Software for the trajectory analysis of blood-drops: a systematic review

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Abstract

Blood-drop trajectory analysis can provide investigators with retrospective information regarding the spatial positioning of an injured person. To assist with bloodstain pattern analysis, various commercially available software have been developed and deployed. A systematic review was conducted to understand the extent of experimental validation and applications of blood-drop trajectory analysis software to case work. Ninety-two sources between 1987 and 2020 were identified including peer-reviewed studies and commercial websites. Thirty-four of these were validation studies, of which, only two involved impact patterns generated from greater than 1m from the main target surface. Fifteen software were identified during this review with six documented to have been applied in casework. The reviewed software do not appear to fully satisfy relevant forensic validation criteria, based on publicly available literature. In some cases, software underwent limited experimental validation prior to real-world application with subsequent references to this in later literature. This review provides forensic investigators and bloodstain pattern analysts with a comprehensive overview of all available software options, knowledge of the extent of research into validating these techniques and highlights documented applications of these software in criminal cases.

Keywords: Bloodstain Pattern Analysis; BPA; laser scanning; forensics; crime

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Bloodstain Pattern Analysis (BPA) is a forensic discipline which analyzes blood and bloodstains to aid in the reconstruction of events at a crime scene (Bettison et al, 2020). Any number of different stains and patterns may present themselves at a scene including transfer stains, projected patterns, expiration patterns, impact patterns and others. Due to the number of variables involved, analysts' findings are primarily based upon interpretation of the evidence, informed by their observations, training and experience (Peschel et al, 2010). However, uncertainties in BPA can be significant with analysts drawing variable and sometimes erroneous conclusions (Comiskey et al, 2017; Hicklin et al, 2021. The National Research Council (NRC, 2009:p179) stated that 'uncertainties associated with bloodstain pattern analysis are enormous' and conclusions derived are mostly subjective, rather than scientific. Quantitative approaches, including software, have been explored to provide greater objectivity, reproducibility and traceability to some aspects of BPA.

There are a number of commercially available and open-source software for blood-drop trajectory analysis which are sometimes advertised as BPA software or plugins (HemoSpat, 2020). However, these applications only provide one specific type of BPA; the estimation of Area(s) of Origin (AO) of a bloodletting event. The AO is typically calculated by the measurement of elliptical, directional bloodstains and consequent linear trajectory analyses. These software packages are computer-based alternatives to manual stringing (Carter et al, 2005) and consequently a tool for the analyst, not a replacement of the expert (Gardner, 1995). An accurate and reliable determination of the AO can provide investigators with knowledge of where the Injured Person (IP) was positioned when they were assaulted (Peschel et al, 2011).

Therefore, there is a clear rationale for forensic investigators to conduct AO analyses in order to ascertain information in crime scene reconstructions.

Forensic Standards for BPA

Any new method used to generate forensic data is required to have been validated and peer-reviewed to ensure admissibility in court trials (CPS, 2021). The UK Forensic Science Regulator (FSR) specifies that validation provides assurance that a forensic method is reliable and that the *"importance of ensuring that methods are validated before they are used in casework should, therefore, be self-evident"* (FSR-G-201, 2021:p9). It is imperative that any conclusions drawn from AO calculations are accurate and interpreted with an awareness of the limitations derived from comprehensive experimental testing. Section 9.1.7 of the FSR Code of Practice and Conduct for BPA states that *"computer-assisted methods (and software used) shall be validated"* (FSR-C-102, 2021:p16). Specific developmental validation requirements for new BPA methods in the UK are defined in the ANSI/ASB Standard 072 (ASB, 2019). One condition of developmental validation is that it must be appropriately documented and *"peer reviewed within the scientific community"* (ASB, 2019:p3). Developmental validation requires *"a description of the applicability of the procedure"* (ASB, 2019:p3) and: *a) Specificity studies, b) Sensitivity studies, c) Reliability studies, d) Accuracy studies and, e) Testing of the limitations*. In addition, European guidelines advise that forensic evaluative opinions must also be accompanied by a likelihood ratio or a verbal equivalent (ENFSI, 2016). These evaluations are to be considered meaningful only when two or more competing and mutually exclusive propositions are considered (FSR-C-118, 2021:p16). Furthermore, any forensic evaluative opinion must be founded on a "*sound scientific basis and validated such that any limitations are known and transparently reported"* (FSR-C-118, 2021:p16).

In the USA, the Daubert standard is used in federal courts, and some state courts, to determine the validity of a forensic method (Legal Information Institute, 2021). The criteria include: *"(1) whether the theory or technique in question can be and has been tested; (2) whether it has been subjected to peer review and publication; (3) its known or potential error rate; (4) the existence and maintenance of standards controlling its operation; and (5) whether it has attracted widespread acceptance within a relevant scientific community."* The Scientific Working Group on Bloodstain Pattern Analysis (SWGSTAIN, 2021) and the National Institute of Standards and Technology (NIST, 2021) also detail similar requirements to the Daubert standard and the ANSI/ASB Standard 072. Clearly, for admission as evidence in court, forensic methods and processes need to be reliable, validated and robust with strong consensus amongst the scientific community, often achieved through peer-reviewed studies. Reliability, validity and robustness of forensic methods are especially vital for BPA, in light of the NRC report (NRC, 2009).

Objectives

The purpose of this review paper is to; i) identify all software options available for the determination of AO in BPA, ii) identify accompanying validation research for each software and report on the software error [1], iii) determine the extent to which research has met forensic standards such as the UK's ANSI/ASB Standard 072, iv) consider what further work is required to meet the required standards for BPA software application. This review will include any

[1] The Daubert standard (Legal Information Institute, 2021) refers to the "error rate" which, for the purposes of the content of this review, would be the percentage of occurrences whereby an AO estimate corresponds with the known AO. No validation paper within this review reported a true percentage error rate. This review will focus upon the "error"; the measured difference between the estimated AO and the known AO, and the "tolerance"; a numerical value that gives a maximum error value to be tolerated.

documented application of digital AO software in forensic casework and identify any areas for further research that should be addressed to validate specific techniques, as well as provide investigators with knowledge of different software options and the extent to which they have been researched and documented.

Search Strategy

A number of databases were used to collect sources including peer-reviewed scientific literature, dissertations and theses, news articles and trade journals. This ensured that the review gained an understanding of the validation research and an awareness of any potential applications or commercialisation of the AO software. Search terms were chosen to yield a broad range of results, in order to minimize the chance of excluding relevant sources. The titles and abstracts of the search results were initially sifted according to the inclusion criteria detailed.

Inclusion criteria

i. The document details the controlled testing of AO software. AND/OR

ii. The document details the application of AO software in a criminal investigation.

