ISSN Print: 2394-7500
ISSN Online: 2394-5869
Impact Factor: 5.2
IJAR 2017; 3(1): 200-211
www.allresearchjournal.com
Received: 15-11-2016
Accepted: 16-12-2016

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Bloodstain pattern analysis – A less explored domain

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Abstract
The authors conducting the study are particularly interested in recording, analysis and interpretation of the Transfer Stain and Saturation Stain patterns one can expect to see in the event of head hit by a blunt ended object (such as hammer, golf stick, candle stand etc.). This work is in itself a review of the work that has been undertaken in terms of case based study of stains together with the scientific explanations of the mechanisms that lead to the formation of the stains.

Keywords: Fabrics, bystander, perpetrator, room and victim

1. Introduction

Violent criminal activities under most circumstances are accompanied by large spillage of blood. A bloodstain formed due to accumulation of liquid blood on an absorbent surface such as carpet, fabric, clothing, bed sheet, curtains etc. is commonly referred to as 'Saturation Stain' [3]. Large amount of blood outflow occurs when a person suffers serious head injuries owing to hammer strike or when struck on the head with a blunt ended object, such as a golf stick, candle stand, sticks etc. Under such circumstance one could evidently expect to see stained carpets, clothes etc. depending on the position of the victim, perpetrator and bystander (if any). Again, as a result of the impact mechanism or rather the impact force of hit, certain stain patterns are developed. Because these stain patterns are developed as a result of an object striking liquid blood, these are commonly known as 'Impact Pattern' [1-3].

Bloodstain patterns formed as a result of contact between a blood-bearing surface and another surface is commonly referred to as Transfer Stains by the IABPA [3]. Blood bearing fingers, bloody weapons, half bloody or bloody shoes etc. leave transfer stains in a crime scene as a result of the sequence of events that had occurred at the crime scene. Thus Transfer stains in coherence with other bloodstain patterns such as Voids, Saturation Stain, Cast-off patterns etc. can be effectively used for part/full reconstruction of crime scene.

The authors conducting the study are particularly interested in recording, analysis and interpretation of the Transfer Stain and Saturation Stain patterns one can expect to see in the event of head hit by a blunt ended object (such as hammer, golf stick, candle stand etc.). This work is in itself a review of the work that has been undertaken in terms of case based study of stains together with the scientific explanations of the mechanisms that lead to the formation of the stains.

2. Background

In the IABPA Conference held in Tucson, Arizona, 2004, Peter Lamb presented the investigation report of the late night assault of a young man who was intoxicated at the time of attack and could only recollect part of the savagery that he had been subjected to [5]. Due to rain drop that had soaked the garment at the time of the assault it was difficult to examine the bloodstains on the soaked garment [5]. However there was evidence of kicking and stomping [5]. Based on the evidence the case finally proceeded for trial and the accused was proved guilty and hence imprisoned [5]. In his review of the Windsor city homicide case Scott Lamont pointed out that barefoot transfer impressions and footwear transfer impressions were found on the floor [6]. Foot morphology confirmed that the prints were left by the suspect who was wearing boots [6]. In the words of Lee Ann Singley, in the murder case of 2 women (74 year old mother and her 48 year old daughter) in their holiday home in a small town in Pennsylvania, while DNA evidence answered 'who ?' in identifying the perpetrator at the trial, the bloodstain pattern evidence proved to be valuable to the jury in answering the 'how?' [7]. To add to the list, in the case of Regina vs. Sion Jenkins, expirated and other bloodstains on clothing were used as relevant evidence within the legal setting to acquit Sion Jenkins of the murder of his 13 year old daughter Billie Jo [8]. In the case presented by Paul Treudson, at a particular crime scene bloody transfer impressions of an apparent right hand holding a knife was found on top of a sheet that lay at the foot of the bed [9]. The impressions included knuckles and a blade [9]. As Erin Sims puts it, for one particular case the evidence particularly the bloodstain pattern evidence was the only honest teller of the course of events that had led to the victim' sinjury [10].

Again, as per the Federal Bureau of Investigation (FBI) Chart reports each year more people are killed by hammer, club or blunt ended object hit as compared to the number of people killed wt rifle or shotgun [11]. In this respect it might be interesting to mention that, in a case reviewed by Stuart H. James at the 2008 IABPA Annual Training conference, he reiterated that bodies of 4 Mexican construction workers were found in a rented apartment at Ohio [12]. The bodies of the victims remained undiscovered for almost a week [12]. When examined the victims were found to have suffered blunt and sharp force injuries [12]. The highlight of the case review were the interesting bloodstain patterns found at the crime scene which were studied in conjunction with the wounds suffered/sustained by the victims [12]. In their study, the authors came across many such cases where victims suffered blunt force injuries. Given the large possibility of instruments that can be easily obtained and hence deliver blunt force injuries to the human skull, the authors decided to particularly focus on the possible Transfer and Saturation stain patterns formed at a crime scene as a result of assault particularly with blunt ended objects.

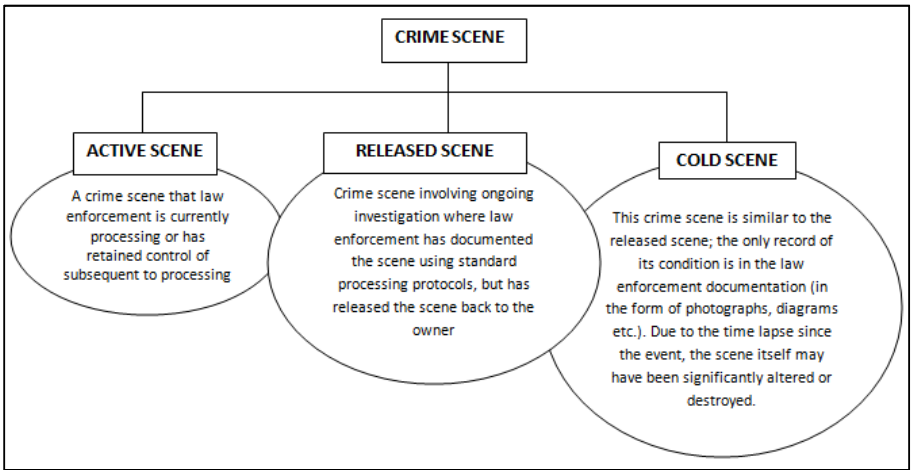
Thus in a violent crime scene with sufficient amount of bloodshed, bloodstain pattern analysis often plays a significant role in proving or refuting the statements of the suspect, victim, bystander/eyewitness(if any) within the juridical setting. The stains along with the wound suffered by the victim/s could also be used for part/full reconstruction of crime scenes. These case studies particularly set out the background for this review paper.

