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3D bloodstain pattern analysis: Ballistic reconstruction of the trajectories of blood drops and determination of the centres of origin of the bloodstains

Ursula Buck [a,b,*], Beat Kneubuehl [a], Silvio Näther [a,b], Nicola Albertini [c], Lars Schmidt [d], Michael Thali [a]

[a] University of Bern, Institute of Forensic Medicine, Buehlstrasse 20, 3012 Bern, Switzerland
[b] State Police Bern, Accident Service, Schermenweg 9, 3001 Bern, Switzerland
[c] State Police Vaud, Forensic Service, Centre Blécherette, 1014 Lausanne, Switzerland
[d] State Police Ticino, Forensic Service, Viale Franscini 7, 6500 Bellinzona, Switzerland

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ABSTRACT

For crime scene investigation in cases of homicide, the pattern of bloodstains at the incident site is of critical importance. The morphology of the bloodstain pattern serves to determine the approximate blood source locations, the minimum number of blows and the positioning of the victim.

In the present work, the benefits of the three-dimensional bloodstain pattern analysis, including the ballistic approximation of the trajectories of the blood drops, will be demonstrated using two illustrative cases.

The crime scenes were documented in 3D, using the non-contact methods digital photogrammetry, tachymetry and laser scanning. Accurate, true-to-scale 3D models of the crime scenes, including the bloodstain pattern and the traces, were created. For the determination of the areas of origin of the bloodstain pattern, the trajectories of up to 200 well-defined bloodstains were analysed in CAD and photogrammetry software. The ballistic determination of the trajectories was performed using ballistics software.

The advantages of this method are the short preparation time on site, the non-contact measurement of the bloodstains and the high accuracy of the bloodstain analysis. It should be expected that this method delivers accurate results regarding the number and position of the areas of origin of bloodstains, in particular the vertical component is determined more precisely than using conventional methods. In both cases relevant forensic conclusions regarding the course of events were enabled by the ballistic bloodstain pattern analysis.

1. Introduction

For crime scene investigation in cases of homicide or criminal assault, the pattern of bloodstains at the incident site is of critical importance. The morphology of the bloodstain pattern serves to determine the approximate blood source locations in forensic crime reconstructions.

For this approach, up to now, various methods of bloodstain pattern analysis have been used [1–5]. The stringing method, the tangent method and the virtual stringing method are by the use of computer software [6,7]. In the stringing method, the trajectories of the blood drops are simplified as straight lines. The impact directions of the bloodstains are reconstructed by affixing strings at the position of the bloodstains and pulling them away from the surface, on which the bloodstain has spilt, in the approximate impact direction. This direction is determined by the directionality and relation of the length and width of the elliptical shaped bloodstain. The approximate location of the blood source is estimated to be where the majority of strings intersect. In the tangent method, the flight path of the blood drop is assumed to be a hypotenuse of a right-angled triangle. This method is valid only for fast-moving blood drops with a flat trajectory before impacting on the surface. Due to unknown curvatures of the individual flight path, unknown systematic errors in the horizontal value of the location of the blood source may occur [2]. The virtual stringing method is equivalent to the traditional stringing method transposed onto the computer.

In the present work, a ballistic analysis to approximate the trajectories of the blood drops, for the determination of the centres of origin of the bloodstains, is evaluated.

2. Materials and methods

In the following two cases a three-dimensional bloodstain pattern analysis was performed.

* Corresponding author at: University of Bern, Institute of Forensic Medicine, IRM – Buehlstrasse 20, CH-3012 Bern, Switzerland. Tel.: +41 31 631 84 12; fax: +41 31 631 38 33.
E-mail address: ursula.buck@irm.unibe.ch (U. Buck).

