manoeuvres were all performed whilst making a quiet effort with peak mouth pressures typically less than 15 mm Hg, as measured by the method described below. Ten runs, each with a clean mouth and fresh instillation of blood, were conducted for each sound. Following every run, the blood spots on the target were allowed to dry and then each spot visible to the trained naked eye was circled with a pen and counted. Spots of a diameter greater than 1 mm were recorded separately.

In both mouth and nose studies (Studies 2 and 3), the subject spat or blew out the remaining blood. This method, whilst simple, was sufficient to remove all but a thin coating of blood on the tissue lining – such a residual volume of blood was small in comparison to that added for each experiment.

Additionally, mouth pressure was recorded as the subject uttered a series of "PISS off's" (with particular emphasis on the first word) of moderate intensity. These words are built up from lip movements closely resembling the primary forms involved in forming a 'P' or 'S'. The object was to determine if the combined actions reflected those of the fundamentals.

For reasons of blood contamination and to avoid distortion of the mouth with the pressure line, it was considered inappropriate to measure mouth pressure during the actual expiration of blood in Studies 1 and 2. In a separate experiment, performed immediately beforehand, a fast responding, under damped, pressure transducer (1.16 kHz damped natural frequency, with better than 99% amplitude response and 0° phase shift at 100 Hz) was placed in the subject's mouth with the sampling point located just behind the teeth and the pressure recorded whilst performing repeated manoeuvres of the same nature as those used in the blood ejection experiments. The pressure recordings were made for a series of quiet, moderate and vigorous exhalations.

2.3. Study 3: spitting, or nasal snorting, of instilled blood in the semi-prone posture

Studies 1 and 2 involved a subject in an upright posture. It is of interest to know whether or not a subject lying on the ground could produce a respired blood aerosol with similar trajectories and how it might be captured on a target observer some distance from the source.

Experiments were performed by the same subject (author DD) as in Studies 1 and 2, using only moderate effort, either spitting through loosely clenched teeth, or snorting blood through the single right nostril whilst lying stretched out and semi-prone on his left side. Before each exhalation, 2 ml of his own freshly drawn venous blood was instilled into his mouth or nostril; remaining blood was removed before the following run as explained under Study 2. Positioned close to the semi-prone subject was an observer (author MM) acting as a target, kneeling on the left knee with left arm outstretched onto the middle back of the lying subject and fully covered in conventional scene of crime overalls of surface brushed, open weave polypropylene fabric.

Three series of runs, of 5 runs each, were conducted in total.

Series (*A*): the subject exhaled via his right nostril, with the observer kneeling at arms length and square on to the face of the prone body.

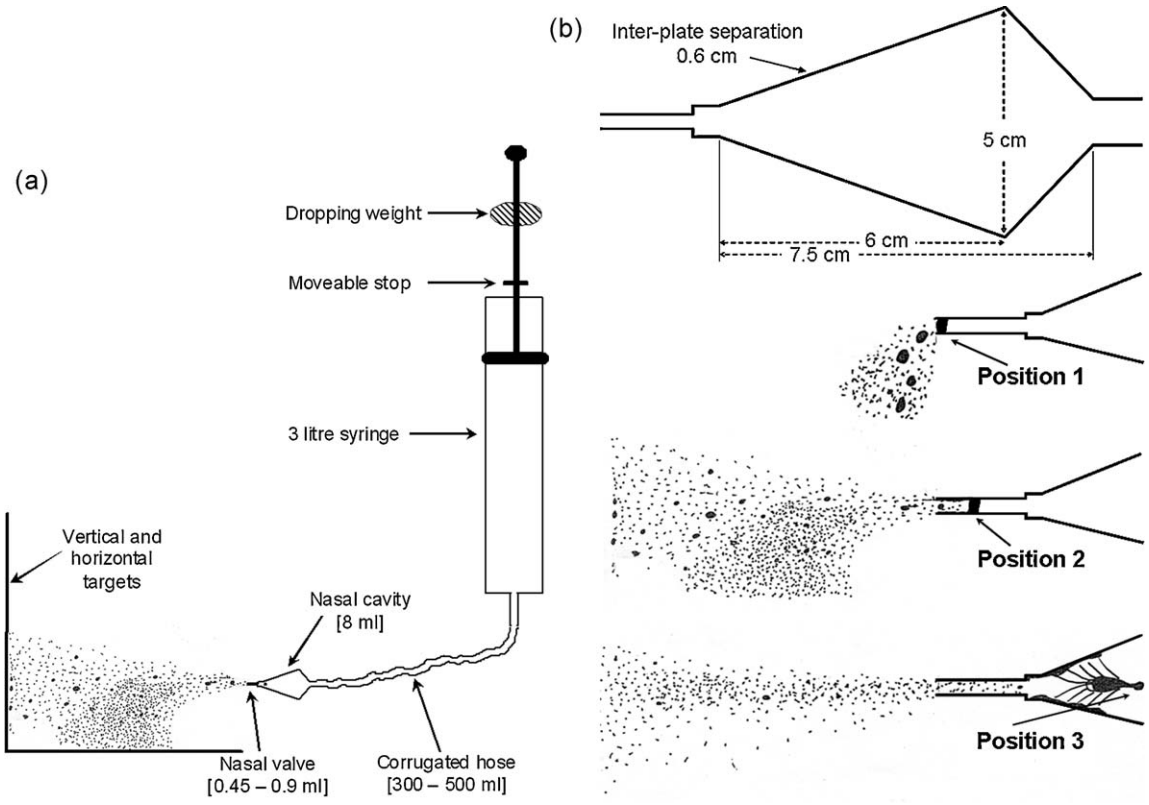

Fig. 1. The physical model used in Study 4. (a) General view and detailed features of the experimental setup and (b) detailed view of the model nasal cavity and valve showing the nature of the resultant aerosol depending on the site of placement of the instilled blood.

Series (*B*): the subject again exhaled via his right nostril, with the observer kneeling at arms length but at the level of the chest of the prone body, and facing and rotated towards the head.
Series (*C*): the subject and observer were placed as in Series A, but the blood was expelled from the mouth.

All participants (the authors of this article) gave their fully informed consent before undertaking each of the above studies (1–3). All runs in Studies 1–3 were video recorded.

2.4. Study 4: use of a simplified physical nose model

The above physiological studies, whilst containing the essential biological relevance, were not entirely controllable or reproducible. Therefore, it was decided to devise an idealised physical nose model and experiment which, though it might potentially be criticised for its extreme simplicity and remoteness from the real biological situation, could be more clearly defined and controlled. The model (Fig. 1a) consisted of a short, 4.5 or 6.0 mm diameter plastic tube representing the nasal valve and more external parts of the nose, connected to a large volume syringe representing the lung via a simplified representation of the nasal cavity (consisting of a flat chamber of two parallel diamond-shaped Perspex plates) and tubing representing the major airways (Fig. 1b).

Three drops of fresh human venous blood (total volume approx. 0.045 ml) were instilled into the nasal valve, or nasal cavity, at one of the three positions shown (Fig. 1b). A controlled, small volume of air was then rapidly expelled through the system by dropping a weight onto the syringe plunger, depressing it in approx. 0.1 s and generating a peak transient pressure within the syringe of less than approx. 15 mm Hg. This exhalation of air always caused an aerosol of blood to be expelled through the nasal tube. Air volumes as small as 62.5 ml were exhaled from the model. This was not the lower limit of volume capable of aerosolising blood, simply it was the smallest volume tested; even this small volume produced copious spots on the targets. The resulting blood droplets were captured on paper surfaces placed horizontally 20 cm beneath the model and vertically at a distance of 50 cm (Fig. 1a). Over 80 individual experiments were performed with the nasal tubes pointing horizontally or inclined upwards at an angle of 30° or 45°.