3. Knowledge Base

3.1 Detection and Documentation of Stains at a Crime Scene

When it comes to documenting Bloodstain Patterns based o visibility of patterns to the naked eye there are in particular 2 types of bloodstain patterns/prints one could come across in real life – latent bloodstain patterns and visible Bloodstain Patterns. Given the fragile nature of bloodstain patterns at a crime scene, stains are often accompanied by noise or are superimposed by other stains in course of subsequent events at the crime scene. Luminol and Bluestar have often been used to detect latent or washed bloodstains that have been a challenge for forensic investigators. Thomas W. Adair and Rebecca L. Shaw highlight that irrespective of which reagent is used to visualize latent bloodstains, analysts should use caution when interpreting diffused or diluted bloodstain patterns occurring over a large area of the clothing under examination [13]. This is because the level of saturation may be the result of the washing process and hence may not relate to any specific bloodletting event [13]. The research undertaken by Adair and Shaw supports the use of Luminol as an effective reagent to visualize latent bloodstain patterns on washed clothing [13]. Though Leuco Crystal Violet was found to be an effective blood reagent on many washed and unwashed surfaces, the results that Adair *et al*. obtained in his study with use of LCV wasn't particularly impressive [13]. James O. Pex clearly outlined with evidential proof that Luminol does not confirm the presence of blood, hence it cannot be used to evaluate latent impact bloodstain patterns [14]. DeWael *et al.* in his research document 'In search of blood detection of minute particles using Spectroscopic methods' devised and put forth an examination protocol for rapid detection of remnants of blood particles on garments of suspects in bloody murder cases [15]. Infrared Digital Imaging (IR), Ultraviolet Digital Imaging (UV), Reflected Ultraviolet Digital Imaging and Hemascein (a fluorescein based material) are some applications that can be used for locating and enhancing bloodstains that are particularly latent or faint to the unaided human eye [16]. The study undertaken C. Middlestead and J. Thornton showed that Luminol tests can be unambiguously interpreted at substantially greater dilutions of blood [17]. The sensitivity of the luminol test was performed on denim fabric [17]. Tontarski *et al*. worked on the chemical enhancement techniques that could be used for making latent bloodstain patterns visible to the unaided eye [18].

By way of experience, an individual can clearly understand the difficulty of visualizing bloodstain patterns on dark colored fabric. The study undertaken by Ted Silenieks, Russell Cook, Kareana Turner and Jose Nunn used hyper-spectral imaging to assess the contrast between bloodstains and different dark colored fabrics at defined wavelengths over the visible and near infrared range [19]. By way of this study Silenieks *et al.* examined the use of appropriate light sources, contrast enhancement techniques, the reliability of near infrared detection of bloodstains and the limitations in bloodstain pattern recognition [19]. Gorn and James are of the opinion that Infrared Photography has primarily been used for documentation of gunshot residue patterns and bloodstain patterns on dark colored clothing [20]. As per Gorn and James, in comparison to other techniques in use this technique is particularly non-destructive in nature [20]. The fact that this technique does not interfere with serological/DNA testing and is relatively simple to use, makes this technique a technique of choice among most analyst [20]. In 2008, Elizabeth van Zanten and Rob Spruit initiated a near infrared imaging project at the crime scene unit of the regional police force Middle en West Brabact in the Netherlands [21]. The main objective of the project was to evaluate near infrared imaging as an additional forensic tool for the visualization of blood on dark surfaces [21]. As per Zanten *et al.* for detection of latent blood on dark porous surface/material near-Infrared photography has proven to be an excellent non destructive alternative as compared to other chemical blood enhancement techniques in place [21].



There are three basic crime scenes/environments from which or in which an analyst needs to study/interpret bloodstain patterns and hence reconstruct the crime scene [22]. They are - Active Scenes, Released Scenes and Cold Scenes [22]. Figure 1 [22] provides an overview of the different types of crime scenes that an analyst might have to work in.

Given that in case of a released or cold scene the only bloodstain pattern evidence that an analyst could have access to proper, effective documentation of the bloodstain pattern at the crime scene stands integral. Tom and Gardener outlined basic guidelines for photograph based documentation of bloodstain patterns at a crime scene in the chapter 'Documenting Bloodstains' of the book titled, 'Bloodstain Pattern Analysis: An introduction to crime scene reconstruction' [22]. Based on the old adage, "a picture is worth a thousand words", R. Daniel Winterich presented a methodical technique for documenting bloodstain patterns at the crime scene [23]. Herbert Leon MacDonell rightly pointed out that photographs cannot allow depth perception whereas models demonstrate this perception quite well [24]. Hence, 3D modeling of the crime scene and intervention of 'live' persons is particularly important in understanding and hence scientifically justifying what happened and what could not probably have happened [24]. Mijntje Arts explains that before clothing or any other items from the crime scene are analyzed or examined for bloodstain pattern analysis, it is important that the information received from the case documentation is pre-assessed [25]. Mijntje believes that pre-assessments of scene prior to evidence interpretation, increases the chance for the results of the bloodstain pattern analysis being particularly focused and hence unbiased [25]. Delft Tech provides support for 3D blood Spatter Analysis and Virtual Crime Scene Reconstruction [26]. Dr. M. Taylor did a systematic study of some of the common bloodstain patterns using a high speed video camera to record the blood transfer as it occurred [27, 28]. He developed a database of 500 digital video clips of common bloodletting events [28].