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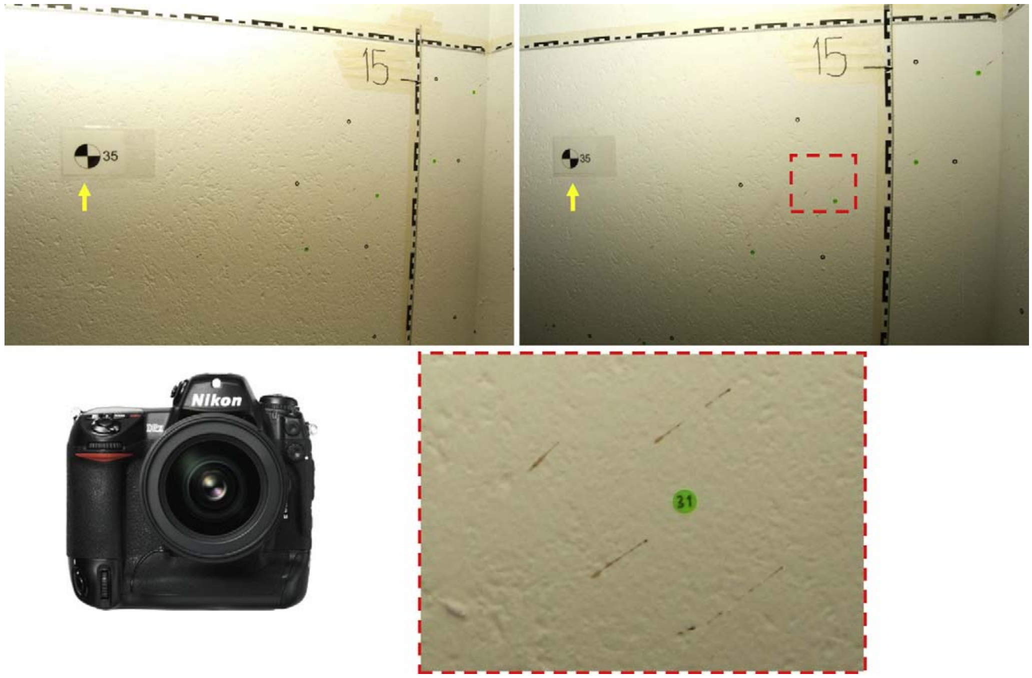

Fig. 1. Photogrammetric documentation of the bloodstain pattern, using a digital single-lens reflex camera. Reference points are stuck on the wall to support the fusion of the photogrammetric analysis with the tachymetry or laser scanning measurements (yellow arrows). One photogrammetric image pair consists of two images taken from the left and the right-side of the same part of the object. A blown up detail of the right image (red rectangle) shows well-defined bloodstains.

2.1. Case 1

In a homicide case a woman was attacked by her husband with blunt force to the head. She was found in a lying position in the bed of their bedroom and died 2 h later in hospital due to the fatal head injuries. DNA analysis suggested a hammer as the likely injury-inflicting instrument. At the scene of the crime a bloodstain pattern was found on the ground, wall, ceiling and furniture, as well as bloodstained quilt and mattress. The pattern on the ground likely resulted from the work of emergency personnel and as such was no considered further.

The question as to whether the woman was attacked in a sitting or a lying position was addressed by the bloodstain pattern analysis.

2.2. Case 2

A decomposing male corpse was found in a lying position on the living room floor in an apartment. The approximate time of death was 2 weeks previously. The autopsy findings included several patterned injuries on the head and three patterned bone injuries on the skullcap, caused by blunt force.

Bloodstains in the living room were located on the carpet, walls, ceiling and furniture. Bloodstains were also located on the dinette and on the kitchen. A 3D match analysis of the cranial bone injuries and the presumed injury-causing tools located within the apartment concluded that a pistol was used to hit the victim (http://www.virtopsy.com) [8,9].

The majority of the attacks occurred in the living room. In order to define other locations in which the victim was physically attacked, a bloodstain pattern analysis was performed.

2.3. Basic information about the creation of blood spatter

Blood drops, which fly through the air, are from the ballistic point of view always spherical [10]. Some oscillation at the beginning of flight can be neglected [11]. In blood drops produced by blunt force, the diameter of the drops is generally between 1 and 3 mm [2,4]. When a drop with a defined angle of less than 90° strikes a flat surface, an elliptical bloodstain arises.

The flight distance of blood drops depends on the starting velocity and the cross-section stress (relation of mass to the cross-section plane). The (initially unknown) starting velocity cannot overstep a value of something around 10 m/s. This value can be derived by two physical laws, the ballistic air drag and the surface tension of the blood drop. When a drop exceeds a certain velocity the pressure due to the air drag overcomes the internal drop pressure due to the surface tension and the drop bursts into smaller ones. This threshold velocity depends on the size of the blood drop and lies between about 10 m/s (for bigger drops, 6 mm) and 17 m/s (for small drops, 2 mm). Blood drops moving on a parabolic like trajectory must have a quite smaller velocity because the burst of blood drops due to a too high velocity happen only in the immediate vicinity of the source.