3. Results

3.1. Puffing through short, blood coated straws in an upright posture

The peak pressures recorded whilst puffing through dry straws (Fig. 2) ranged from approx. 20 to 30 mm Hg and each puff lasted approx. 0.5 s. On average, a 3.3 cm straw generated 244 captured droplets and a 5.3 cm straw generated 298 such droplets (Fig. 3). The spot size ranges were comparable to those found in the study of mouthing sounds (Study 2).

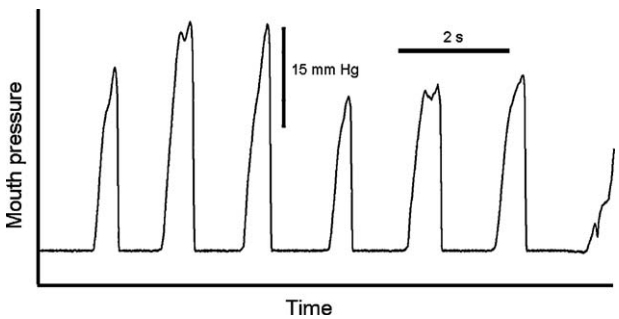

Fig. 2. Typical mouth pressure–time tracing during simulation of puffing on a straw to expel blood as described in the text.

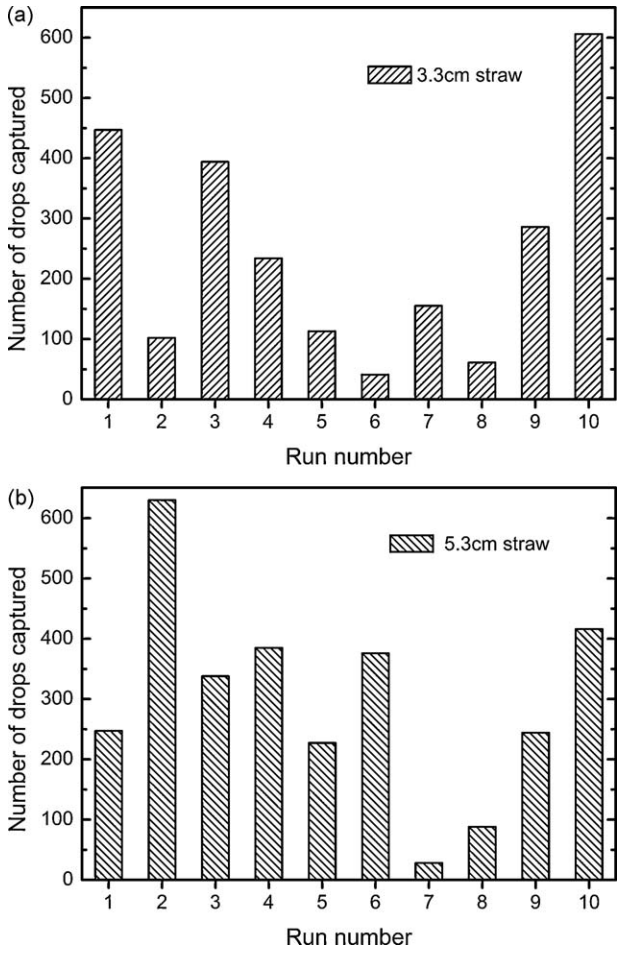

Fig. 3. Number of exhaled droplets of blood expelled from a straw captured on a target placed approx. 1 m horizontally from the mouth. (a) Straw length = 3.3 cm. (b) Straw length = 5.3 cm.

To investigate if the effort, as judged by the video recorded sound level associated with expelling the blood, was a good indicator of the number of droplets captured, the sound level, as judged by ear listening to the video playback, was ranked as high, medium or low for each run. The number of spots in each run, thus ranked for sound level, is given in Fig. 4.

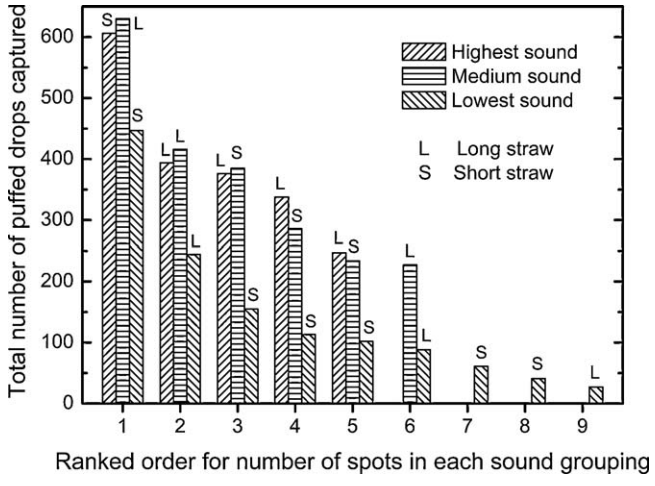

Fig. 4. Ranking of the captured droplet numbers reported in Fig. 3 based on observed sound level linked to the manoeuvre as described in the text.

Table 1
Captured droplet numbers on targets placed 1 m in front of the subject.

Run	Voiceless quiet 'P'		Voiceless quiet 'S'	
	Total no.	No. >1 mm	Total no.	No. >1 mm
1	323	2	1*	0*
2	191	0	550	2
3	83	1	204	0
4	420	0	40	7
5	389	0	199	11
6	292	3	34	2
7	338	8	297	2
8	42	0	1139	6
9	117	0	256	2
10	164	2	377	10

* Note: this run involved a misfire.

3.2. Mouthing sounds and words in the upright seated posture through a bloody mouth

The number of spots of blood captured on the target for each run is shown in Table 1. On average, each 'P' produced 271 captured spots of which 2 were more than 1 mm dia.; each 'S' produced 313 captured spots of which 4 were more than 1 mm dia. For the 10 'P' runs, a total of 2060 spots were recorded including 16 large spots – that is 1 large spot per 128 small spots. For the 'S' runs, there were 43 large spots in a total of 3196 – that is 1 large spot per 73 small spots.

Note that the quiet 'P' sounds, used in the experiments with blood, were associated with rapidly developed peak pressures (Fig. 5) of less than 15 mm Hg; moderate sounds involved peak pressures of around 25 mm Hg and the loudest ones were associated with peak pressures of less than 35 mm Hg. In all cases the manoeuvre was effectively impulsive, lasting for approx. 1 s, and pressure fell rapidly at the end.

The pressure recordings for an 'S' were of a different shape (Fig. 6), with an initial rapid rise to the peak value followed by a progressive fall through the remainder of the manoeuvre as the sound was released and sustained. The tracings to the right of the dotted line in Fig. 6 were representative of the quiet manoeuvres produced in Study 2, involving peak pressures of approx. 10 mm Hg.

In uttering the two words (''PISS off''), a complex pressure waveform was produced (Fig. 7). The initial sounding of a 'P' was associated with a rapid rise in pressure to around 30 mm Hg or more with a subsequent rapid fall off; this was then followed immediately by a second, but less emphatic peak as the 'ISS' was enunciated. The 'off' involved a disconnected small amplitude pressure wave of less than 10 mm Hg for all utterances. The pressures associated with each of the component sounds were similar to those measured for the individual components as noted in Figs. 5 and 6.