3.2 Scientific Basis of Interpretation of the Stains

As suggested by many forensic analysts, bloodstain pattern analysis is not particularly a new discipline in itself. The roots of bloodstain pattern analysis as forensics know it in the modern day world dates back to the 1800s [29]. To understand the different stain patterns (particularly Transfer Stain and Saturation Stain Patterns in this case) it is indeed important to have a clear understanding of the physical mechanism and scientific principles that control the fall, spattering of blood at the crime scene. Forces of cohesion, adhesion, gravitation, surface tension primarily control the formation of bloodstain patterns at a crime scene. The document put together by the University of Western Australia on Blood Spatter [30] and Dr. J.J. Nordby's 'Basic Bloodstain Pattern analysis Text' [31] give a precise yet lucid description of the different forces that control the formation of the different bloodstain patterns in a crime scene. To add to this, Ed Bernstein in his article published in the Journal of Bloodstain Pattern Analysis, December 2005, highlighted the science that governs the formation of bloodstain patterns at a crime scene [32]. These papers describe how the forces of adhesion, cohesion, gravitation and surface tension act in coherence with each other and hence control the shape of the bloodstain pattern formed [30, 32]. Mark Reynolds provided a stepwise description of the transition phases of a blood droplet to a bloodstain upon contact with a planar surface in an eloquent way thereby simplifying the complicated fluid dynamics involved [33]. The study conducted by M.E. Reynolds, M.A. Raymond and I. Dadour shows that an apparent power law relationship may exist between the size of a parent blood droplet and the role of viscous and surface tension forces on subsequent bloodstain formation particularly for those bloodstains caused by small droplets impacting the planar surfaces obliquely [34]. Elizabeth Williams worked on 'the biomechanics of blunt force trauma' [35]. In order to accurately and quantitatively reconstruct the events at the scene of a blunt force trauma assault, she undertook a detailed study of the kinematic sequences and mechanisms involved in the striking action [35]. She thereby developed a 3D biomechanical model for data analysis [35]. Attinger *et al.* did a comparative review of the literature on Bloodstain Pattern Analysis and Fluid Dynamics (FD) relating to 5 basic aspects, namely, the physical forces driving the motion of blood as a fluid; the generation of the drops; their flight in the air; their impact on solid or liquid surfaces; and the production of stains [36]. Attinger *et al*. hence made suggestions on the probable areas of interdisciplinary research involving BPA and FD [36]. The study by Ross Gardener shows that the variables of force and volume affect the resulting size of an impact spatter [37]. As force increases there is a general decrease in spatter size. Again as volume increases there is a general increase in spatter size [37]. The study therefore suggests that spatter size is not a specific predictor of force or mechanism in a crime scene [37]. Impact spatter stains are again quite common in a crime scene where a victim has suffered blunt force trauma. Young II Seo performed a comparative study of the velocities of swinging hammer and how it affects the formation of blood spatters using a high speed camera [38]. He documented that when the average velocity of a hammer swung with all the experimenter's strength at a pool of blood was recorded to be about 12.5 m/sec, the average velocity of impact spatter that was generated by the swinging hammer was found to be 52 m/sec [38]. By way of experimentation, the velocity of the swing cast off spatter that was generated was found to be 4.7 times the velocity at which the hammer was swung by the experimenter and again it was found to be 3.9 times faster than the expectorate spatter that was generated by emitting blood from the mouth with all the experimenter's strength [38]. Strikingly however, the velocities of cast off spatter and expectorate spatter showed similar distributions [38].

To study or rather interpret impact spatter stains proper selection of regular geometric stains in an impact spatter is particularly important for calculation of the area of origin of the impact that created the particular spatter stain. Illes *et al*. presented a set of criteria for selection of patterns in an impact spatter using a statistical model[39]. Shen, Brostow, Cipolla developed an algorithm for automated estimation of a body's 2D location on a floor plan when the body is impacted given that the blood stains are formed as a result of impact spatter [40]. In order to improve the estimation of the point of origin, it is important to select bloodstains that lie close to the presumable location of the blood source. Individual stains that are large (width > 1.5 mm) and that which have an elliptical form should be selected [40]. As per K. G. de Bruin *et al*., bloodstains from different walls should be taken into account in order to improve the methodology to determine the point of origin of a particular impact spatter in consideration [41]. Experiments undertaken by Behrooz *et al.* showed that some error stands inherent in the process of blood disintegration but this does not greatly affect the calculation of the area of origin as per known scientific methods [42].

As per Karger, Rand, Fracasso and Pfeiffer, the morphology of bloodstain distribution patterns at the crime scene carries vital information for reconstruction of the events that occurred at a crime scene [43]. Norman Reeves did an initial study of the sequencing of multiple bloodstain patterns that were present at a crime scene [44]. He examined blind samples to determine if there were re-occurring indicators when looking for a layered bloodstaining that could be used when conducting an analysis [44]. One often comes across angled surfaces in real life. Carter *et al*. designed experiments to compare and contrast bloodstain spatters formed on angled surfaces with spatters formed on flat surfaces [45]. Joseph A. Slemko in his work particularly looked at the effect of droplet velocity and fabric composition on bloodstain patterns [46]. In his work he experimentally compared bloodstain patterns created on a collection of various fabrics based upon fabric composition, fabric texture, new vs. used/worn out fabrics, and chemically treated fabrics [46]. Within the experimental design, a collection of various fabrics placed at different distances were exposed to blood droplets generated by a high speed fan [46]. The droplets were hence compared on the basis of bloodstain size versus distance travelled in relation to fabric composition and chemical treatment of fabric [46]. Based on the experimental results, Slemko concluded that the degree of distortion of bloodstain observed on the fabric is a function of both, the ability of the fabric to absorb blood and the texture of the fabric [46]. However owing to the distorted nature of the bloodstain on fabric, interpretation of the impact angle often becomes difficult [46]. F. Adolf put in place the guidelines that should be abided by when examining textile fiber/s within the Forensic context [47]. B. Karger *et al*. developed an experimental setting to evidentially highlight the differences between contact/transfer stains and projected droplet patterns on fabric surface [48]. It was found that even on similar surfaces contact stain patterns lack the characteristic features of dynamic stains (i.e. projected droplet stains) [48]. However mode of formation of micro-stains on rough surface structure when the blood volume is small (< 1 microlitre) is difficult to predict as the characteristic features of dynamic stains in case of such micro-stains are reduced [48]. Tronnberg *et al.* worked on and thereby provided essential guidelines for recognition of expirated bloodstain pattern on cotton fabrics [49]. There have also been other works done documenting the recognition of expirated stain patterns on different fabrics [50]. White summed up the effect of droplet volume, dropping height and impact volume on the bloodstain formed on a fabric [51]. It might surprise the readers to know that one could for a matter of fact come across a regular stain being formed on an apparently porous fabric surface depending on the volume of blood in the droplet and the location at which the droplet falls (refer Figure 2) [51a, b].