At this point, 72 sources were selected from the database searches which are listed in Table 1. In addition, the reference lists and citation lists of selected sources were examined for any further relevant literature that was missed by the database searches. Websites of AO software identified from the searches were also searched for any additional literature. On 2nd December 2020, a Forensic Science International email alert notified the author of the publication of another article relevant to this review, which was consequently included (McCleary et al, 2021). In total, 20 additional sources were identified as a result of this part of the search strategy. Therefore, 92 sources in total were selected for this review (Table 1).

In Web of Science and Scopus, the search terms were used to search all fields. 48 sources were selected as relevant from the Scopus database, but 9 were duplicates from Web of Science, resulting in a total of 39. ProQuest Dissertations and Theses yielded 96,810 results when searching the full document text, so the search was narrowed to the search terms within the abstract. The Nexis News database yielded 1552 results and these were filtered by the keyword "blood" and the subjects "Crime, Law Enforcement and Corrections *or* Criminal Law *or* Criminal Offenses *or* Law Enforcement" in order to focus the results. Eight documents were inaccessible to the researcher for this review (Carter, 1991; Carter, 1995; Carter & Laturnus, 1995; Laturnus, 1998; Carter & Laturnus, 2000; Wright, 2002; Collins et al, 2003; Iul et al, 2014). In particular, a number of resources from the IABPA News prior to June 2000 were no longer available to the public on the IABPA website and required membership for access. Finally, data regarding the year of publication, author, author's institution and geographic location was collected from each source.

Table 1: Databases and Search terms

Database	Search Date	Search Terms	Filters	Results	Selected
Web of Science	06/07/2020	"forensic *or* police" **AND** "software *or* digital *or* 3D *or* computer" **AND** "blood pattern analysis *or* blood pattern *or* BPA *or* blood trajectory"	None	52	13
Scopus	07/07/2020	"forensic *or* police" **AND** "software *or* digital *or* 3D *or* computer" **AND** "blood pattern analysis *or* blood pattern *or* BPA *or* blood trajectory"	None	520	39
ProQuest Dissertations & Theses	13/07/2020	"blood pattern analysis *or* blood pattern *or* BPA *or* blood trajectory" **AND** "software *or* digital *or* 3D *or* computer"	Search **abstract** only	566	4
ProQuest Reports & Trade Journals (ABI/INFORM Trade & Industry)	13/07/2020	"forensic *or* police" **AND** "software *or* digital *or* 3D *or* computer" **AND** "blood pattern analysis *or* blood pattern *or* BPA *or* blood trajectory"	Excluded a range of irrelevant subjects inc. "novels, fiction, parenting, elections".	254	5
Nexis News	20/07/2020	"forensic *or* police" **AND** "software *or* digital *or* 3D *or* computer" **AND** "blood pattern analysis *or* blood pattern *or* BPA *or* blood trajectory"	**Subjects:** "Crime, Law Enforcement and Corrections *or* Criminal Law *or* Criminal Offenses *or* Law Enforcement", **Keyword:** "Blood"	311	11
				Subtotal	**72**
Additional sources (mailing lists, software websites)					20
				Total	**92**

Search Results

Publication by Year

Approximately half (45 out of 91) of the search results were published between 2013 and 2020, with the remaining half (46) published in the preceding 23 years. Since 2008, there has been an average of 5 publications per year, and it is clear from Figure 1 that publication of digital AO software literature has increased in recent years, with peaks of 8 publications in 2016 and 2020. Between 1987 and 2004, there was an average of 1 publication per year. The increase in volume of the literature over time could be explained partly by the development and release of new software. However, some studies were published more than 10 years after the initial introduction of certain software in academic literature (Nowack et al, 2011., Illes & Boués, 2011). This review cannot therefore provide a definitive conclusion as to the increases in volume over time.

The Royal Canadian Mounted Police (RCMP) was the most frequent author institution identified by this review, followed closely by Carleton University which was the institution of BackTrack™'s Alfred Carter, who was also the most frequent author (Figure 3). Institutions such as RCMP and Carleton University collaborated on some studies which would have increased their frequency in this analysis. Ai2-3D is Eugene Liscio's private forensic company and both the institution and author were the 3rd most frequently identified in this review. Yamashita was the 4th most frequent author of digital AO software in this review, however he was never noted as the first, second or third author (Figure 3). Yamashita was 4th author in 5 articles and 8th, 9th and 10th author in 3 others. Yamashita was a common thread in the literature, as he was credited in articles first authored by Carter, Illes, Liscio, Maloney, K and Nowack.

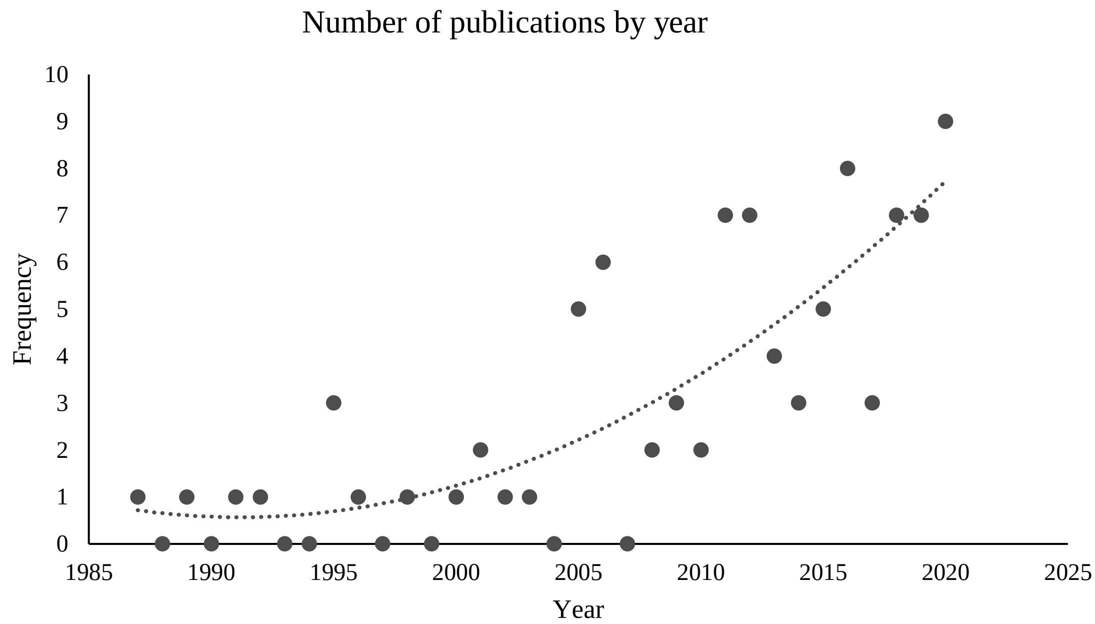

Figure 1. Number of articles regarding AO software published each year between 1987 and 2020.