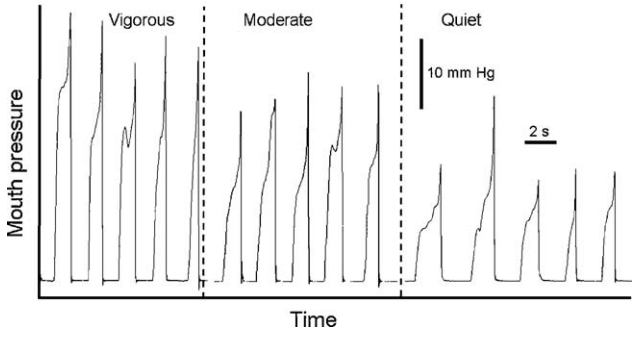

Fig. 5. Mouth pressure recordings for a series of 'P's made with differing intensity.

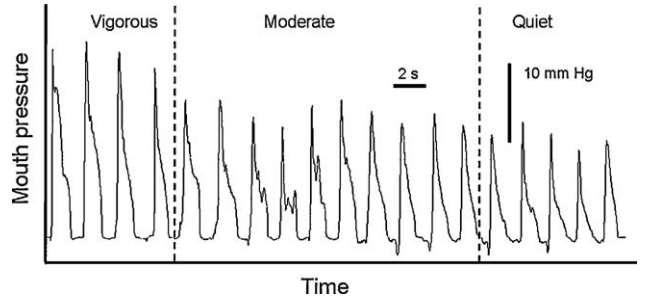

Fig. 6. Mouth pressure recordings for a series of 'S's of varying intensity. The recordings to the right of the dotted line were chosen to mimic the utterances used in the blood spatter experiments described in the text.

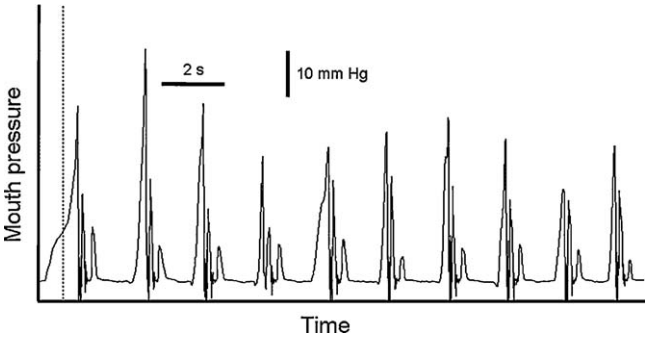

Fig. 7. Mouth pressure recordings for a series of 'PISS off's of varying intensity.

3.3. Spitting, or nasal snorting, of instilled blood in the semi-prone posture

The average total numbers of spots on the overalls for each type of manoeuvre are shown in Fig. 8. In all experiments, the great majority of spots were less, or much less, than 1 mm diameter. Spots were widely distributed on the overalls, but especially to the left arm and chest in the nasal exhalations; they were biased to the hips and thighs and the right leg for the spitting exhalations; this probably reflected differences in the primary direction of the exhaled stream.

In Series A, the bulk of the spots were on the left forearm which appeared to shield the remaining body regions and the left chest took a reasonable density of droplet hits, the remainder of the body was relatively balanced between left and right sided hits. In Series B, the target was moved down from more the face level to chest level and it would appear that the heaviest capture density was left chest to waist. The target had possibly moved more into the firing line of the nasal exhalation, which would be expected to be more in this direction than in Series A. This would also explain the generally higher total counts overall. In Series C, the mouth spit would have been expected to be more directed to the target than was the case for Series A with nasal exhalations. The distribution was relatively balanced left to right.

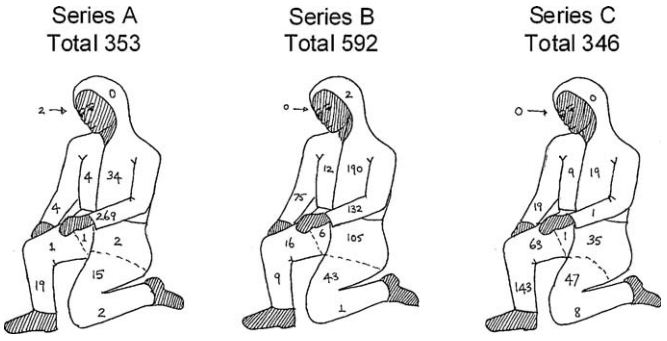

Fig. 8. Exhaled blood spatter patterns on an observer near to a semi-prone subject. Series A: subject exhaled via right nostril, observer kneeling at arms length and square on to face of prone body. Series B: subject exhaled via right nostril, observer kneeling at arms length at chest level of prone body, facing and rotated towards the head. Series C: the two bodies were placed as in Series A, but the blood was exhaled from the mouth.

The deposition distributions in the three series relate reasonably to the relative positioning and means of exhalation. The fact that the nearer body parts often had the highest spot counts did not diminish the explicitly recorded observation that significant numbers of spots were found on the more distant body regions that were in line with the exhalation and not shielded by other parts, more proximal to the source.

3.4. Use of a simplified physical nose model

Drops of blood, placed at the distal tip of the nasal tube (Fig. 1, position 1), tended to be propelled only a short distance on exhalation, producing only a small amount of spray. The moment the exhalation was initiated, a small amount of spray was produced, blood predominantly fell out of the tube to the ground below creating a few splashes several millimetres diameter.

When blood was instilled approx. 1 cm behind the tip (position 2), a different pattern of elimination was observed. The blood film surface was torn by the airflow and the expelled droplets transported along with the exhaled air. In all cases, the vertical target surface intercepted many hundreds of very small droplets, producing spots typically much less than 0.5 mm diameter, many being less than 0.1 mm dia., along with some larger spots. Some spots, mainly larger ones, were also detected on the horizontal target surface. When the nasal tube was inclined upwards, the interception distance was observed to be greater than 1 m for many droplets, both small and large.

When blood was instilled further back within the cavity (position 3), the blood film was again torn by the emerging airflow into droplets of a range of sizes. However, the larger droplets tended to impact on the walls of the cavity upstream of the valve, leaving a stream of smaller droplets to emerge as before, generating a pattern of interception on the vertical target of almost entirely small spots with comparatively few being observed on the horizontal target.

3.5. General

Whilst the diameter of the droplets producing the individual spots could not be measured directly, the captured blood wetted the paper surface and thus spread to cover an area larger than the originating droplet; in consequence, the measured spot sizes were certainly larger than the droplet diameter.

The typical speed of the exhaled air package varied considerably between the four studies on the basis of the estimated exhaled volumes and periods. The transient maximum air speed in the model studies could have been as high as 20 m s^{-1}. This may be compared with an estimated speed of around 3.5 m s^{-1} in the straw puffing study or about 2 m s^{-1} in the upright spitting and prone mouth exhalations, assuming a pursed lip and teeth configuration providing an orifice of about 3 cm × 0.1 cm. The prone nasal study, assuming an orifice similar to the straws, would generate a typical exhaled air speed nearer 2 m s^{-1}.