The mass of the blood drop can be estimated approximately by the diameter (width of the bloodstain) and the density of blood. This estimation is precise enough because a 10% error in the mass leads to a distance error of less than 1.5%. When the drop obliquely impacts on the surface, the minor axis of the elliptical bloodstain can be determined as the diameter of the drop [3]. The influence of air resistance is a known factor because of the spherical shape of the blood drop.

2.4. 3D documentation of the bloodstain pattern and the scene of crime

For the 3D documentation of the scene of crime [12], including the bloodstain pattern and the traces, we employed a digital close-range photogrammetry system (Elcovision 10, PMSAG, St. Margreten, Switzerland) and a tachymeter (Leica TPS 405), or a laser scanner (Leica ScanStation 2, Leica Geosystems, Gladherbrück, Switzerland) (http://www. leica-geosystems.com).

The digital close-range photogrammetry is a 3D optical coordinate measuring system that is used to determine precise 3D coordinates of discrete points of an object. Therefore, several pairs of images are taken from different angles so that every object point is visible in a photogrammetric image pair. A pair consists of two images taken from the left and the right-side of the same part of the object (Fig. 1). For taking the photographs, a calibrated digital reflex camera Fuji S3 with a focal length of 17 and 30 mm is used.

The tachymeter (other term: total station) is a type of theodolite with an electro-optical laser distance-measuring unit. It is used to determine the terrestrial or spatial position of points by measuring angles and distances between them. With the tachymeter, distances are measured to a reflector or directly to an object and the measurements are drawn automatically in 3D CAD software (AutoCAD 2006 software, Autodesk, San Rafael, USA with plug-in ElTheo, PMSAG, St. Margreten, Switzerland) on a connected laptop at the scene (Fig. 2a).

The 3D laser scanner sends laser beams to the investigation environment whilst rotating with a horizontal field of view of up to 360° and a vertical field of view of up to 310°. The scanner measures the distances and angles from the reflected laser beams and computes the 3D coordinates of all reflected objects to generate a 3D point cloud consisting of millions of points (Fig. 2b). These point clouds represent the crime scene in detail and with high accuracy.

The photogrammetric analysis is combined with the scanned data or with the measurements taken by tachymetry, using reference targets.

With the point clouds of the laser scans or the tachymetry measurements, a true to scale drawing of the traces and the crime scene in 3D is created using the AutoCAD 2006 software.

The shapes of the bloodstains are measured and drawn by photogrammetric analysis using the software Elcovision 10 integrated in the AutoCAD platform. The result is an accurate, true-to-scale 3D model of the crime scene including the bloodstain pattern and the traces represented in 2D situation plans and 3D views (Figs. 3 and 4).

Fig. 2. 3D documentation of the crime scene. (a) Tachymeter on a tripod, used to measure discrete object points. (b) The laser scanner can be placed on a tripod or directly on the ground, as shown in this figure. With the "Leica ScanStation 2", the scanning of one room from two or three different stations takes about 30 min.

2.5. Determination of the directions and angles of impact and the centres of origin

The direction of impact and the vertical flight path plane in the room can be determined by using the angle of impact and the directionality of the bloodstain. The angle of impact of the blood drop, which is formed between the direction of the blood drop and the flat surface that is struck, is calculated based on the relationship between the length of the major and minor axes of the elliptical bloodstain. In addition, the directionality of the bloodstain is ascertained from the longitudinal axis of the ellipse and the direction in which the spin points (Fig. 5). In this manner, the directionality and length of the major and minor axes of the ellipse of all well-defined bloodstains on walls, ceilings and on furniture that has not been removed are accurately measured. Based on these measurements, the assumed straight line for the flight path of the bloodstains is calculated and drawn in the 3D model of the crime scene using CAD software. To reduce errors in determinating impact angles, only bloodstains with low impact angles have been considered in the analysis [13–15].

In a top view of the impact directions of the bloodstains, convergence areas are shown in groups of straight lines in high concentration, which intersect one another. These convergence areas are possible centres of origin for the corresponding bloodstains. In a side view, the height of the centres of origin is determined by finding the average intersections of only the straight lines of the bloodstains which occur at a short distance from the blood source location.

The photogrammetry software Elcovision 10 in combination with the AutoCAD software performs an automatic calculation of all measured ellipses and draws the calculated straight lines of the directions of impact of the bloodstains in the 3D model of the crime scene. Then the centres of origin are determined automatically by software, or manually, based on the produced 3D model.

2.6. Ballistic determination of the trajectory of the blood spatter

For the determination of the blood source location, the trajectories of bloodstains, which are of a short distance from the blood drop origin, can be assumed as straight lines.