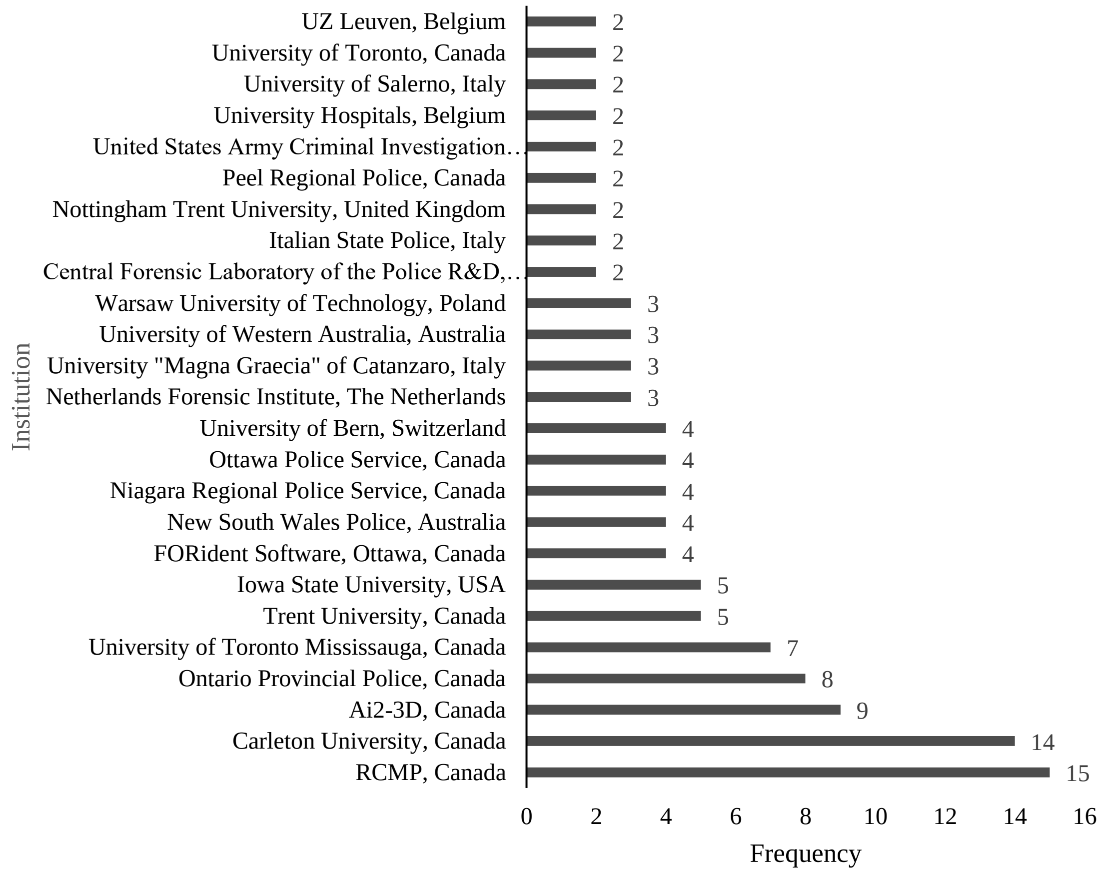

Figure 2. Number of articles published by institution regarding AO software 1987 and 2020

(excluding 57 institutions named in only 1 publication)

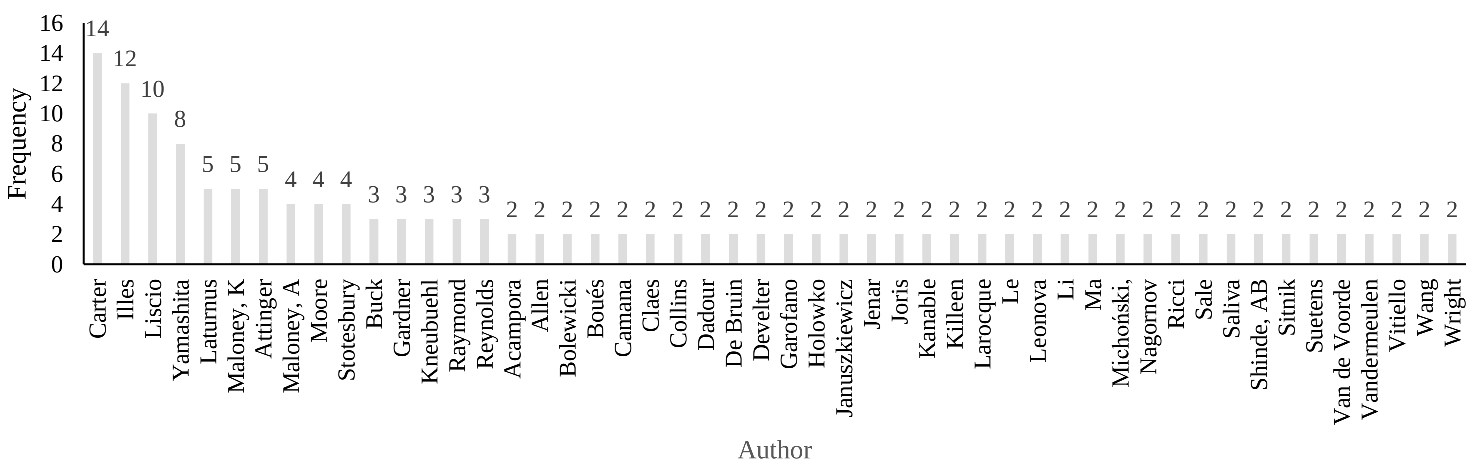

Figure 3: Number of publications by named author (exc. 138 authors named once)

Software Options

Table 2: BPA Software identified during this review, their AO method and analysis approach

Software	**AO Method**	**Bloodstain/Ellipse Measurement**	**Analysis Planes**	**Available?**
Wilson & Schuessler	String	Physical	Two perpendicular surfaces	No
BackTrack™	String	Physical	Orthogonal room/box	No
No More Strings™	Unknown	Unknown	Unknown	No
ESCrime	Unknown	Unknown	Unknown	No
HemoSpat	String	Digital, manual	Flat surfaces	Yes
Microsoft Excel 2003 Autoshapes	Tangent	Digital, manual	Two perpendicular walls	Yes
Buck et al (2010)	Parabolic	Digital, manual	Flat surfaces	No
Attinger et al (2010)	Parabolic	Digital, manual	Flat surfaces	No
Laan et al (2015)	Parabolic	Digital, manual	Flat surfaces	No
Crime Scene Command	Unknown	Unknown	Unknown	No
AnTraGoS	Tangent	Digital, automatic	Single, flat surface	No
HemoVision	String	Digital, automatic	Flat surfaces	Demo
FARO Scene (Forensic Wizard)	String	Digital, manual	Flat surfaces	No
CrimeView3D	Unknown	Unknown	Unknown	No
GigaPan®, Bonaccordo (2018)	String	Digital, manual	Single, flat surface	Yes
FARO Zone 3D	String	Digital, manual or automatic	Any	Yes
Sherlock	String	Physical	Two perpendicular surfaces	Yes
Leica Map360	String	Digital, manual	Any	Yes

Various software were identified during the systematic review and are listed with a broad overview of features in Table 2. In order to provide a clear and thorough account of the literature reviewed and to aid the reader in understanding the development of this field, the different software are described below in the order in which they first appeared in the literature, from 1987 to 2021.