In a separate unpublished study, we filmed initial blood droplet ejection speeds produced by aggressive hitting of a hand-held heavy metal bar on a bloody surface designed to model the human skull. The study design and choice of weapon were determined by the wish to replicate a possible alternative scenario causing the

observed pattern of blood spatter on the clothing of the murder suspect [1–5]. The initial velocity of this impact spatter blood was measured (from frame by frame video analysis) to be in the region of 4 m s^{-1}. For purposes of comparison as developed below in the present paper, it has been assumed that an aerosol may be expelled by either impact or respiratory processes at an initial speed of 5 m s^{-1}.

4. Underlying physical processes

4.1. Formation of blood aerosols

The formation of liquid droplet sprays, or aerosols, by the action of air moving over a liquid surface is exceedingly commonplace. Sprays formed by the passage of wind over water surfaces, cosmetics sprays, therapeutic inhaled liquid aerosols, atomisation of fuel in combustion engines and boilers, industrial paint and agricultural sprays are all examples of the process, as are respiratory derived water aerosols resulting from sneezing, coughing or spitting. In all cases, the airflow entrains drops with a spectrum of diameters. In most industrial situations, great care is taken to attempt to control the size range and concentration of the resultant droplets.

Despite the ubiquitous nature and importance of such aerosols, the underlying physical processes determining their formation are not well understood other than at the descriptive level. Mathematical modelling of the process is still very much a challenge at the detailed level (e.g. Ref. [9]) and beyond the scope of this paper. One of the principal objectives of much research endeavour is to explain the mechanics of water aerosol formation by the action of airflow, however the same physical laws and processes apply to the formation of blood aerosols when resulting from the action of the flow of air over a blood wetted surface. The relevant physical properties of blood at 37 °C (particularly the bulk viscosity {plasma: 1.2 mN s m^{-2}, blood 3–4 mN s m^{-2}} [10]; density: 1.05×10^3 kg m^{-3} [11]; surface tension: 0.055–0.075 N m^{-1} [11]) are not identical to water, but they are functionally similar and the aerosolisation processes of blood can be considered in the same way. The two phase nature of blood at the microscopic level would not be expected to be of significance as it is at a much smaller scale than that of the process of interest, just as is the case with spray production of multiphase liquids such as paint or solid–liquid slurries.

The formation of a spray of water or blood can be thought of in a number of stages, all of which occur very rapidly in a time of the order of a millisecond. The whole process is driven by the shearing force at the interface of the air flowing over the stationary or relatively slow moving liquid surface [9,12,13]. The wall shear force causes an instability in the liquid surface that is manifested first as ripples in the surface; these develop rapidly into deeper waves that over-crest and give rise to ligaments of liquid that are pulled out by the friction of the airstream. The wind generation of waves on the surface of a pond is an easily recognisable example of the process.

As a ligament stretches, it thins and ultimately breaks up into several blobs which are rapidly pulled into spherical droplets of a range of diameters, but with a statistically reproducible size distribution [9,14] which is strongly dependent on the liquid density, viscosity and surface tension, but less so on air velocity. The droplet size distribution is likely to range from larger than 1 mm to less than 0.05 mm in diameter.

4.2. Flight characteristics of respiratory blood aerosols

Gentle oral or nasal exhalation of a small puff, or package, of air on a very cold day provide simple examples of both the considerable distance a quiet breath will travel into a still air environment and of the retention of very small water droplets derived from condensation of the water vapour in the breath within the vortex structure of the exhalate. Even at higher exhaled flow rates, when the structure is not visually as evident because of the turbulence in the motion, the same transport mechanisms apply. Were the very small droplets not carried by the air in this way, they would come to rest within a few centimetres of the mouth.

The flight characteristics of aerosols such as respired blood, entrained in the airflow by which they are generated, are fundamentally different from those whose ballistic flight is caused by impact or cast off. The entrained aerosol blood droplets, particularly smaller ones (less than approx. 0.5 mm diameter), will travel generally with the air in which they are contained [15,16]. The droplet flight paths cannot be predicted in the same way as droplets – such as impact spatter – ejected into still air.

Because the respired blood droplets are contained within the exhaled breath, they too travel as a slowly diverging package and will propagate forwards even through stationary air [15,16]; the aerosol does not fan out and radiate as widely as it may do for an impact derived spray of blood. Furthermore, the initial ejection direction of the respired blood will depend strongly on the nature and orientation of the conduit (e.g. a normally shaped, or distorted, mouth, nose or wound) near its outlet and the direction of the emanating airflow in which it is entrained.

The process by which the package of air will fan out and increase in width progressively with distance is destroyed when the vortex closely approaches and impinges on a solid wall or obstruction in its path; the forward motion is stopped abruptly and the vortex destroyed. The entrained droplets are ejected sideways to spread over a wider area than that of the unperturbed vortex [15] so that the area over which droplets will be captured by the wall is also wider than the air package by which they were delivered to the obstruction.

4.3. Initial acceleration of droplets within the mouth, nose or a short straw

Once droplets are stripped off the blood surface, they are pulled along by the airflow as the result of the viscous drag forces due to the local difference in speed between the droplet and the carrier air. As they travel along the conduit, they are accelerated towards the speed of the air, but may not reach it. The extent to which a droplet will reach the carrier air speed within the conduit will depend on the droplet size, or inertia, and may be estimated on the basis of Stokes' Law for drag on a sphere [17].

If air is travelling within a 6 mm dia. tube at a speed of 10 m s^{-1}, droplets of the size range of interest will increase their velocity from rest as shown in Fig. 9 as they travel along the conduit. Only the very smallest 0.01 mm droplets reach the carrier velocity within a short distance of some 5 mm along the tube; a 0.01 mm droplet's behaviour would therefore be essentially uninfluenced by the length of the tube. Larger droplets, even as small as 0.05 mm dia., continually accelerate along the length of a 30 mm long tube, though will never reach the carrier air speed; as the differential between droplet and air speeds reduces, so does the level of the drag force causing the acceleration. A 0.1 mm droplet will only have reached less than 40% of the carrier speed by the time it has travelled 30 mm and a 1.0 mm dia. droplet would attain less than 10% of the air speed. Droplet acceleration will continue for some distance beyond the conduit exit whilst the local air velocity is high; once speeds match, the droplets become entrained within the package and are transported within it.

The acceleration process for small droplets within a conduit that is far wider than the droplet is viscosity dependent and has no

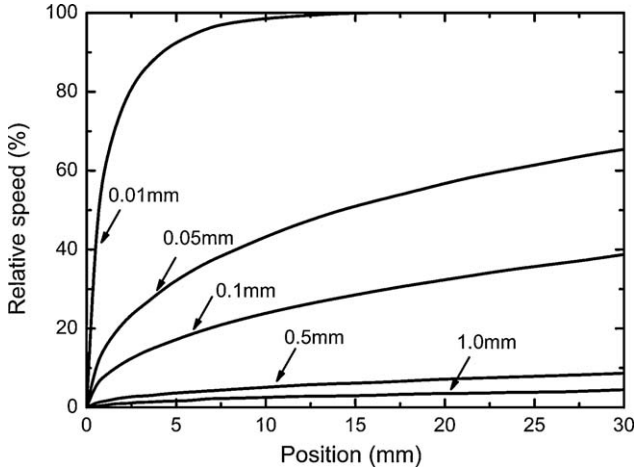

Fig. 9. Droplet velocity as a function of distance along a 30 mm long, 6 mm dia. tube when accelerated by airflow with a characteristic speed of 10 m s^{-1}.

relationship to the mechanism by which a peashooter or gun barrel operates. The latter devices work by the action of high pressure on the rear of the projectile acting to accelerate it, pushing it along the tube without significant leakage of the propellant gas or air around the sides of the projectile. The acceleration is continually high throughout the length of the barrel, not diminishing significantly as the projectile increases speed.