In cases of longer distance, a difference in the vertical component between the spatial direction of impact (in the vertical plane) and the expected centre of origin arises, because of the curved trajectory of the drop. In these cases a ballistic determination of the trajectory of a blood drop is performed in order to show whether these bloodstains arise from the determined centre of origin or from a different origin.

Fig. 3. The analysis of the photogrammetric data and the tachymetry measurements resulted in an accurate, true-to-scale 3D model of the crime scene including the bloodstain pattern and the traces (case 1).

Fig. 4. A detailed view of the 3D model of the crime scene displays the bloodstain pattern on the wall and the furniture (case 1).

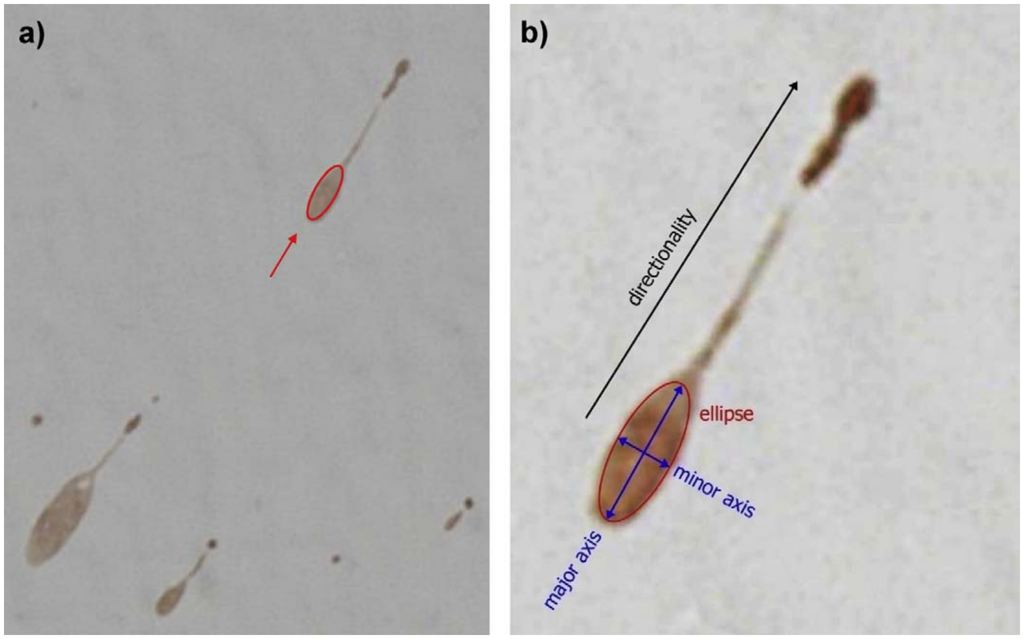

Fig. 5. The geometry of a well-defined blood spatter. Based on the directionality (a) and the length of the major and minor axes of the elliptical bloodstain (b), the impact direction of the blood drop and the vertical flight path plane in the room are calculated.

For the ballistic reconstruction of the blood drop trajectory of a specific bloodstain we apply the well-known technique of ballistic trajectory reconstruction based on the impact condition, as is used in forensic ballistic analysis. These calculations are only made for bloodstains whose spatial impact direction contradict the results of the stringing method. For such a blood drop, we know the horizontal distance to the expected source area (by the stringing method), the impact angle and its mass. These data determine the angle of departure of the blood drop within a certain range. We then search for the starting velocity that is necessary to have the same starting height as the expected source area. If this velocity is much higher than the possible travelling velocity for blood drops as explained at Section 2.4, then it is very probable that the bloodstain in question cannot come from the expected point and we have to look for another source. In the case where the velocity is lower the mentioned limit, it is quite possible that this drop came from the expected source.

Trajectory calculations can be done with any exterior ballistics software which contains the air drag coefficient function of the sphere. We calculated our trajectories using ballistics software (k-ballistics 4.0, Switzerland, http://www.kneubuehl.com) [16] (Table 1).

The determined flight paths of the bloodstains are drawn in the 3D model of the crime scene using CAD software.

3. Results

3.1. Case 1

All analysed bloodstains were located at four or possibly five centres of origin. All centres were sited above the pillow, two or three between 20 and 25 cm above the mattress in the middle of the pillow (group 1) and two centres on the right-side of the pillow, closer to the wall and up to 10 cm higher (group 2) (Figs. 6 and 7). The centres are the possible blood source locations and the groups the different locations of the head of the victim.