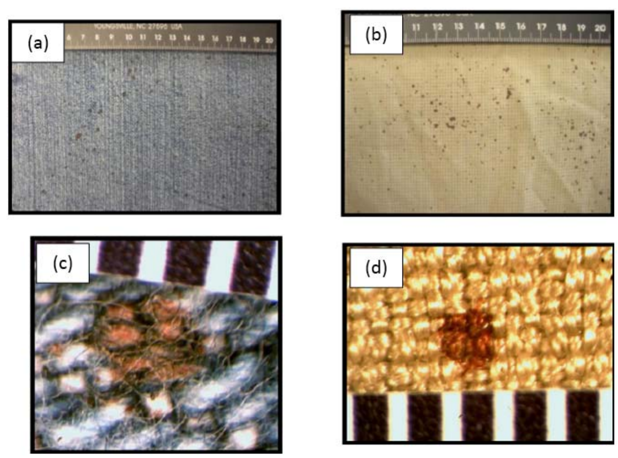


Fig 2: (a) Spatter on Denim, (b) Spatter on 100 % Silk, (c) Spatter on Denim(25x), (d) Spatter on 100% Silk(25x)

Higher velocity blood droplets again may produce satellite spatter upon impact with the cloth surface [46]. The satellite spatter appearance in its turn is also dependent on the blood droplet volume [51]. Washing as also Scotchgard type fabric treatments directly affect bloodstain pattern appearance [46]. Hence these effects must be taken into account when interpreting bloodstain patterns on fabric [46, 51]. Wound analysis is often done, in order to trace out the murder weapon that has been used by the perpetrator to cause injury to the victim. Given that the authors intend to study bloodstains commonly produced in the event of a head hit by a blunt ended object particularly hammer, hence it would be relevant to mention that when the head of an individual is forcefully hit with a blunt ended object with an intention to cause injury, not all areas of the skull show similar deformation [52]. Hence Rex Spark's study on wound analysis and how the wound pattern correlates to the accompanying bloodstain patterns is indeed relevant for this study [53]. If a living human being is struck by a blunt ended weapon (namely say hammer), one could very well expect the living being to move when struck. This dynamic aspect of a person being hit by an object was first recognized by Dr. Pitrowski [54]. He hit live rabbits on the head with a claw hammer at various angles or rather at all possible angles in order to record their movement when hit by a blunt ended object (eg.Hammer) on the head [54].

Mike Barnes designed an experiment to test how the variables such as cloth type, weapon type, impact force, target surface relative hardness affect the pattern of the transfer stain [55]. To justify that these factors have noticeable effects in bloodstain formation he provided certain real time case facts alongside experimental results [55]. Peter D. Barnett presented a case study to show how the bloody fingerprint transfer stain pattern could be effectively used for refuting or proving the statement of the defendant within a legal setting [56]. As Barnett puts it, "In this particular case, the problem was not whether the fingerprint was made with wet blood or not, but whether the wet blood could have been obtained when the defendant revisited the scene or only earlier" [56]. The police investigators misconstrued the problem [56]. As per expert testimony, the bloody fingerprint marks could not have been deposited in a way that was described by the defendant [56]. Rob Bone in his work highlighted how the analysis of fingerprint/palm print transfer stains at a crime scene could aid the overall process of crime scene reconstruction [57]. By analyzing the fingerprint mark an analyst would be able to determine if the finger/palm was wet with blood when it came in contact with the object, whether the clean finger had come in contact with blood already present on object or if blood had come into contact with an existing finger/palm mark on the object [57]. Experiments devised by Huss *et al.* clearly aided understanding of the mechanism involved in the creation of a fingerprint pattern in blood [58]. As per the distinguished British analyst, Frederick Wood Jones, the human feet are the most distinct part of his anatomical makeup [59]. Thomas W. Adair experimented with several casting materials on red colored concrete, fabric and human skin which are particularly known as difficult surfaces for interpretation of stain patterns, in order to transfer bloody shoe impressions onto a medium which offers better contrast for general photography [60].

3.3 Drying and Clotting of Blood

Although regionally extreme temperature were found to make the drying time of blood vary, the project undertaken by Brady *et al*. clearly showed that temperature does not affect the overall characteristics of bloodstain patterns [61]. Zeid *et al.* demonstrated the ways in which relative humidity affects the drying time and also the blood stain pattern formation [62]. Relative Humidity influences the contact angle, the final wetting diameter together with the final deposition pattern at the end of the evaporation process [62]. Laber *et al*. demonstrated the effect of substrate on the drying time of blood [63]. In the IABPA conference held in Atlantic City, New Jersey on October, 2010, Dr. Silke Brodbeck discussed the basic principles of the human blood coagulation system and its relevance in the field of bloodstain pattern analysis [64]. In the review of Shirley McGill's murder case, Stuart H. James emphasized the significance of clotted bloodstain pattern evidence on the clothing of Robert McGill that was in all likelihood produced as a combination of impact and expirated blood [65]. By experimentation, F. Nour-Eldin *et al*. determined the nature of blood clotting factors in the saliva of normal patients and of patients with haemophilia or Christmas disease [66]. Berckmann *et al*. proved by experimentation that the saliva-induced shortening of the clotting time of whole blood for healthy subject was dependent on the tissue factor [67]. Snake venom accelerates blood coagulation. Human saliva accelerates the prothrombin time as much as it gets accelerated by snake venom [67]. Thereby H.K. Doo and P.H. Lee undertook an investigation to identify the nature of these acceleration factors and how they inter-relate to other factors that accelerate the process of blood coagulation [68].

3.4 Digital Aid in Interpretation of Bloodstain Patterns

In the research project undertaken by A.L. Carter, Rachel Collins, Serge Larocque and Brian Yamashita, blood was spattered on a combination of flat and angled walls The bloodstain patterns were first analyzed using the stringing method and then the data was subsequently entered into the modified Back Track program to demonstrate that the new version of the Back Track program could also handle angled surfaces [69]. In this regard it might be interesting for the readers to know that Back Track [70, 71] and Hemospat [72] are popular toolkits that are used for manual yet partly computer assisted analysis of bloodstain patterns obtained at a crime scene. Though widely used, yet these toolkits require the intervention of an experienced bloodstain pattern analysis to determine parameters of input and hence interpret results. Carter *et al.* devised a methodology for documentation and hence interpretation of bloodstain patterns at a crime scene using a video camera and a computer [73]. In 1999, Andrew Fitzgibbon *et al.* suggested an efficient methodology for least square fitting of ellipses to scattered data [74]. This method could very well be used to fit ellipses to individual spatter stains in an impact spatter [74]. Sergeant Mark Reynolds in his presentation at the October, 2008, IABPA conference described an innovative and improved alternative to current manual bloodstain measurement methods using Microsoft Office Excel, 2003 Autoshape function that allows for the on-scene computer assisted fitting of theoretical ellipses to regular bloodstains for measurement purposes [75]. Mathew Noedel demonstrated a technique to use Adobe Photoshop to measure and document the length and width ratios of individual regular bloodstains [76]. He also demonstrated additional procedures to use features in Photoshop to manipulate multiple images to produce the same approximate scale and methods to extract useful information from digital images taken with poor lightning and contrast [76]. Michael Taylor designed experiments to explore the dynamics involved in the creation of a cast off pattern with the aim to enhance the importance of the input provided by a BPA analyst within a crime scene investigation team [77]. Dr. Silke Brodbeck described how anatomy related movement analysis (ARMA) could effectively be used as a tool for reconstruction of body movements in the creation of transfer stain patterns [78]. The presentation focused on how ARMA combines practical knowledge of BPA and functional anatomy at predicting body movements that could lead to the formation of a particular transfer stain [78]. Detective Kevin Maloney presented 3D representation of Bloodstain Pattern Analysis by integrating data from Back Track into a standard AutoCAD program in order to represent the virtual flight paths of blood droplets in a 3D space [79]. As put forward by Philippe Esperanca, eSCrime is a software package that helps investigators locate in a crime scene the computed origin of the examined bloodstains [80]. As the software allows modeling of the crime scene, hence it stands easy for investigators to study the 3D virtual origin within a modeled environment [80].