4.4. The flight characteristics of spherical drops fired into still air

A droplet or particle allowed to fall in still air will speed up from rest in its downward motion due to the force of gravity causing it to accelerate. However, as the droplet moves through the surrounding air, it will experience viscous drag forces acting to slow it down in the manner described by Stokes' Law. Ultimately, it will reach a mathematically predictable constant vertical terminal settling velocity when the drag and gravitational forces balance.

Very small droplets (0.01 mm diameter, typical of a water fog) have an exceedingly small terminal settling velocity (3×10^{-3} m s^{-1}). For progressively larger droplets of increasing mass to surface area ratio, the terminal velocity increases rapidly with size. Droplets of 0.1 mm dia. (typical of a mist), whilst still strongly dominated by the viscous effects of the air, have a settling velocity of the order of 0.3 m s^{-1}. 1.0 mm drops (small rain drops) have a far higher settling velocity of around 30 m s^{-1}; their aerodynamic behaviour is somewhat different from the smaller ones and they are less vulnerable to any environmental airflow disturbances.

The flight characteristics of spherical drops fired impulsively into still air, rather than simply dropped, also may be calculated using well established mathematical ballistic descriptions of their behaviour. The flight behaviour of spherical, unit density, droplets of a range of size fired into still air at an initial velocity of 5 m s^{-1} at angles of 0°, 30° or 45° to the horizontal, assuming the viscous drag force to be described by the classical Stokes' Law are illustrated in Fig. 10a and b. The initial trajectory of 45° was chosen as this is very close to the ideal angle to achieve the maximum horizontal flight distance of a large drop; greater or lesser angles produce flight paths of shorter range measured along the horizontal at the level of firing.

1.0 mm dia. droplets follow a near parabolic trajectory (Fig. 10a) because their motion is dominated by the effects of gravity; they can cover significant horizontal ranges and also reach significant heights. Their behaviour is near to that of the traditional cricket ball flight.

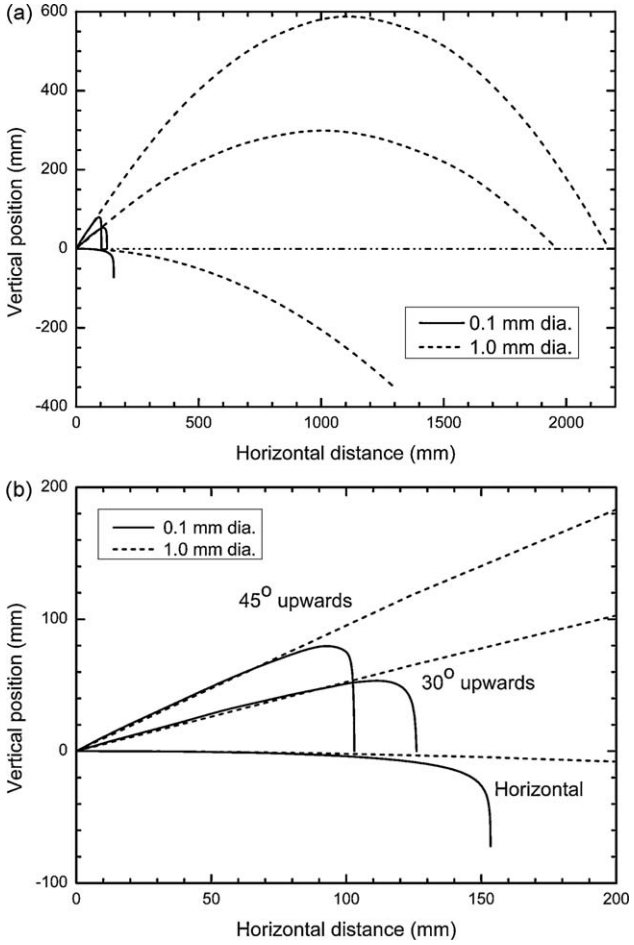

Fig. 10. (a) Computed trajectories of 1.0 and 0.1 mm dia. drops ejected at 5 m s^{-1} into still air horizontally and upward at angles of 30° and 45°. (b) Expanded scale showing detailed trajectories of 0.1 and 1 mm droplets for the same conditions as in (a).

Droplets less than approx. 0.5 mm dia. behave very differently from larger ones. Their flight is progressively attenuated because of the dominant viscous effects and they travel only very small distances from the point of ejection. As these droplets reach the limit of their forward motion, they settle out reaching their terminal velocity in due course. The horizontal distance reached by 0.1 mm drops, when fired at 5 m s^{-1}, is around 10–12 cm whilst the vertical travel is less than 8 cm (Fig. 10b). Furthermore, apparently paradoxically, small droplets fired upwards at 30° travel further horizontally than those at 45°; this is because they are not being slowed down as much by drag due to their vertical motion.

The level of drag exerted on a spherical particle with increasing velocity appropriately scaled as the Reynolds number (Re) is very well known (see for example Ref. [17]). Stokes' Law adequately defines the viscous drag on spherical drops or particles travelling at speeds where the appropriate velocity scaling, or Re, is less than approx. 1. As Re increases, so the drag law changes through the intermediate region (for Re in the range of approx. 1–10^3) to Newton's Law for Re in the range 10^3–10^5 and the drag is more than would be expected on the basis of Stokes' Law, with the droplet being slowed down more quickly and in a shorter distance than indicated in the trajectories in Fig. 10a. In the circumstances of present interest, drops may be travelling at speeds governed by differing laws at various stages of their flight (thus, for 1.0 mm drops projected at an initial velocity of 5 m s^{-1}, the initial Re = ~350; at the same ejection speed, 0.1 mm drops would have

an Re = ~35). However, in all cases the highest Re would be at the moment of ejection; it would fall rapidly thereafter as the droplet slowed down and the motion would obey Stokes' Law for the large majority of its flight.

The assumption of the universal applicability of Stokes' Law is an acceptable approach for the calculations above; they would overestimate, to a small extent, the distance a droplet would travel when fired into still air at a specified initial velocity and vertical angle. For present purposes, it is important not to underestimate the distance a drop could travel in still air. By using Stokes' Law, it is possible to indicate safely that such droplets could not travel as far as observed experimentally in our expired blood studies, had they simply been "fired" into still air by the expiratory process.

5. Discussion

5.1. Fluidity of blood

Care was taken in all the above experimental studies to ensure that the subject's own fresh blood had not clotted detectably and thereby lost some of its fluidity. Blood was used within 5 min of being drawn, and in the interim period was held in the sterile plastic syringe into which it had been collected, without the addition of any anticoagulant. Therefore, it is reasonable to assume that the physical properties of the blood used in these experiments were essentially that of blood expelled from a living subject whilst bleeding. The relevant properties of importance in relation to aerosol formation would have been essentially normal and not functionally dissimilar to those of water.

The nature of the process by which respired blood is formed relies fundamentally upon its fluidity and significant clotting would be very liable to diminish the ability to produce aerosols containing a dispersion of fine droplets. Expiration would be expected to shear off less fluid, clotted, structures that were much larger in size than those observed and the ligament formation and stretching processes would be compromised with a loss of the ability to create any significant quantity of fine aerosol.