The bloodstains of group 2 overlapped the bloodstains of group 1 (Fig. 8). Therefore, the stains in group 2 arose after those in group 1, which meant that the head of the victim was first sited in the centres of group 1 and then lifted and moved to the centres of group 2.

Table 1
A selection of the results of the ballistic determination of the trajectory of the blood spatters (case 1).

Bloodstain	Bloodstain coordinate			Ellipse		Centre of origin coordinate			Blood drop mass [g]	Ballistic analysis			
	x [m]	*y* [m]	*z* [m]	Length [m]	Width [m]	*x* [m]	*y* [m]	*z* [m]		*v* [m/s]	Elevation [mils]	Dh	Angle of descent [mils]
25.3	1.655	2.528	0.972	0.0032	0.0014	1.063	2.231	0.641	0.0015	3.59	905	0.339	−285.0
31.1	1.830	2.530	1.455	0.0034	0.0010	1.027	2.225	0.662	0.0005	7.30	884	0.799	559.0
31.2	1.792	2.530	1.448	0.0076	0.0012	1.314	2.342	0.776	0.0010	5.70	1040	0.670	764.4
32.1	1.948	2.531	1.506	0.0038	0.0008	1.000	2.270	0.697	0.0003	8.89	794	0.809	552.7
32.2	1.965	2.530	1.456	0.0018	0.0006	1.063	2.231	0.641	0.0001	6.80	983	0.815	−78.6
33.1	2.059	2.531	1.638	0.0112	0.0018	1.000	2.270	0.697	0.0032	10.20	791	0.941	639.2
22.1	1.543	2.527	0.723	0.0078	0.0040	1.063	2.231	0.641	0.0352	2.69	675	0.082	−479.7
27.1	1.637	2.527	0.625	0.0086	0.0020	1.000	2.270	0.697	0.0044	2.60	859	−0.071	−976.5
28.1	1.707	2.527	0.542	0.0066	0.0016	1.292	2.320	0.700	0.0023	2.01	958	−0.158	−1157.3
28.2	1.954	2.528	0.611	0.0050	0.0010	1.027	2.225	0.662	0.0005	3.41	720	−0.052	−886.8
30.1	1.790	2.528	0.899	0.0066	0.0016	1.000	2.270	0.697	0.0023	5.59	400	0.203	58.3
34.1	2.068	2.234	0.576	0.0186	0.0062	1.314	2.342	0.776	0.1310	2.95	1137	−0.202	−1233.2
35.1	2.070	2.055	0.414	0.0130	0.0040	1.027	2.225	0.662	0.0352	3.80	1195	−0.247	−1277.8
37.1	2.078	1.611	0.887	0.0042	0.0032	1.000	2.270	0.697	0.0180	4.49	558	0.192	−337.1
37.2	2.079	1.547	0.772	0.0032	0.0018	1.314	2.342	0.776	0.0032	3.78	520	−0.005	−581.4
37.3	2.078	1.423	0.810	0.0046	0.0018	1.314	2.342	0.776	0.0032	4.09	517	0.034	−529.5

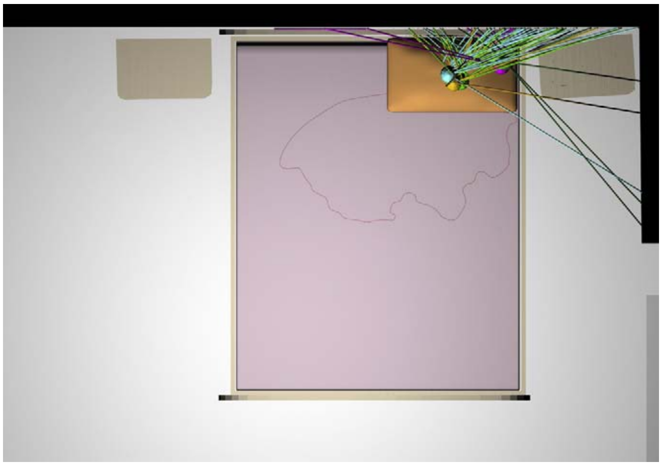

Fig. 6. In the aerial view of the scene, different coloured spheres represent the convergence areas of the calculated impact directions of the blood spatters (case 1). These areas of trajectory intersections are the centres of origin of corresponding bloodstains. Two groups of centres of origin were determined based on up to 150 analysed blood spatters. Both groups were sited above the pillow. The group 1 was sited between 20 and 25 cm above the mattress, approximately in the middle of the pillow. This group consisted of three centres, marked by green, yellow and blue colours. The green and yellow centres were very close together, the blue one was slightly higher and closer to the wall. The group 2 consisted of two centres, marked in red and sea-green colour, which were sited between 25 and 35 cm above the mattress on the right-side of the bed, closer to the wall than the group 1.