3.5 Presentation as Evidence within a juridical setting

In 1955, Dr. Paul Kirk first presented a bloodstain evidence affidavit in State of Ohio v Samuel Sheppard [81, 82]. Thereafter, expert testimony in bloodstain pattern interpretation gained widespread acceptance with the US legal framework. Kirk's contribution to the study of bloodstain pattern evidence within the legal framework is indeed commendable [83]. Bart Epstein felt that the Indiana v David Camm case was particularly significant because of the concerns it triggered with respect to admissibility of bloodstain pattern evidence in the court room [84]. The major concerns the case raised for bloodstain pattern analysis practitioners can be summarized as follows – 1) the qualification of individuals presenting bloodstain pattern evidence within a legal setting, 2) associated error rates, 3) validation studies and 4) the need to know science as it relates to Bloodstain Pattern Analysis [84]. Given the critical role bloodstain pattern analysis often plays in violent crime scene reconstruction, Louis L. Akin prepared a document that could provide legal practitioner a basic understanding of the principles and procedures of bloodstain spatter analysis thereby allowing the defense attorney to hold an intelligent conversation with the defense bloodstain spatter analyst or cross-examine the prosecution's expert pattern analyst on the bloodstain evidence together with the evidence drawn up [85]. On similar lines the book on Scientific and Legal Applications of Bloodstain Pattern Analysis discusses research, applications and the current status of bloodstain pattern interpretation within the legal system at the trial and appellate level courts [86]. By outlining on the scientific approaches and developments in the field of bloodstain pattern analysis this book is particularly aimed at equipping legal professionals with the basic working knowledge of BPA required to present as also cross examine bloodstain pattern evidence within the juridical system [86]. The paper 'Legal and Ethical Aspects of Bloodstain Pattern Evidence 'by Carl Henderson and Brittan Mitchell clearly represented the issues of bloodstain evidence admissibility, weight of bloodstain pattern evidence, required qualification of an expert bloodstain pattern analyst to present or question such evidence in the court of law [87]. Apart from the methods of presentation of expert testimony and cross examination of evidence, the paper also discusses the ethical issues of the attorney and the expert witness called in court [87]. 'Topics to consider in Preparation for an Admissibility Hearing on Bloodstain Pattern Analysis' by the Scientific Working Group on Bloodstain Pattern Analysis (SWGSTAIN)is an official resource for preparation of admissibility hearing on the topic of bloodstain pattern analysis in the courtroom [88]. On June 28, 1993, the U.S. Supreme court's landmark decision on Daubert v Merrell Dow Pharmaceuticals, Inc. finally resolved the twentieth century debate on the admissibility of scientific evidence in the court of law thereby taking to more enduring admissibility standard that would accept the use scientific evidence for technical issues but would at the same time protect the jury from being unduly persuaded by swindlers who proclaim themselves as experts [89]. On the flip side based on the qualifications of the expert witness and when there is a lack of scientific basis for presentation of bloodstain evidence in the court or when the court feels the evidence has been contaminated in some way, the court might very well treat such bloodstain pattern evidence as inadmissible [90].

4. Controversies

In the book 'Bloodstain Pattern Analysis – an introduction to Crime Scene Reconstruction' Bevel and Gardener had introduced a bloodstain pattern classification system that deviates from the terminology and classification system followed by the IABPA [22]. In the review of the book, Dr. R. R. Ristenbatt III clearly mentions that a new terminology as also bloodstain pattern classification system based on taxonomy was totally unnecessary. Again the book describes surface tension as the "force holding the blood mass to the object", which is particularly incorrect. Though an informative read, some of the concepts highlighted in the book are highly debatable [91]. The stain pattern classification system put in place by Stuart H. James is however well accepted within the community of bloodstain pattern analysts [92].

For micro stains having a volume of less than 1 micro-liter it is often difficult to predict the physical mechanism that has led to the formation of the particular stain pattern [48]. Again, on similar lines it has been proved by various experiments undertaken that bloodstain patterns cannot be particularly classified on the basis of velocity of impact alone. In the IABPA conference held in October, 2004 Herbert Leon MacDonell showed several patterns that are similar in appearance to high velocity impact spatter, but in fact are not. He thereby concluded by mentioning that it is actually impossible to say anything from a bloodstain pattern more than that the pattern is consistent with and therefore could have been produced as a result of high velocity impact on a blood source [93]. Again, to add to this, the study undertaken by Young II Seo highlight that expectorate spatter stain as also cast-off spatter stain having different velocities were found to create similar distribution patterns [38].

As is quite evident from Section 3.2, substantial work regarding the behavior of blood on varying fabric surfaces has been undertaken [46-51, 94]. The effect of saliva on blood coagulation on fabric surface has also been widely studied [66-68]. But questions as to how blood reacts to sweat on fabric, does pattern distribution change on fabrics due to sweat formation - still remain unanswered. From study conducted by J.A. Slemko it can be safely concluded that pattern formation on worn out, washed fabric is distinctly different as compared to pattern formation on new fabric [46].

Like most other disciplines in science, forensic science and particularly bloodstain pattern analysis is also affected by bias. Bias related to bloodstain pattern analysis can particularly be classified under two broad heads [95]. They are context bias and confirmation bias [95]. Figure-3 [95] represents the different types of biases that plague bloodstain pattern analysis.