Wilson and Schuessler

The earliest article identified detailed an un-named computer program that analyzed "*medium*" and "*high-velocity*" impact spatter digitally to determine an AO (Wilson & Schuessler, 1987). Wilson and Schuessler (1987) stated that their program had been accepted as a BPA technique and had been utilized in missing person, assault and homicide investigations. In the case of the homicide, Wilson and Schuessler (1987) described that the multiple AOs determined by the software were later attributed to specific injuries. No further articles by Wilson or Schuessler were identified however Gardner (1995) acknowledged the program but stated that they had not seen a working version.

BackTrack™

Two computer programs were presented in 1989 at an International Association of Bloodstain Pattern Analysts (IABPA) training conference by Staff Sgt. Podworny of the Royal Canadian Mounted Police (RCMP) and Dr Carter, a physics professor from Carleton University. DROPLETS was described as a computer aid for teaching the physical laws that affect blood droplet projectiles such as gravity and air resistance. DROPLETS eventually became the program TRACKS, which was specifically designed as a training tool for courses taught at Carleton University and the RCMP. TRACKS was a simulation and not an analysis tool (Gardner, 1995).

TRAJECTORIES was the 2nd program designed to perform calculations for blood drop trajectories (Podworny & Carter, 1989). TRAJECTORIES was later commercially released as BACKTRACK and utilized parabolic trajectories which considered blood droplet volume, air resistance and gravity (Gardner, 1995). BACKTRACK/STRINGS was consequently released and differed to the initial BACKTRACK as it utilized straight-line strings.

In 2001, Carter published a peer-reviewed study which introduced the concept of 'directional analysis' of impact bloodstains which was described as *"a procedure developed by the author … based on the string method"* (Carter, 2001:p173). Directional analysis is a top-view analysis of blood-drop trajectories in the software which provides the analyst with an AO position that negates any indication of height. Projections on a horizontal plane can also be defined as the area of convergence (ASB Technical Report 033, 2017). From 2001, Carter's literature referred to his software as BackTrack™, which involved the collection of blood stain data with a digital camera and a subsequent computer-based directional analysis which Carter (2001) claimed would direct the analyst to a 3-dimensional AO directly above the blood source location. However, the software could only analyse stains collected from perpendicular surfaces, such as walls, floors and ceilings, and couldn't be used to analyse angled surfaces (Maloney et al, 2005).

Carter (2001) performed the first experimental validation of a digital AO method by producing bloodstains with known AOs and applying BackTrack™. These stains were produced in optimal conditions thereby minimizing the potential for error. Carter (2001) concluded that the experiment only validated the directional analysis theory and his method of elliptical stain measurement. Wright (2002) later presented at the IABPA training conference on the validation of BackTrack™ for use in UK casework and Illes (2001) described that BackTrack™ had been applied to cold case work in The Netherlands. Unfortunately, Wright's (2002) presentation is no longer accessible, and no peer-reviewed literature consequently referred to the validation of BackTrack™ for forensic applications specifically in the UK.

Illes and colleagues (2005) tested the accuracy of BackTrack™ for analysing stains from downward moving drops, noting that it was an easier approach compared to manual stringing and tangent methods. Interestingly, Maloney and colleagues (2005) manually integrated BackTrack™ virtual strings into a 3D model created with AutoCAD, to present such evidence in court. However, the submission of BackTrack™ as evidence in court may have been premature as Carter (2005) acknowledged a paucity of BackTrack™ validation studies, despite the program having been commercially available for a number of years.

Cechetto and Heidrich (2011:p370) described BackTrack™ in their conference paper, stating that it was the most used commercial software and *"a reasonably accurate method for most results"*, citing Carter and colleagues' (2006) study. Furthermore, Carter offered BackTrack™ training courses prior to the publication of the validation paper (Carter et al, 2006) to many law enforcement institutions including the Canadian Police College, Arizona Homicide Investigators Association, Federal Bureau of Investigation (FBI), Netherlands Forensic Institute and the RCMP. Kanable (2006a) also noted that police services in 17 states and 12 countries were BackTrack™ customers. Pace and colleagues (2005) applied BackTrack™ at a homicide crime scene, with collaboration from RCMP and Niagara Regional Police Service, Canada. Although this case-study described the application as a proof of concept it did not detail how the BackTrack™ findings were included in investigative and court proceedings.

Carter, in a book chapter explaining the functionality of BackTrack™ (James et al, 2005:p241), described the software as scientifically valid and defendable within any law court. This chapter also contained documented applications of BackTrack™ in criminal investigations, dating back as early as 1999 (James et al, 2005) and included the AO calculation of an expirated bloodstain pattern. Carter co-authored a paper which described BackTrack™ being used by multiple police agencies in Canada, USA and Europe (Nowack et al, 2011; Illes, 2001).

McClorry and Kastelic (2010:p281) described BackTrack™ as having been *"shown to be a robust procedure"* and attempted to apply the software towards the directional analysis of shotgun pellet patterns. They described that their results were not suitable for the judicial system and no further research examined BPA from shotgun pellets with BackTrack™.

Illes and Boués (2011) published a method for improving the accuracy of the BackTrack™ technique. Their statistical model showed that stain zone location was relevant to AO accuracy and highlighted the importance of stain selection in AO estimation. Supported by Carter, Illes conducted more research into the application of BackTrack™ (Connolly et al, 2012; Illes & Boués, 2011) and developed non-orthogonal surface analysis in BackTrack™ but highlighted that the updated version was not commercially available at the time of publication (Nowack et al, 2011). Illes and Stotesbury (2016) described BackTrack™ as a validated digital stringing method, however prior studies had not fully satisfied the validation requirements of relevant forensic standards (ASB, 2019., Legal Information Institute, 2021). At the time of this review, BackTrack™ was no longer available online for purchase.

No More Strings™

MacDonnell (1996) promoted the tangent method in his writing within the IABPA newsletter in 1996 but also acknowledged an interest in BackTrack™ and an appreciation of the graphical aspect of the software. However, he also mentioned another software that had become recently available: No More Strings™ V3, reportedly developed by a company called Miller Forensic Software from California, USA (MacDonnell, 1996). Gardner (1995) described that No More Strings™ was initially developed in 1990. No further literature regarding No More Strings™ was identified by this review process.