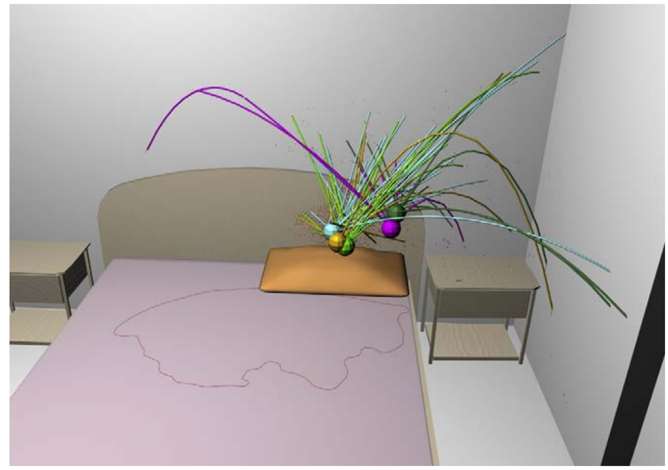

Fig. 7. All analysed bloodstains were located at four or possibly five centres of origin (case 1). The 3D model shows the ballistic determined trajectories and the centres of origin.

3.2. Case 2

Based on the analysed well-shaped bloodstains, the groups of centres of origin were determined on two additional locations in the apartment, in the kitchen and in the dinette above a chair.

Group 1 in the kitchen consisted of three centres, marked with dark and light blue colour (Fig. 9). The centres were sited in the middle of the kitchen at a height of between 160 and 173 cm, the dark-blue centres were closer to the fridge and slightly higher than the light blue centre.

Group 2 in the dinette consisted of one centre (green colour), which was sited 77 cm above the seat of a chair next to the wall (Fig. 10). This indicated that the victim sat on the chair whilst being beaten. In fact, because of the low number of blood spatters, and their small size, it was presumed that the victim suffered a blow to the head at an early stage of the attack.

4. Discussion

The approximate areas of origin are mainly used to deduce whether the victim was standing, sitting or lying down when the bloodstain pattern was created. In this case, the height of the blood source locations is of great importance. Using only the classical stringing method, in cases of longer distance between the blood source location and the bloodstain, a difference in the vertical component between the spatial direction of impact and the expected centre of origin arises because of the curved trajectory of the drop. A principal task of ballistic analysis of the bloodstain pattern in these cases is to confirm if these bloodstains are also from the determined blood source locations. Therefore, the ballistic determination of the curvature of the flight paths of the blood drops is of great importance.

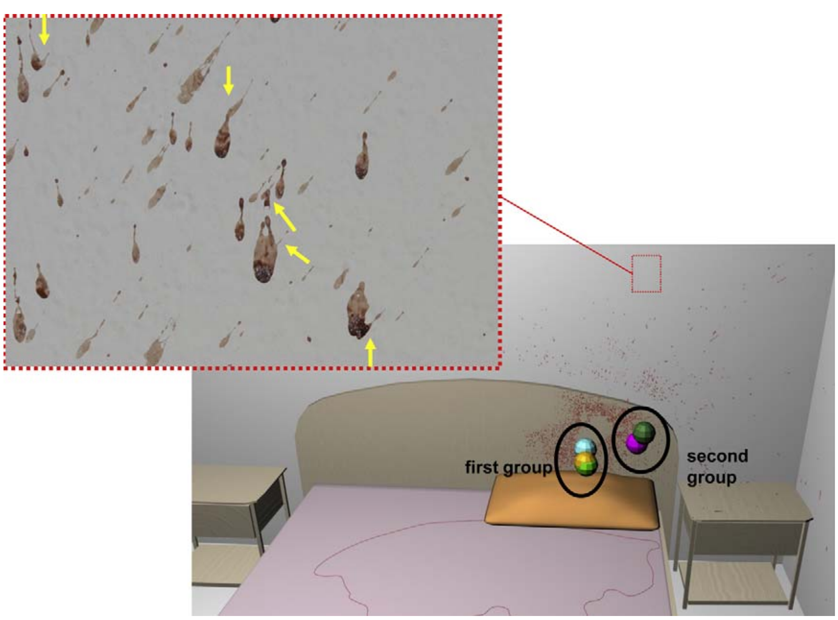

Fig. 8. On account of the overlapping bloodstains (yellow arrows) the group 1 of the centres of origin in the middle of the pillow appeared before the group 2 on the right-side of the pillow appeared (case 1).