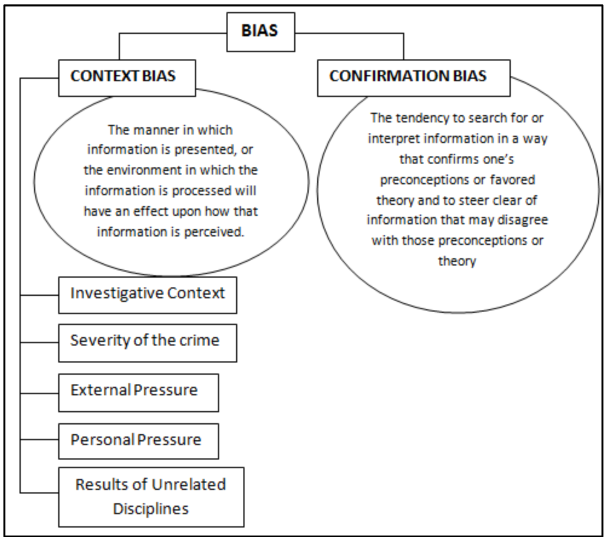


Fig 3: represents the different types of biases

Though validation tests, blind folded studies, evidence interpretation by qualified experienced professional have been suggested yet the associated error rates, the magnitude of the problem and how often or how readily it plagues the interpretation made my eminent bloodstain pattern analysts still remain debatable.

5. Contributions to Mend Loopholes

From the information provided in the previous sections of the document, one can very well conclude that bloodstain pattern analysis is indeed an interdisciplinary study area that has generous contribution from fields of mechanics, physics, mathematics, computer science, chemistry and medical science. Substantial work has been done with relevance to the target surface and how it affects the formation of bloodstain patterns. But there still remain certain loopholes as mentioned in Section 4(Controversies). As illustrated by MacDonnell, stain patterns cannot be expressed as a function of velocity. The idea of the research undertaken by Kabaliuk *et al*. was to analyze drip stains from hand held weapons. Kabaliuk *et al*. in their work analyzed the parameters that affect the formation of a passive drip stain in a crime scene. As per Kabaliuk *et al*., as the object size increased the number of accompanying passive drops also increased. The size of the primary drop size was reported to decrease from a blunt to a sharp object. As is quite evident, the idea that propels the Bloodstain Pattern Analysis is the ability to backtrack from the stain patterns. On similar lines, if the possible sources of a blood drop stain or trail could be identified then that would contribute to the reconstruction process.

In order to mend this loophole within the domain, a supervised learning model (refer Figure 4) has been developed to predict the source of a passive blood drop from the characteristics of the drop (such as length, breadth, angle of impact, fall height, interaction features). Again, these characteristics are only available for a plain/smooth, non-absorbent target surface. The model developed can distinguish between blood drops from target surfaces whose radiuses vary, thereby making it possible to predict the possible source of a drip stain from other circumstantial evidence present at a crime scene. The 'Breadth' of the stain irrespective of angle of impact and fall height was found to be statistically significant towards prediction of source radii from which the blood drop had passively dripped.

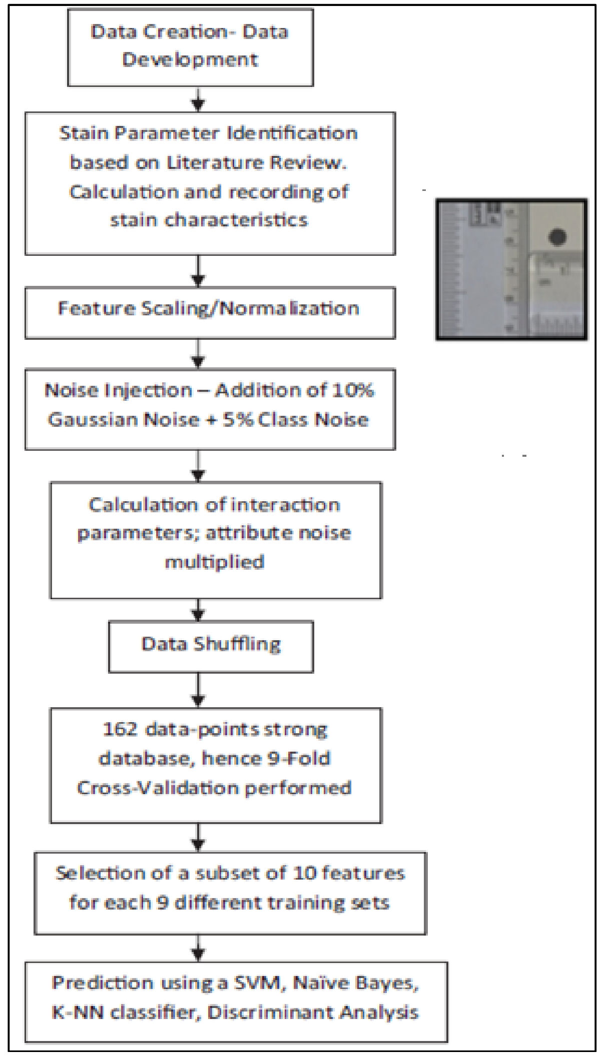


Fig 4: Data model developed to predict the source of single passive drip stains on a plain, smooth, non absorbent target surface

Transfer stains are common stain patterns at a crime scene. Commendable work has been done towards locating and enhancing bloodstain patterns on difficult surfaces. Difficult surfaces in this context include dark colored surfaces, human skin, fabrics etc. [19-21, 60]. Weapons have steep geometric edges. In lieu of circumstantial evidence, it is often straightforward to identify the weapon that had particularly left the imprint. However, prediction of gender from bloody broken prints left at crime scene is way more complicated and difficult to analyze. While fingerprints have been vastly dealt with, work relating to prediction of gender of an individual from broken bloody footprint impressions stands limited.

To mend this loophole a dataset was created to document the bloody footprints/shoeprints of individuals (refer Figure 5 for a snapshot of the dataset). As a precursor, human subjects who consented to be part of the project were asked to step on blood pool and thereby walk on herbarium sheet plank with and without shoe. Five men and five women (i.e total of 10 individuals) in the age group of 18 to 65 years consented to be a part of the experiment. Data collected was curated. Supervised learning techniques were used to predict gender of an individual from a broken bloody footprint/shoeprint irrespective of the color, texture of the target surface on which it was recorded. The features used for gender classification were length of footprint transfer stain, breadth, angle of walking, aspect ratio of stain, length calculation based on closest possible geometric approximation of the stain pattern, breadth approximation, length of approximated digit ends from the approximated tip of foot, heel area etc. Only morphological features are used by the system(refer Figure 6). Hence, other broken foot/shoe patterns (namely, muddy footprint, dirt print etc) can also be used by the system for gender prediction. However, in developing the software only plain, smooth, non-absorbent target surfaces were considered for recording of stain patterns. So on these terms the workings of the software is limited to predicting gender only from a broken footprint stain formed on a plain, smooth, non-absorbent target surface.