ESCrime

Maloney and colleagues (2005) cited Esperanca (2005) who published a paper called *"ESCrime: A new software for bloodstain pattern analysis in 3-dimensions"*. Although this paper is not accessible, it was presented at the IABPA annual conference in October 2005 (IABPA, 2005). The abstract of this paper is viewable within the Journal of Bloodstain Pattern

Analysis from December 2005 (IABPA, 2005). The ESCrime software was developed by the French Gendarmerie Forensic Institute (FGFI) and allowed for the analysis and visualisation of bloodstains within a 3D environment. The abstract suggests that ESCrime was being applied by FGFI crime scene investigators in forensic cases (Esperanca, 2005) however no further information could be identified.

HemoSpat

In 2006, Kanable (2006b) described a new BPA software arriving to the market. HemoSpat was developed by the brothers Andy and Kevin Maloney (Kanable, 2006b) and marketed by the former's company FORident Software. Kevin Maloney had worked with Carter as an author of two BackTrack™ articles prior to the release of HemoSpat (Maloney et al, 2005; Carter et al, 2005). A technical paper was produced that used the same data from a previous BackTrack™ paper (Carter et al, 2005) that Maloney had co-authored. The technical paper was titled *"HemoSpat Validation"* (FORident Software, 2009), however, it may not be considered a suitable validation of software for forensic application by itself. Published on the developer's website, this paper may not have been subject to the same peer-review process required for academic publications and, as such, cannot fulfill the criteria outlined by the ANSI/ASB Standard 072 (ASB, 2019) or the Daubert standard (Legal Information Institute, 2021). Thereafter, a peer-reviewed article showed how HemoSpat could analyse bloodstains on non-orthogonal surfaces (Maloney et al, 2009) which provided a unique-selling-point relative to BackTrack™ at the time, in addition to computer-mouse controlled ellipse fitting (FORident Software, 2009).

HemoSpat was still commercially available at the time of this review and their website lists many customers including a number of USA and Canadian police forces, as well as Dubai

Police, Israel Police, the Swiss Forensic Service, Netherlands Forensic Institute and the Belgian Federal Police (FORident Software, 2020). Anecdotally, HemoSpat and BackTrack™ has been described as *"being widely used in the field"* (Polacco et al, 2018:p64).

A study that directly compared the accuracies of BackTrack™ and HemoSpat found forensically irrelevant differences between the two (De Bruin et al, 2011). Impact stains were generated from known AOs 50cm and 100cm away from the target surface, the latter being a greater distance tested than in previous validation studies (Carter, 2001; Carter et al, 2006).

De Bruin and colleagues (2011:p1481-1482) made recommendations for improving the AO accuracies with the two software including; i) choose bloodstains that are closest to the presumed position of the blood source, ii) choose large bloodstains (width >1.5 mm), iii) choose bloodstains that have a distinct elliptical form, iv) use bloodstains from more than one wall, v) be cautious in using HemoSpat and BackTrack when the blood source is presumably more than 50 cm away. De Bruin and colleagues (2011p1481) advised caution in analyzing stains from blood sources greater than 50cm away from the target surface. However, digital AO analysis for distances less than 50cm would likely not require software, suggesting that validated investigative applications could be redundant. De Bruin and colleagues (2011:p1481) also stated that HemoSpat and BackTrack™ *"are both used at crime scenes to estimate the PO of an impact pattern"* (PO: Point of Origin; another term for the AO). This admission was not supported by a citation but contributed to a developing narrative within the literature that these software were being commonly deployed in criminal investigations, despite there being a lack of case-study based documentation publicly accessible or at least discoverable by this review process.

Maloney and colleagues (2011a) applied the HemoSpat software towards visualising cast-off stains in an experimental setting. Cast-off patterns were generated from bloody objects moving through the air, including a hammer, a knife and a spring-loaded device, resulting in the detachment of blood drops which projected onto a surface (Peschel et al, 2011). This study served as proof of concept for the digital analysis of cast-off stains, but it recommended further research with known planes of motion under controlled conditions (Maloney et al, 2011a). Maloney and colleagues (2011b) then tested the accuracy of AO calculations with a single bloodstained surface and concluded that it was feasible for BPA analysts to perform digital AO calculations in these conditions in casework, describing that their accuracy results complied with literature tolerance standards. However, their known AO did not exceed 30cm from the target surface and the literature tolerance that Maloney and colleagues (2011b) cited was their own previous HemoSpat study (Maloney et al, 2009). Davison and Palmbach (2014) tested the effects of stain measurement error upon AO calculations within HemoSpat and with the tangent method and found no substantial effect. Small stains with an upward directionality that resided close to the "perceived area of convergence" (Davison & Palmbach, 2014:p202) were selected and the AO was located at a distance which did not exceed 61cm from the target wall. The authors of this work suggested that the choice of these parameters minimized the potential for gravity and drag to affect the trajectories of the blood-drops in the air, encouraging travel in straight lines and reducing the potential for error in analysis (Davison & Palmbach, 2014).

An instructive article for Crime Scene Investigators (CSIs) described how to collect impact pattern data from scenes for BPA experts to analyse with HemoSpat off-scene (Gardner et al, 2012). The accuracy of BackTrack™ and HemoSpat was comparatively tested, with the former achieving more accurate results, but it was concluded that both software performed to specification. Maloney, developer of the HemoSpat software, was acknowledged for his assistance in Gardner and colleagues' (2012) article.

Microsoft Excel 2003 Autoshapes

Reynolds and colleagues (2008) conducted a study that preliminarily validated the computer-assisted impact bloodstain elliptical measurement techniques in BackTrack™ and Microsoft Excel 2003 Autoshapes. However, they did advise that further research should test the accuracy of these elliptical measurements upon surfaces of differing charactisteristics (Reynolds et al, 2008). They also utilised Microsoft Excel 2003 Autoshapes and BackTrack™ to help prove the concept that smaller elliptical impact stains were now suitable for AO calculations, as a consequence of the introduction of digital techniques (Reynolds et al, 2009). However, they recommended that further research was warranted and urged caution when bloodstains smaller than 3.0mm were used for digital AO evidence in justice systems (Reynolds et al, 2009).

Ballistic analyses

Buck and colleagues (2010) published examples of laser scanning and photogrammetry for 3D BPA modelling. Aiming to develop upon straight-line trajectory software (Carter et al, 2005), they utilised ballistic software to generate parabolic trajectories from impact bloodstains and visualise multiple AOs in two criminal investigations in Switzerland. They concluded that their ballistic analysis enhanced forensic conclusions and provided investigators with evidence regarding the AO, minimum number of blows and the reconstruction of events (Buck et al, 2010). Kneubuehl (2012), a member of the same academic forensic institution as Buck, published a paper regarding the same ballistic analysis of the two cases from the previous study (Buck et al, 2010). Kneubuehl (2012) highlighted how their analysis had aided in disputing the claims of the defendant. Murray's (2012) Masters thesis appeared inspired by Buck and colleagues (2010) study and noted the disadvantages of straight-line trajectories and recommended a ballistic analysis for when stain impact angles exceeded 10°.