Indeed, it has been generally assumed in the past, by those analysing blood spatter, that any observed spatter patterns that might be respired aerosols will have been produced during life, or within a very short period of time after death. This judgement is based on the presumed inevitable rapid clotting of the blood which will have prevented formation of such an aerosol within a short time after death. The lack of detection of clotted blood in spatter patterns of possibly respired blood has been taken as self-supporting evidence for this truism. Conclusions based on this assumption of the timing of the observed patterns have been used to eliminate or implicate suspects of crimes. However, it is well known that blood may, in certain circumstances, retain its fluidity for very protracted periods of many hours or even days.

Whilst for a long time it was widely accepted by most that the deceased human may contain blood that is entirely fluid, there was some dispute as to the truth of this until the work of Morawitz in 1906, as quoted by Mole [18], demonstrated that fluid cadaver blood was free of fibrinogen and frequently contained a fibrinolysin. Earlier, Virchow in 1871 [as quoted in Ref. [18]], had noted the very important point that capillary blood in the cadaver is always fluid and incoagulable. Lenggenhager in 1938 [as quoted in Ref. [18]], was perhaps the first to ask why the blood in a cadaver is never found completely coagulated.

Mole [18] investigated carefully the conditions which determine the fluidity of blood in human cadavers as seen at autopsy as well as the properties of the fibrinolysin found in the blood, particularly of subjects whose death was sudden and trauma related. Based on a study of 61 randomly investigated autopsies, he demonstrated that the more sudden the death, the more likely was the blood to be found completely fluid. Virtually all the subjects showing fibinolytic activity could be described as suffering from shock or cardiovascular collapse whilst still alive; the fibrinolysin appeared in the blood after death in those who were healthy before the incident causing their death. He deduced that the fibrinolysin might be produced by the vascular endothelium, consistent with the earlier observation of Virchow regarding the incoagulability of blood in the capillaries.

The work of Mole was subsequently confirmed and extended by that of Takeichi et al. [19] in the first of a series of three papers on the fluidity of cadaveric blood after sudden death. Amongst other findings of forensic interest, they demonstrated that fibrinolysis is activated by physical exercise or by vasoactive agents such as adrenaline or noradrenaline [19] and the onset of the short lasting activation process (of less than 1 min) is very rapid, occurring within 1 min of secretion of the agent into the blood [20].

It is therefore unsafe to presume the existence of a respired blood aerosol in relation to a crime can only be explained on the basis of its production during life or immediately after death. Furthermore, the spatter may have originated from any source of a bloody nature through, or over which, air has been blown with sufficient force at the air–liquid interface. Thus, for instance, it could be from stab wounds to the chest or a cut windpipe as well as from a normal or distorted mouth or nose.

5.2. Behaviour of experimentally generated respired aerosols

Whilst the experimental studies reported in this paper are of a very simple nature, they demonstrate collectively the qualitative nature of respired blood aerosols and their behaviour and enable more objective interpretation of their relevance and significance to the evaluation of a crime scene. The explanations for the properties of such blood aerosols and their spatter properties are in agreement with the known behaviour of other aerosols produced in different situations.

The purposes of the various studies were not identical in all respects. A number of pertinent questions were addressed. Each study stands in its own right; it was not considered appropriate to use identical conditions for all experiments.

The straw experiments (Study 1) demonstrated just how little blood was needed and how small a surface could be coated with blood to generate a significant amount of aerosol. The small volume of air required was also demonstrated. The more physiological study (Study 2), involving upright spitting of voiceless sounds demonstrated again the small volume of air and effort required together with the link to speech. The semi-prone study (Study 3) was inevitably different from Studies 1 and 2 because of posture and the fact that the nose was also used. The other studies demonstrated the ability of the fine blood droplets to travel a significant distance, Study 3 demonstrated similar behaviour for both sources of aerosol. The use of the same target was not considered an essential requirement for this experiment – instead use of a human target was considered helpful for explicitly demonstrating how a person might capture such a respired aerosol.

Study 4 demonstrated in a simple unquestionably mechanical environment that similar blood aerosols could be created for comparable, if not identical, situations. Using the mechanical model it was possible to explicitly alter key variables. There could be no question as to the small pressures or short timescales involved, nor about the small volume of air required. These variables had to be estimated in all the human-based experiments.

The use of different instilled blood volumes was not considered a major problem because it was clear that not all blood was aerosolised in each experiment. It was considered most important to ensure that enough blood was placed in the region likely to

generate the aerosol. It is reasonable to note that the volume of blood instilled varied only between 1 and 2 ml. It is reasonable to consider this to be a small amount of blood compared to what might be expected in any real life situation.

5.2.1. Mechanism of formation

Study 4 demonstrated, in a very controlled manner, that a very small quantity of blood wetting a surface may be aerosolised by a small volume of air forced to flow over it. The equipment used is a realistic representation of the critical elements of the respiratory system if one is interested in the formation of aerosols in the vicinity of either the frontal aspects of the nose or possibly the clenched mouth or pursed lips. The detailed nature of the geometry and flow conditions far upstream of the site of the blood are not important other than to produce a controllable pulse of a known volume of air.

The production of respiration derived aerosols is not dependent on high overall driving pressures being generated by the respiratory system. Furthermore, it is not a prerequisite for generating such an aerosol that large breaths, or sustained flows, are involved in its production. Rather, the process of forming the droplets is extremely rapid (of the order of 1 ms [9,13]). The levels of shear force caused locally by the airflow at the liquid surface required to break down the blood liquid surface can be generated by short expiratory-like puffs of air.

5.2.2. Size characteristics of aerosol droplets

One of the important properties of respired blood aerosols, as demonstrated throughout our work, is the smallness of their droplet size The aerosol contains a spectrum of droplet size, from very small (less than 0.1 mm dia.) to over 1 mm dia. The experiments did not permit exact measurements of the diameters of the aerosol droplets which, on landing, would have spread to some extent through the matrix of the paper targets, which were capable of wetting by blood or water. The measured spot diameter would therefore be greater than that of the related droplet. Consequently, the measurement approach throughout this work has been to conservatively over-estimate that parent droplet size.

Only the most general nature of the droplet size distribution was deduced in our studies. The spot detection and counting method was limited by the ability of a trained observer to detect spots with the naked eye, or a low power hand lens. As a general result, only spots larger than approx. 0.1 mm were detected, and some of them may have been missed; as a result the spot counts resulting from the smallest droplets could have been somewhat under-estimated. The larger spots, say over 1 mm diameter, were far more easily detected and not missed in the counting process.

Throughout the present work, it would be reasonable to interpret results as indicating that the observed pattern of spatter spot numbers and sizes relate to aerosols of a size distribution including droplets maybe smaller than 0.1 mm, with few larger than 1 mm diameter. The distribution of actual droplet numbers, or number density, would, in reality, be more biased towards the small size than as measured. Furthermore the targets used would not have captured all the droplets that were generated, some would have dropped out of the airstream without reaching the target.

The general, sub-millimetre size characteristic of the respired blood aerosols is consistent with the size distributions reported elsewhere [9] for water aerosols generated by shearing of air over a liquid surface.

The distance travelled by the aerosol droplets (both large and very small) can exceed 1 m. Whilst there might be an argument that could explain the travel of the largest droplets over such a distance based on ballistic theory, this is not the case for the smaller droplets. Their travel can only be explained on the basis of the assisted transport via the exhaled breath, or puff of air, as explained above.