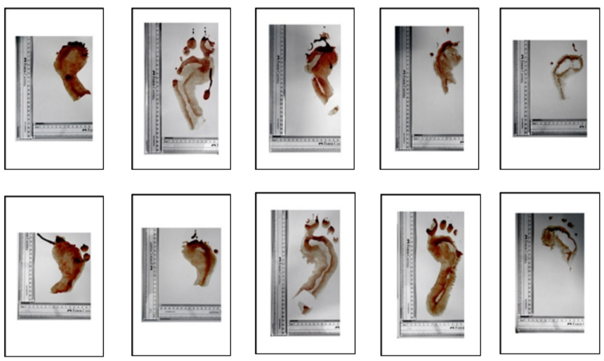


Fig 5: Snapshot of the Footprint database that has been developed. The aspect ratio for each image was maintained when mounting the images on a canvas, so that each image in the database could be of the same dimension (250 x400 pixel^2)

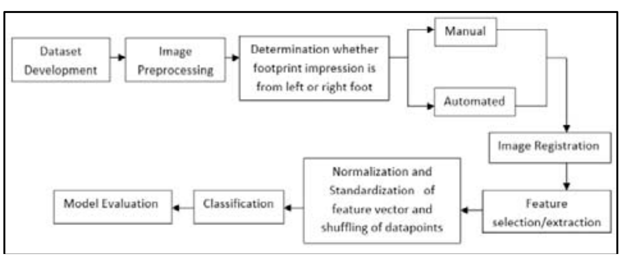


Fig 6: Data model developed for gender estimation from bloody broken crime scene footprint/shoeprint images.

A closer look at the aforementioned methodologies developed shall highlight that both the systems cannot work on prints developed on Fabric as also on other porous /absorbent, rough target surface. In particular fabric stains are difficult to analyze owing to the flexibility of fabric target surface, large variance in the weave, permeability etc. In case an individual faces fear, threat, as a result to prepare him/her for either of the two modes flight or fight, the body starts sweating to regulate the unwarranted increase in body temperature. Such sweating occurs particularly at the armpits, foot and palm soles. From research conducted, it can be safely concluded that presence of water, saliva do affect the formation of stain pattern on clothing. However, an interesting aspect that the authors would want to investigate how sweat on worn clothes affect bloodstain patterns on different types of fabrics. On a more precise note, does sweat affect stains formed on fabric, if at all it does, what are the basic differences that it induces into the pattern?

Again, though attempts have been made to standardize human sweat, it is indeed challenging. Sweat composition is largely dependent on the food habits, ethnicity ad environment an individual lives in. As a result, it is difficult to compare the result of experiments conducted with human sweat. To overcome this anomaly, human sweat was artificially simulated as per the different standards followed internationally and regionally and the effect of the sweat on stain formed was compared against the stain formed on new cloth (i.e. control) using statistical tests. Additionally, the difference in stain patterns on cloth soaked in sweat and hence dried was compared with stains formed on cloth soaked in sweat using statistical tests. To simulate real life situation, cloth shall be washed with detergent and hence soaked with artificial sweat formed as per different standards and its effect on bloodstain shall be tested and compared against control. In order to compare stains on cloth, the stains shall be recorded on the same fabric target surface held at the same tension when blood drips. All the standards however do not include presence of amino acids which is present in human sweat as trace elements. To document the effect/impact of amino acids on the stain pattern formed on fabric and to compare the same with the standards of sweat (both acidic and alkaline) in place, artificial sweat inclusive of all trace elements that could be present in human sweat shall be developed as per the standards well accepted within the scientific community. Testing of the change in stain patterns formed on cloth stained with such artificial sweat shall also be documented.

Work has been undertaken with respect to blunt force trauma and the stains that accompany blunt force hit [35, 54]. In this regard, Dr. Pitrowski's experiment involving live rabbits to record the movements of a victim when it suffers blunt force trauma is of particular relevance. Cast-off stain patterns are common outcomes of blunt force hit. What are the factors that control cast off patterns? What can be predicted from cast off patterns/ cessation cast of patterns? To answer these questions the authors intend to recreate blunt force hit crime scenes with due reference to literature and case studies. It is believed that creating such a database shall help to correlate the position of the victim/s, the stain patterns, the number of blows struck etc. The room dimensions as also the height of an individual shall be varied within tangible and logical limits to investigate how these parameters affect the formation of stain patterns at a crime scene when a blunt force hit is made. For real life simulation, the movement of the neck, the hip joint, the knee joint shall be replicated. Being computer science professionals, the aim is to use semi supervised learning techniques and bloodstain patterns on ceiling, walls and other circumstantial evidence shall be used as features to provide probabilistic prediction the positions of the victim, perpetrator, bystander/eyewitness(if any), thereby inducing more objectivity into the study and interpretation of bloodstain patterns using statistical methods. The methods developed as part of the research work shall be aimed to add objectivity to the process of crime scene reconstruction based on bloodstain patterns in coherence with other circumstantial physical evidence. Figure 7 provides an elaborate documentation of the research plan that shall be executed in due course of time.

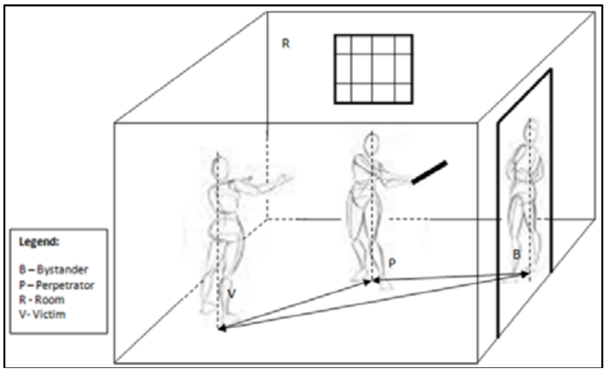


Fig 7: A 3 dimensional representation of a head hit scenario indoors (Blood stains haven't been marked in the 3D representation)