Pizzola (2012) published a commentary of Buck and colleagues' (2010) study that criticised fundamental premises of the analysis, and the lack of experimental validation. Pizzola (2012) argued that Buck and colleagues (2010) had wrongly assumed that blood drops travelled through the air as a sphere and that calculating the volume of a blood drop with stain width was questionable. Buck and colleagues' (2010) study relied upon an assumption that the diameter of blood-drops could be determined by the minor axis of the elliptical bloodstain. However, this is conceptually incorrect, as explained in Attinger and colleagues' (2013:p387) description and illustration of the lateral spreading of obliquely impacting blood-drops, which clearly demonstrated how a blood-drop can create a bloodstain with a minor axis larger than the diameter of the drop. Buck and Kneubuehl (2012) responded to Pizzola's (2012) commentary by arguing that the calculations did not need to be that precise but did not directly respond to the criticism of applying a novel technique to forensic casework without requisite validation. Ceccheto and Heidrich (2011) presented a conference paper for a parabolic trajectory AO method and applied an experimental approach to their study, but their conclusion was that extensive further research would be needed before applying their algorithm in forensic casework.

Fetisov and colleagues' (2017) review paper, (google translated from Russian to English), cited Buck and colleagues' (2010) study throughout. They reviewed foreign literature regarding photogrammetry in forensic bloodstain investigations and concluded that it was feasible to incorporate similar techniques in forensic medical institutions of the Russian Federation. Zotova and colleagues (2018) referred to Fetisov and colleagues (2017) and described how promising they observed these technologies to be. Buck's (2019) article reiterated that 3D BPA could provide investigators with information regarding the number of violent impacts, citing Buck and colleagues' work (2013). Despite Pizzola's (2012) criticisms, Buck and colleagues' (2010) study has been cited by 83 authors.

Attinger and colleagues (2013) highlighted relationships between fluid dynamics topics and BPA in their comparative review, including the study by Buck and colleagues (2010). Attinger and colleagues (2013:p384) described these digital AO software solutions as being *"routinely used in crime scenes"*. Kunz and colleagues (2015) documented the application of ballistic analysis for bloodstain trajectories in death investigations which supported Attinger and colleagues' (2013) statement regarding crime scenes. A fluid dynamic method, developed by Attinger and colleagues (2019), was described as being able to determine AOs greater than one metre away from the stained surface, within a tolerance of 10cm. They also stated that their errors did not increase with greater distances.

After De Bruin and colleagues' (2011) study comparing the accuracies of HemoSpat and BackTrack™, their research focus shifted towards a fluid dynamic model for AO determination (Laan et al, 2015). They (Laan et al, 2015) stated that their fluid dynamic model would provide investigators with the opportunities to link particular impact stains to sitting or standing IPs, and even particular wounds upon the body. However, they did also highlight that their study served only as a proof of concept (Laan et al, 2015), suggesting that further research would be needed before forensic application.

Crime Scene Command

Chapter 8.8 of Nissan's (2012) book argued that law enforcement officials found programs such as BackTrack™ and HemoSpat difficult to learn and required classroom instruction. Crime Scene Command was created by the company On Scene Forensics with the intention of providing a more user-friendly software to law enforcement. However, this review could find no further literature resources or websites that detail Crime Scene Command or the company On Scene Forensics.

AnTraGoS

Camana (2013), of the Italian State Police, outlined their own probabilistic solution to digital blood-drop trajectory analysis with their software AnTraGoS (*https://sites.google.com/site/bpantragos/home/en*). This software used an algorithmic approach involving a probability density map for the determination of the area of convergence, a calculated area where blood-letting occurred in a 2-dimensional, horizontal plane. Camana (2013) described AnTraGoS as approved for internal use only and that it was employed by the Italian State Police' Forensic Science Service. In what capacity this software was deployed was unclear, as no case-study application was documented in Camana's (2013) paper. Consequently, no further literature was discovered regarding AnTraGoS until 2020. Camana and Gori (2020) explained that AnTraGoS had been deployed by Italian State Police for almost a decade. Camana and Gori (2020) produced a study that aimed to validate their software; however, it does not appear to have been published in a journal or subjected to peer-review.

HemoVision

The concept of automatic bloodstain ellipse recognition was initially explored both by Shen and colleagues (2006) and Boonkhong and colleagues (2010). Boonkhong and colleagues (2010) attempted to simplify the process but did note that their results would need manual adjustments in some cases in order to improve the accuracy by up to 300%. In addition, a conference paper on automatic BPA, detailed the use of drones at crime scenes to collect photographic data of impact stains and analyse them (Acampora et al, 2016). However, no consequent drone BPA research has been published.

An Active Bloodstain Shape Model (ABSM) was developed by Joris and colleagues (2014) which they argued could perform better than previous methods for automatic ellipse fitting (Shen et al, 2006; Boonkhong et al, 2010), allowing for a quicker, more accurate and objective analysis of impact stains. The ABSM was a database of stains with known impact angles that automatically learned shape variations. A statistical shape model *"linked to impact angles through a polynomial regression"* allowed for the analysis of new bloodstains to derive their impact angle (Joris et al, 2014:p189).

Joris and colleagues (2015) went on to publish a paper in Forensic Science International which presented HemoVision; a digital impact stain software that had integrated the ABSM and provided an automated approach to perspective distortion from the digital photography of impact stains. They argued that HemoVision was less time costly than BackTrack™ and HemoSpat but that it did not provide an AO analysis. They also explained that HemoVision trajectories could be integrated with the HemoSpat software for AO analysis. Joris and colleagues (2015) suggested that their HemoVision method was applicable to real criminal cases but required further validation tests. At the time of this review, HemoVision was not yet commercially available (*https://hemovision.be/*) and there appears to be no publications involving the independent testing of the software or the ABSM.

FARO Scene

Eugene Liscio is the founder of Ai2-3D, a forensic service company, which supplies training courses in BPA with FARO Scene and FARO Zone (Ai2-3D, 2020). Hakim and Liscio (2015) introduced the FARO Scene AO software plugin to academic literature, utilizing a laser scanner and digital camera to collect the measurement data. The laser scanner collected lower resolution data of the scene, whilst a digital camera captured high-resolution photographs of the stains, which were then registered onto the scan data's surfaces. The controlled testing of the AO accuracies did not exceed distances of 80cm from the front wall, however this was more than had been attempted in previous validation studies for digital BPA software (Carter et al, 2006; Maloney et al, 2011b; Davison & Palmbach, 2014), but not as much as De Bruin and colleagues (2011). Hakim and Liscio (2015) cited Carter and colleagues' (2006) paper for an acceptable tolerance of 20cm. FARO Scene has been compared against HemoSpat; revealing similar AO accuracies from controlled impact patterns (Liscio et al, 2015).

Dubyk and Liscio (2016) suggested that HemoSpat is a traditional method of BPA, but this has been disputed (Vitiello et al, 2016). However, Liscio conducted research with police organisations in Canada, and could have had an insight into standard processes. They compared a FARO Scene analysis with HemoSpat in controlled conditions and concluded that the FARO method was less time-costly.