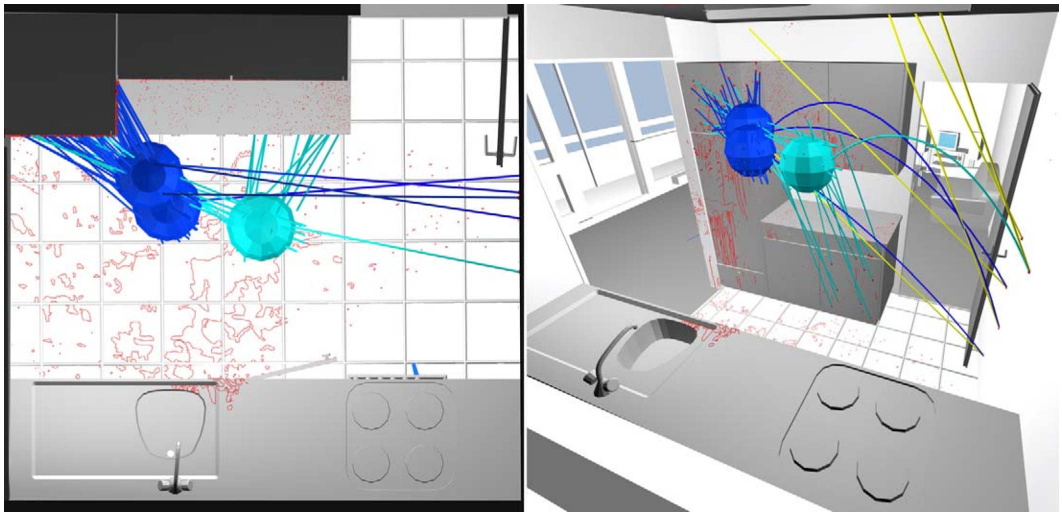

Fig. 9. CAD drawing of the kitchen in a top view left and perspective view right (case 2). The bloodstains are drawn in red and the determined trajectories of the blood drops and the centres of origin of the bloodstains are drawn in dark and light blue colour. The yellow lines represent the determined trajectory of the bloodstains when they are misleadingly treated as straight line. The light-blue centre was sited in the middle of the kitchen at a height of about 160 cm and the dark-blue centres were sited closer to the fridge and between 165 and 173 cm. This indicates that the victim was struck at least twice on the head in a standing position in the kitchen.

This study describes a three-dimensional method of bloodstain pattern analysis including the determination of the trajectory of all blood spatters, which occur at a far distance from the centre of origin. Furthermore, in case 1, the determination of the sequence of events, in which order the bloodstains of the different groups of areas of origin arose, are ascertained by the overlapping of the bloodstains.

The advantages of the three-dimensional crime scene documentation using photogrammetry and laser scanning include the short preparation time on site and the high accuracy and resolution for even the smallest bloodstains. These efficient methods are performed without contact, and if necessary or requested, everything that is recorded can be measured and drawn in a CAD program.

In our setup, the first photogrammetric images are taken in the early stages of the investigation, before the deceased is transported, in order to document the bloodstains before they are possibly destroyed during the securing of evidence. The complete crime scene is documented in 3D, after the securing of evidence.

Using the photogrammetry and 3D scanning methods, bloodstains on vertical, horizontal and oblique surfaces, as well as on complex shaped objects, can be analysed.

To reduce the random measurement error [13–15], elliptical shaped bloodstains with low impact angles are analysed and the shapes of the ellipses are first drawn completely and then the length of the major and minor axes are automatically computed by the CAD software. Furthermore, the analysis of a large number of bloodstains is enabled using the computer-based method, which increases the accuracy of the determined origin of bloodstains and eliminates the random measurement error.