5.2.3. Volume of blood required to produce a respiratory aerosol

Studies 1 and 4 also amply demonstrated the large number of spots that can be generated from a very small sample of blood placed within the nasal tube. If the whole of the instilled blood (0.045 ml) used in any run in Study 4 were fragmented into droplets of 1 mm diameter, it would produce over 90 droplets; were it fragmented into the smaller size of 0.1 mm, it would produce over 90,000 droplets. The message is very clear, it requires only a very small amount indeed of blood to be aerosolised for it to be seen as a spatter pattern of a very considerable number of spots. It is easy for an observer to be seduced into thinking of it as a sizeable amount of blood from which the spots were formed. The amount of blood from which the aerosol is formed demonstrates that it is not necessary for a considerable surface to be copiously covered in blood, the spray can come from a very small area of blood-wetted surface.

5.2.4. Comparison of the aerosols produced in the various studies

All the experiments using a human subject (Studies 1–3), were inevitably less controlled in some ways than was the case with the physical model. However, use of a compliant subject enabled the introduction of manoeuvres that would have been difficult to simulate in the physical model. The human studies also overcame any possible criticism that the real human anatomy and physiology were inconsistent with the geometric and dynamic needs for aerosol production in the situations of interest.

In essence, Study 1 (involving puffing through a straw) replicated the physical model (Study 4) and demonstrated without question that a human subject, when exhaling a short puff of air of a similar volume to the smallest investigated in Study 4, could produce an expirated blood aerosol. Air blown over a thinly blood-coated inner surface of a short straw, that perhaps mimicked a bloody nose or a constricted mouth, can produce an aerosol that travels over 1 m horizontally. The speed and duration of the airflow could be relatively small (speed $\sim$3.5 m s^{-1}; duration $\sim$0.5 s) and little pressure was required, indicating that it did not require much effort to undertake the manoeuvre.

The resulting spatter pattern on the distant target (Study 1) was comprised of spots of a similar size distribution and number to those obtained in Study 4, again indicating the similarity of the two manoeuvres. Whilst some larger spots were detected on the target, numerous small diameter spots were present too and their presence could not be predicted on the basis of ballistics. The size characteristics of the captured spatter reflected those of air generated sprays in other situations [9,14].

The ranked results presented in Fig. 4 demonstrate that, although there was a small difference in the average number of captured spots between the two straw lengths, length is not a major influence on the amount of aerosol captured. Furthermore, expirations of all sound levels were capable of producing copious aerosol droplets. The highest and medium sounds clearly produced the greater, fairly similar, numbers of captured spots, the low sound level produced fewer spots. If sound level is an indicator of effort, this implies that even the runs of low effort were able to produce a considerable number of droplets, but the perceived effort, in the opinion of an onlooker, would not be a simple reliable indicator of the likely amount of a respired aerosol generated or captured on a person close by.

Study 2, using scenarios more representative of real life, demonstrated that the spatter pattern is as to be expected on the basis of the simpler, or more primitive models. Blood exhaled through the small mouth orifices used to produce the sounds was readily aerosolised. Again, only very small, short exhalations were

required to produce a respiratory aerosol comprising many small droplets of considerably less than 1 mm dia., that could travel a considerable distance. In both cases there were very many more small droplets (less than 1 mm dia.) than large ones, demonstrating the ability to produce aerosols that may be categorised as essentially of small droplet size.

Interestingly, although the 'P' and 'S' involved similar peak pressures, the 'S' produced somewhat more captured droplets. The mouth and lip movements are not the same in the two manoeuvres, their close juxtaposition is more sustained in the 'S' and it is likely that this is the reason for the greater production of droplets.

The pressure–time profiles of a 'P' and 'S' were clearly independently detectable when expressing the composite 'piss off' and this suggests that the amount of aerosol produced by vocalising such expressions in stressful circumstances may be significantly increased beyond that of either of the individual fundamentals.

For a semi-prone subject (Study 3), the observed blood spots appeared not to be of a noticeably different nature from those observed on the paper targets in the other studies. Despite the different posture of the subject, the relevant expiratory flow manoeuvre could be performed and the resulting blood aerosol behaved as expected, with a similar size distribution to that found in the other studies. The distribution of the captured spots on the overalls of the observer was as expected allowing for partial shielding of the torso by the outstretched arm and kneeling posture.

5.2.5. Respiratory aerosol transport mechanism

The expected initial speed of expulsion of the aerosol (estimated at approx. 1–4 m s^{-1}) in all three human studies was far too low to expect any but the larger droplets (approx. 1 mm dia.) to reach the targets, were they to depend on conventional ballistic propulsive travel. The capture of the smaller droplets by the targets required them to be transported by some other mechanism. An initial speed of 5 m s^{-1} would enable larger droplets to travel ballistically well in excess of the distance required to hit any of the targets used in these experiments, however, such an initial speed would not carry the smaller droplets, of less than 1 mm dia., this far – as demonstrated in Fig. 10a and b.

Both rudimentary observation of commonplace actions such as puffing out an expiratory bolus of air on a cold winter's day and more exacting studies [15] indicate the clear plausibility of the entrainment of the aerosolised blood in the puff of air. This structured bolus of air is capable of travelling considerable distances, greater than that to the targets used in the present studies, and of transporting smaller blood droplets within it.

Interestingly, because the transport mechanism favours retention of the smaller droplets, it can act as a filtration mechanism by which the larger droplets are able to be progressively lost, or indeed not be caught up significantly in the formation of the aerosol. The smaller ones are retained within a relatively slowly expanding package and not dispersed in a wide arc as might possibly be expected if they were to behave like impact spatter. The way in which individual droplets, once formed, are accelerated by the viscous drag of the air flowing past them favours the smaller droplets reaching the carrier airspeed and being transported by the bolus; the larger droplets will not be as strongly accelerated towards this speed and thus possess even less inertia to propel them to the target. This separation mechanism explains the observation in Study 4 that large droplets were found on the horizontal target placed near the nasal tip, whereas the small droplets were transported to the distant vertical target.

Although the process was not investigated in the present experiments, Hunt et al. [15] point out that the forward motion of an exhaled vortical structure is vulnerable to being deflected in its forward path by extraneous sideways air movements such as environmental air currents; such currents could significantly deflect, but, neither destroy the vortex nor prevent, its transport of entrained aerosol droplets. The manner in which an exhaled structured package of air breaks down suddenly by lateral dispersion on close approach to an obstacle in its path explains the observed spread of captured blood spots on the various targets used and why many spots are to be found high up on a target well above a horizontal line from the point of origin.

The fact that respiratory aerosols are prone to filtering out larger droplets as they are transported is liable to lead to a misinterpretation of captured spatter patterns some distance from their origin because of the apparently small mean size and distribution. Such patterns may be classified as small droplet size distributions and thus be confused inadvertently with impact spatter patterns resulting from higher speed processes.

5.2.6. Contamination of blood droplets

Dilution of blood with saliva, air bubbles within droplets, or frothing of blood, were not evident in any of the studies reported. Neither the straw studies (Study 1) nor the physical model studies (Study 4) involved blood being introduced at sites at risk of saliva contamination and the aerosolisation process was not liable to cause air entrainment within droplets. As would be expected, all observed spots showed no signs of such effects.