Lee and Liscio (2016) stated that BackTrack™ and HemoSpat had been used in real crime scene investigations, and cited Maloney and colleagues (2009) and Nowack (2011) but neither of these papers described any case-study application of the software. Lee and Liscio (2016) described a general agreement within the literature for an acceptable tolerance, citing Bevel and Gardner (2008), his own previous study (Hakim & Liscio, 2015) and others (Peschel et al, 2011; Shen, 2006; Karger, 2008).

Lee and Liscio (2016) described a success in a previous study (Hakim & Liscio, 2015) for achieving results within a literature accepted tolerance of 30.5cm. However, in their previous article they had described Carter and colleagues (2006) study as presenting a 20cm tolerance. This 30.5cm tolerance, mentioned by Lee and Liscio (2016), most likely originated from Bevel and Gardner (2008). The main conclusion of this study revolved around the results of the FARO

Scene method being within an acceptable tolerance, therefore justifying the software's use as an alternative to HemoSpat and BackTrack™ (Lee & Liscio, 2016), however multiple tolerances were being referred to in the literature. Liscio also attempted to apply FARO Scene AO analysis to bloodstains applied to a car door (Kwan et al, 2016).

Raneri (2018) and Aquila and colleagues (2019) described a range of applications for laser scanning technologies in crime scene investigation, including BPA. Carew and Errickson (2019) stated that criminal investigators could utilise 3D imaging for BPA, citing Hakim and Liscio (2015) and Raneri (2018). However, neither Hakim and Liscio (2015) nor Raneri (2018) provided examples of case-work applications of digital AO tools.

CrimeView3D

Holowko and colleagues (2016) also utilised various laser scanning technologies to document a simulated murder scene and conduct an AO analysis, however they did not outline the use of any particular digital stringing software. In a conference proceeding that Holowko collaborated on, Adamcyzk and colleagues (2017) described a new software for crime scene documentation, including searching for the sources of blood spatter. This conference proceeding contained the same image of digital stringing from Holowko and colleagues (2016) study and named the software as CrimeView3D. However, at the time of this review no further literature has described CrimeView3D and it does not appear in online search engines.

GigaPan®

Bonaccordo's (2018) Masters thesis documented panoramic blood spatter images being integrated with the GigaPan® system to perform trajectory analyses. Bonaccordo (2018) investigated multiple parameters including the hardware settings and distance between camera and subject in order to improve the dimensional integrity of the panoramic images. Bonaccordo

(2018) also conducted an accuracy validation study. Further research has not documented this particular method but it is included in this review for completeness.

FARO Zone 3D

Liscio (2018) published a preliminary validation study of FARO Zone 3D (FZ3D), a separate FARO software application for digital AO analysis introduced in 2018 (Le & Liscio, 2019). Liscio (2018) argued that there were no established tolerances for AO analysis but referred to Carter and colleagues' (2005) paper which reported errors of no greater than 20cm. However, this differed with Liscio's previous studies where a 30.5cm tolerance was described as successful (Hakim & Liscio, 2015; Lee and Liscio, 2016).

Patterson (2018) submitted a thesis regarding the calculation of AOs with FARO Zone 3D. Patterson (2018) credited Liscio for the majority of validation tests in the field. They also mentioned a 7cm acceptable tolerance outlined by Dubyk and Liscio (2016) although this seems to conflict with the acceptable limit outlined in Lee and Liscio (2016). Patterson's (2018) research was far more extensive than previous studies (Dubyk & Liscio, 2016; Lee & Liscio, 2016) as it tested a number of different substrates including stainless steel. Patterson's (2018) research rejected the validity of FARO Zone 3D for AO determination and listed a number of problems with the software. However, he argued that FARO Zone 3D had potential if it were to undergo substantial revision.

Le and Liscio (2019) directly compared the performance of FARO Scene's AO tool, with FZ3D. Le and Liscio (2019) described FARO Scene as already validated and that previous research had been extensive. Le and Liscio (2019) cited Bevel and Gardner (2008) for a literature tolerance of 30cm. This contradicted the previous tolerance of 20cm referred to in Liscio's (2018) previous FZ3D study. Le and Liscio (2019) found no statistical difference between errors generated by FARO Scene and FZ3D, but calculated AOs did statistically differ from the known. FZ3D was found to be more accurate than the manual stringing method in one study (Esaias et al, 2020), under certain conditions. However, the calculated AO's distance from the wall was always an underestimate, and this effect increased by a greater degree as the true AO's distance from the wall increased. Research has recently focused on the application of FZ3D for the analysis of cast-off stains (Liscio et al, 2020; McCleary et al, 2020), which as a concept had only been examined once before (Maloney et al, 2011a).

An application of FZ3D in a criminal case in China detailed a blood-soaked bed clearly visible in the point cloud data and a FZ3D AO located directly above the blood-staining (Wang et al, 2019). The conclusion from the FZ3D analysis was that an incident occurred on the bed (Wang et al, 2019), however it's likely that this assertion could have been reliably made without the software.

Sherlock

Sherlock was first mentioned in Pollacco and colleague's (2018) paper which compared the accuracy of the program with HemoSpat and BackTrack™ under controlled conditions. No significant difference in accuracy was found between the programs. Sherlock was designed as a training tool for forensic science students at Trent University, Canada (*http://sherlock.trentu.ca/*). Orr and colleagues (2019) validated Sherlock as a training tool for BPA students, finding no statistical difference between results obtained from the program and BackTrack™. However, it was concluded that both programs AO results statistically differed from the true, known AO.

Leica Map360

Leica Map360's BPA functionality was first detailed in a news article (Police1.com, 2020). The article described that *"computer aided software is… well accepted within the* *bloodstain pattern analysis community"* (Police1.com, 2020; Leica Geosystems, 2020). Within the article, a link to a white paper detailing the testing of Leica Map360 was provided. The white paper was authored by Amy Santoro, a forensic scientist at the Johnson County Sheriff's Office Criminalistics Laboratory, USA. Santoro (2020) compared Leica Map360 with HemoSpat and described that there was no industry accepted tolerance for digital AO analysis, but cited Bevel and Gardner (2008) who referred to a 30cm tolerance. This paper was not peer-reviewed and therefore may not be considered a validated forensic technique according to the ANSI/ASB Standard 072 (ASB, 2019) or the Daubert standard (Legal Information Institute, 2021). At the time of this review, no further literature has been published for Leica Map360. However, Leica's website describes the software as: *"Proven. Validated. Reliable."* (Leica Geosystems, 2020).

Software Accuracy Validation Studies

Table 3 details the results of accuracy studies where a known AO was created under controlled conditions and its location compared with the software's AO calculation. Numerous studies created many sets of impact patterns from multiple AOs. Therefore, this table only includes the results from the AO furthest from the target wall. Comparisons between different studies for accuracy should be considered carefully, as there were many variations in experimental methodology including differing definitions of the x, y and z values, as well as impact implements and substrates.