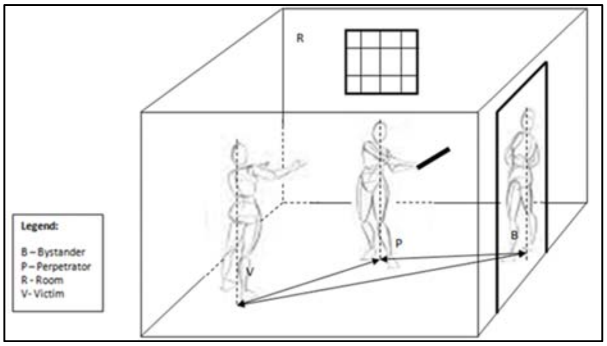
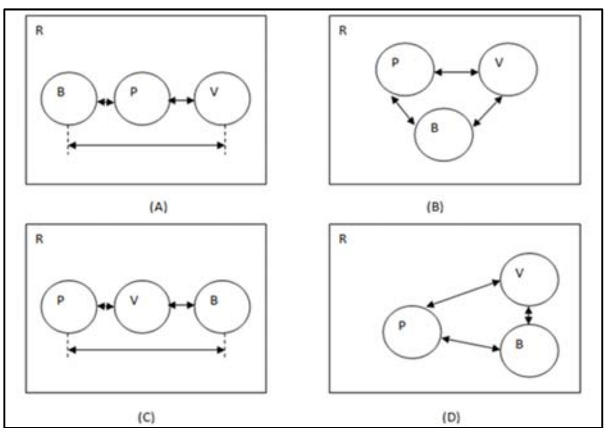
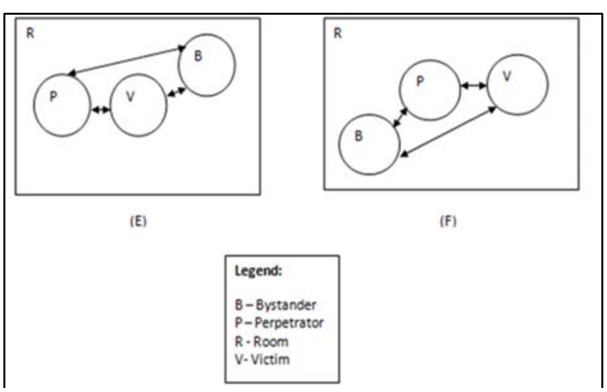


Fig 8: provides all possible relative positions of the victim, bystander (if any) and the perpetrator indoors for the event of blunt force trauma being suffered by the concerned victim.





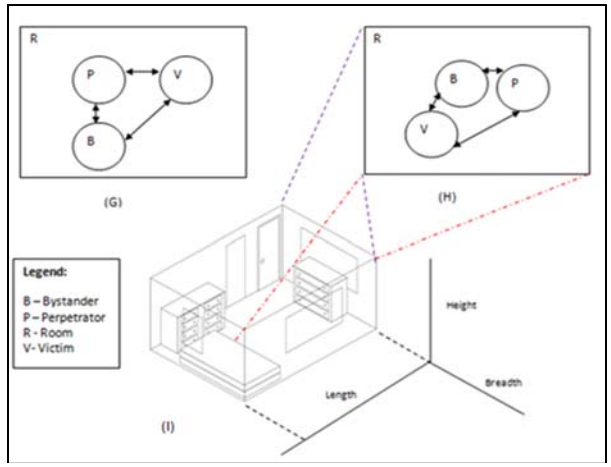


Fig 8: (A-H) 2 Dimensional representation of the position of a victim, perpetrator and bystander (if any) along with their relative positions represented by double headed lines, (I) Figure I represents the 2D representation of a 3D room. In all the Images, B represents the position of the Bystander, P represents the position of the perpetrator, R represents the room and V represents the Victim (refer Legend). Similar images can also be generated in an outdoor environment.

6. Conclusion

The research work on BPA in its very core is based on the age old Biblical dictum "Blood never lies". The authors believe that the multidisciplinary nature of bloodstain pattern analysis is what truly makes this domain of study lucrative and indeed interesting. The fact that blood follows the laws of fluid mechanics and reacts similarly under similar physical conditions forms the basis of bloodstain pattern analysis. From the literature and from case study experience the authors conclude that the basic most common bloodstain patterns that an individual can expect to see when an individual is hit by a blunt ended object are– transfer stain patterns from fingers, weapon, saturation stain patterns, impact spatter, cast off pattern and even expirated stain patterns on certain occasions. These can be accompanied by drip trail patterns, flow, wipe and swipe patterns as well. But this work is particularly focused at studying the most common pattern stain associated with blunt force hit. From literature review it can be safely concluded that various surfaces, concrete, fabric react differently to bloodstain dropped by similar physical mechanisms. There also exist intra- surface differences that impact or rather influence the formation of bloodstain pattern formation. For example, fabrics based on texture, porosity, absorbing power impact the formation of the bloodstain pattern. Again, study shows volume of blood, impact force as also fall height have significant effect on bloodstain pattern formation.

Proper documentation of crime scene is the first step towards accurate interpretation, reconstruction and hence presentation of bloodstain pattern evidence within a legal setting. Guidelines for proper documentation of crime scene bloodstain pattern are well laid out in the book 'Bloodstain Pattern Analysis – an introduction to crime scene reconstruction (3rd. edition)' by Bevel and Gardener. A well accepted classification of bloodstain patterns based particularly on the mechanism of formation of the bloodstain patterns have been put forward by Stuart H. James. Work on the fluid dynamics of bloodstain patterns have been well reviewed by Daniel Attinger.

Owing to case studies put forward by Peter D. Barnett, Charlie Marie, Scott Lament, one could very well infer the critical role that foot, finger, palm and weapon transfer stains play in crime scene reconstruction. Again wound analysis helps the study of bloodstain patterns thereby helping the analyst in drawing up inferences relative to the type of tool that had been used to cast the wound.

There are well drawn up methodologies in place for directional analysis, location of the area of origin of an impact spatter in a crime scene. Tools like Back Track and Hemospat have truly aided the rigorous manual process of bloodstain pattern interpretation that was undertaken by analysts in previous times.3D virtual representation of a crime scene adds to the suite of technical support that is available to crime scene analysts.

Dr. Pitrowski's experiment involving live rabbits to record the movements of a victim when it suffers blunt force trauma, is of particular interest to the authors. In order to fill in the gaps within the literature on bloodstain pattern analysis, the authors intend to build a system that could correlate the bloodstains on the clothing of the individuals to other bloodstains at the crime scene, based on which it could thereby make probabilistic predictions on the positions of the victim, perpetrator, bystander/eyewitness(if any). The authors believe that such a system would add objectivity to the inference that could be drawn about the position of individuals in a crime scene together with predicting their role in the same. As per the FBI chart report, each year more people are killed by blunt force hit as compared to the number of people killed by rifle or shot gun. Therefore, at the very onset the authors would like to focus on study and re-creation of criminal events involving blunt force hit. In due course of time this work can be extended to bloodletting events involving knife, rifle and shotgun respectively.

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