The upright spitting and semi-prone studies (Studies 2 and 3) involved blood placed in the mouth – in front and immediately behind the teeth, or in the nostril and vestibule of the nose. In all these studies, the subject did not cause contamination of the blood with his saliva, nor was frothing evident. Again, no spots captured on the targets showed signs of either saliva contamination or evidence of encapsulated air bubbles. It might be expected that contamination with saliva or the entrapment of air bubbles in the droplets would be more likely if the exhaled blood were derived from deeper into the mouth, or the lung airways as is possibly more common in cases of respiratory derived spatter.

Dilution of blood with saliva would not significantly alter the physical properties of the liquid and thus the production and flight characteristics of contaminated or uncontaminated blood droplets would not be expected to be discernibly different. Entrapment of air within droplets would make individual droplets less dense, they would then have a smaller effective aerodynamic diameter and be more likely to behave as the experimentally observed smaller droplets in the present work.

5.2.7. Comparison of small volume exhalation droplet transport with coughs and sneezes

Whilst the objective of the current work was to investigate small exhalations of air and blood aerosols, it is potentially instructive to compare their behaviour with what might be expected for large expired volume phenomena, particularly coughing and sneezing, which are associated with a relatively explosive expulsion of air and liquid droplets on release of a high pressure constriction in the respiratory tract. Interestingly, despite the relevance of coughing and sneezing to the spread of respiratory airborne infection, still little is known about the fluid mechanics of these processes [21].

Coughing is commonly associated with respiratory infection, chronic bronchitis and asthma. The process is able to help clear the central airways as far peripherally as about the seventh generation of bronchial airway and is thus a potentially potent process by which airborne infectious material can be spread. Cough is a reflex mechanism which may be triggered by irritation of the larynx,

bronchial airway irritability or local obstruction or other stimuli. Coughing starts with a brief rapid inhalation, usually greater than the normal breath volume followed by closure of the glottis for 200 ms or so which is accompanied by a rapid rise in upstream pressure to around 75 mm Hg through diaphragmatic and expiratory muscle contraction. On opening the glottis, an explosive expiration is produced predominantly through the open mouth.

The initial phase of a cough is a horizontal plume of air from the semi-open mouth [21,22]. The peak velocity of airflow, reached within approx. 0.1 s, depends upon the effort involved and has been reported to range from 8 [23] to 13 m s^{-1} [24]. The second phase is strongly associated with a nasal exhalation aimed more downwards. The final phase is again predominantly oral with the total process lasting typically less than 1 s. These phases are associated with a rapidly diminishing driving pressure and resultant flow rate of air. Typical volumes of air exhaled in a single cough range from over 1 l to 2 l [24], but depend on effort and the initial inhalation volume.

Sneezing is a reflex action caused by irritation of the wall of the nasal cavity. As with a cough, a sneeze follows an unusually large inhalation and brief closure of the respiratory tract – mainly at the level of the soft palate and uvula rather than the larynx – coupled with a rapid build up of upstream pressure. When this is released, a very high flow rate of air passes through both the mouth and nose helping to clear foreign matter. There appear to be no authoritative estimates of the exhaled volumes and flow rates via each orifice, but speeds of exhalation are reported to be of the order of 50–100 m s^{-1} [25].

Because of the large volume of air exhaled by either a cough or sneeze, they are able potentially to expel droplets that originate from deeper into the respiratory tract than is possible for the small volume manoeuvres with which this paper is principally concerned. Whilst both large volume actions exhale air from the alveolar regions of the lung, how far down into the depths of the bronchial tree airborne droplets may be formed cannot be predicted readily. Droplet creation will depend upon the transient local level of the wall shear force achieved in the peripheral generations of bronchi. It is known that the level of wall shear force can be high in the more central bronchial airways, but that it diminishes rapidly towards the periphery of the airway tree (on either inhalation or exhalation) because of the architecture and expanding cross-sectional area of the bifurcating bronchial system [26,27]. Whilst coughing is conventionally believed to be helpful in clearing airways of obstructions as peripherally as approximately the seventh to tenth generations, information is not available regarding the source of exhaled droplets. The same holds true for sneezing.

Whilst both coughing and sneezing are capable of generating aerosols of copious numbers of aqueous droplets by shearing the mucosal walls of the respiratory tract, the two processes appear to generate somewhat differing numbers. A cough is said typically to generate around 3000 droplets [28] whilst a sneeze may be associated with 40,000 droplets [29].

The typical size ranges of droplets are not available though it is recognised that individual droplets, in either a cough or sneeze, are strongly liable to surface evaporation during their lifespan and thus can become very small – of the order of 0.005–0.012 mm dia. It is also recognised that the exhaled aerosol is highly heterogeneous in size, containing many much larger droplets; such larger droplets are known not to travel through the surrounding air with the same characteristics as the smaller ones and tend to drop out of the exhaled air envelope under the influence of gravity [23,30].

Small volume exhalations, such as those considered in this paper, establish a turbulent starting vortex ring which propagates as described above transporting the entrained aerosol droplets away from the source. The same process is to be found when exhaling a larger and longer lasting breath [31], but with an attendant jet of exhaled air in its wake. The impulsive starting vortex, leading the turbulent jet has been shown to travel significant distances whilst most of the burden of entrained droplets is retained in the leading vortex and the body of the jet. Owing to the dynamic nature of the jet formation, with potentially changing nose and mouth orifice orientation and shape changes during the process, the emerging jet expands with distance in a similar, but not identical, way to that classically described for turbulent jets emerging into a quiescent environment [17]. The smaller diameter droplets are transported very effectively within the envelope of the vortex and jet and thus are able to achieve long distances from the source, well beyond that predicted on the basis of ballistic flight. The mathematical description of the droplet transport process is discussed in some detail by Hunt et al. [15].

6. Conclusions

Based on the extensive and novel experimental studies undertaken in relation to the Siôn Jenkins case, it is clear that blood can be aerosolised by air being forced through conduits whose surfaces are bloody. This mechanism of droplet production is different from the processes of impact and cast off. Such respired blood could be produced by a person exhaling through a bloody mouth or nose. Similarly, lung air venting through a bloody chest wound, or elsewhere, could also produce a respired aerosol.

Blood aerosols can be produced by the exhalation of very small volumes, certainly less than 60 ml, of air through a single nostril or narrowed jaws, teeth and lips. They can also be produced by use of a simple physical model system and by puffing through straws. The associated physical exertion and speed of exhalation, whilst not measured accurately, were demonstrably not very high.

The respired aerosols produced in the experiments reported contained hundreds to thousands of blood droplets of an estimated range of diameters from less than 0.1 mm to more than 1 mm. The total amount of blood from which these droplets derived would itself have been very small.

The general similarity of the droplet size ranges in the various experiments undertaken in different postures and exhaling through a variety of conduits was noted. The observed size range would appear to be characteristic of aerosols generated by the shear force of air over a bloody surface.

Both large and small droplets in the exhaled blood aerosol are able to travel significant distances of the order of 1 m or more. Particularly, the typical observed distances travelled by small droplets, transported in the exhaled breath, are considerably greater than would be possible if they were propelled ballistically through still air. Consequently, the captured deposition patterns of respiratory derived aerosols may be confused with other patterns caused by airborne blood from other origins.

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Conflict of interest statement

DD acted as an expert witness to the Courts in the R v Siôn Jenkins trials [2–5]. RCS acted in a similar capacity in trials [3–5,7,8]. Fees were received from the Courts and the Legal Services Commission.

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