The 3D documentation methods are easy to use and mobile. For photogrammetric analysis and creation of 3D models, however, a

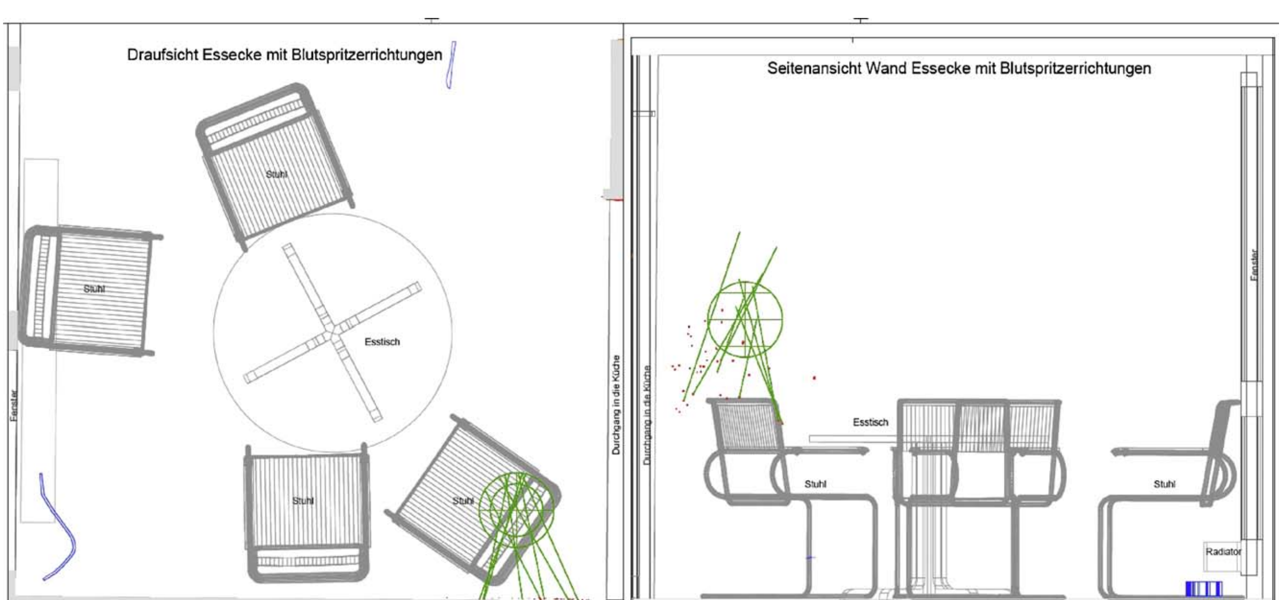

Fig. 10. CAD drawing of the trajectories and the centre of origin of the group of bloodstains in the dinette in a top view left and side view right (case 2). The centre of origin was sited above a chair in the presumed position of the head of the victim, when sitting on this chair.

fair amount of experience is required. For data interpretation and the determination of the trajectory of blood drops, advanced knowledge in physics and ballistics is necessary.

In the conventional stringing or virtual stringing methods, the height of the areas of origin has always been an inaccurate factor because the curvature of the trajectories of the blood drops is not taken into consideration.

The trajectories of bloodstains, which deposit a short distance from the blood drop origin, can be assumed as straight lines. But, the results of our method showed that for bloodstains which deposit at farther distances from the centre of origin, the straight line is sited higher than the presumed centre of origin. In the case of bloodstains, which are located longer distance from the blood drop origin, the straight line was sited up to 2 m higher than the ballistically determined trajectory of the blood drop in the area of origin of the bloodstains. These results demonstrate that a ballistic determination of the trajectories is necessary.

It should be expected that overall, this new method will deliver a more accurate picture of the number and position of the areas of origin of bloodstains, the vertical component especially should be determined more precisely than using conventional methods.

The determined blood spatter directions and trajectories, as well as the areas of origin of the bloodstains, are rendered into the virtual true-to-scale 3D crime scene in order to present the results in a measurable manner.

A general rule to determine which bloodstains should be analysed by ballistic calculation is given by the angle between the impact direction and the straight line (in ballistics sciences the so-called angle of fall). If this angle exceeds 10°, ballistic analysis is recommended. In such cases, the difference between the ballistically determined origin of the blood droplet and origin as calculated by the straight line method is about 18% of the travelled distance.

To perform such calculations requires a computer program for ballistic calculation of trajectories that correctly accounts for air drag as well as some knowledge on the part of the investigator regarding trajectory reconstitutions. However if a virtual true-to-scale 3D crime scene is available, it is not necessary for the investigator to physically visit the crime scene.

5. Conclusions

The results of the ballistic bloodstain pattern analyses gave clues about the areas of origin, the minimum number of blows, the positioning of the victim as well as the sequences of events. In both cases, relevant forensic conclusions regarding crime reconstruction were enhanced by bloodstain pattern analysis based on 3D documentation and analysis and the ballistic determination of the trajectories.

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