The reported errors, detailed in Table 3 with the relevant caveats, are displayed in Figure 5, with % error displayed in Figure 6. Where some studies defined their x, y and z values differently, as detailed in Table 3, that data has been amended appropriately for Figure 5 (X = distance from main wall, Y = orientation along the wall, Z = height/distance from the floor).

Figure 5 illustrates that there were some major outliers across all 3 values. The greater errors were reported for the Z value. The Y axis had a smaller range of error than the X and Z axes. The largest % error was 63.67% for the Z axis and Figures 5 and 6 reveal that the Z axis had the largest range of error. This suggests that any forensic conclusions drawn from the software regarding the height (Z value) of the AO should be made with a lower degree of confidence than that of the X or Y value.

Study	Software	Blood	Impacts	Substrate(s)	Impact Implement	Droplet Directionality	Max distance from main substrate(s)	Reported Error - X	Reported Error - Y	Reported Error - Z	Notes
Carter (2001)	BackTrack/Images, BackTrack/Win	10ml blood, (undefined)	1	1 wall, white paper	Hammer	Upward	60cm	2cm	4cm	16cm	
Illes et al (2005)	BackTrack™/Images, BackTrack™/Win	10ml blood, (undefined)	1	1 wall	Hammer	Downward	112.5cm	10.0cm	4.4cm	No data	
Carter et al (2005)	BackTrack™/Images, BackTrack™/Win	10ml blood, (undefined)	1	1 wall	Hammer	Upward/Downward	57.1cm	4.0cm	3.0cm	22.9cm	
Maloney et al (2005)	BackTrack™/Images, BackTrack™/Win	"pool of blood", (undefined)	2	2 orthogonal walls, white cardboard	Hammer	Undefined	61cm	1.0cm	2.8cm	3.3cm	
Carter et al (2006)	BackTrack™/Images, BackTrack™/Win	10ml blood, (undefined)	1 or 2	2 orthogonal walls, paper, cardboard or melamine	Hammer	Upward	Full list of results not presented.	No data	No data	No data	
FORident Software	HemoSpat	10ml blood, (undefined)	1	1 wall	Hammer	Upward/Downward	61.1cm	5.0cm	2.2cm	20.5cm	
Maloney et al (2009)	HemoSpat	2ml blood, (undefined)	1	3 white melamine board walls, a table	Hammer	Undefined	71cm	1.0cm	0.2cm	15.1cm	*Table object included.*
De bruin et al (2011)	HemoSpat and BackTrack™	1.5ml, Human blood	1	1 or 2 orthogonal walls	Modified mouse trap	Upward/Downward	100cm	13.1cm	2.3cm	44.6cm	*Maximum errors reported.*
Illes & Boués (2011)	BackTrack™	5ml, sheep's blood	1	1 wall, smooth white paper	Striking device	Upward	40.5cm	0.7cm	0.3cm	7cm	
Maloney et al (2011)	HemoSpat	1.5ml human blood	1	1 wall, paper	Hammer	Undefined	30cm	5.6cm	2.2cm	6.5cm	*Average errors*
Nowack et al (2011)	BackTrack™	10ml, sheep's blood	1	2 orthogonal walls, and a 31°upper, angled surface, white cardboard	Hammer	Undefined	30cm	0.4cm	2.5cm	19.1cm	
Hakim & Liscio (2015)	FARO Scene	5ml, sheep's blood	1	1 wall	Impact rig	Undefined	80cm	11.8cm	1.7cm	26.9cm	*Maximum errors reported.*
Liscio et al (2015)	HemoSpat	5ml, sheep's blood	2	2 orthogonal walls, a box.	Hammer	Upward	60cm	0cm	0.2cm	0.3cm	*Box object included.*
Liscio et al (2015)	FARO Scene	5ml, sheep's blood	2	2 orthogonal walls, a box.	Hammer	Upward	60cm	4.1cm	4.1cm	0.8cm	*Box object included.*
Dubyk & Liscio (2016)	HemoSpat	5ml, porcine blood	1	2 orthogonal walls, plastic sheeting, door and frame.	Hammer	Upward	43.0cm	1.0cm	6.5cm	7.3cm	*Door included.*
Dubyk & Liscio (2016)	FARO Scene	5ml, porcine blood	1	2 orthogonal walls, plastic sheeting, door and frame.	Hammer	Upward	43.0cm	6.8cm	6.5cm	4.9cm	*Door included.*
Illes & Stotesbury (2016)	BackTrack™	Undefined.	1	1 wall, white paper	Striking device	Upward	39.4cm	0.4cm	0.7cm	2.3cm	
Kwan et al (2016)	FARO Scene	2ml, sheep's blood	1	1 car door	Impact rig	Undefined	50cm	8.3cm	1.0cm	4.7cm	*Mean errors reported.*
Lee & Liscio (2016)	FARO Scene	1.5ml, sheep's blood	1	2 orthogonal walls, 20° incline roof and a cuboid structure.	Impact rig	Undefined	80cm	11.5cm	11.6cm	5.3cm	*Cuboid structure included, maximum errors reported.*
Bonaccordo (2018)	GigaPan®	Undefined.	1	1 wall	Undefined	Undefined	Undefined	21.5cm	19.5cm	3.5cm	
Liscio (2018)	FARO Zone 3D	5ml, blood substitute	1	2 drywalls, 118° angle	Impact rig	Undefined	74.8cm	2.3cm	3.3cm	4.6cm	*Y coordinate used for distance from main substrate, mean errors reported.*
Patterson (2018)	FARO Zone 3D	1ml, bovine blood	1	1 wall, textured drywall coated with indoor paint	Wooden trap	Undefined	83.82cm	39.07cm	6.42cm	7.5cm	
Polacco et al (2018)	BackTrack™	3ml, forensic blood substitute	1	1 wall, white paper	Impact device, 3m/s	Upward	26cm	1.6cm	2.1cm	7.5cm	*Average errors*
Polacco et al (2018)	HemoSpat	3ml, forensic blood substitute	1	1 wall, white paper	Impact device, 3m/s	Upward	26cm	2.0cm	2.1cm	7.5cm	*Average errors*
Polacco et al (2018)	Sherlock	3ml, forensic blood substitute	1	1 wall, white paper	Impact device, 3m/s	Upward	26cm	0.9cm	1.7cm	8.1cm	*Average errors*
Attinger et al (2019)	Ballistic analysis	1ml, swine blood	1	1 wall, poster board (smooth and rough), butcher paper	Impact device, various	Undefined	190cm	5.0cm	N/A	8.5cm	*Approx, curved trajectory errors. Reported I Fig 7.*

Le & Liscio (2019)	FARO Scene	2ml, sheep's blood	1	2 walls	Impact rig	Undefined	100cm	4.9cm	5.9cm	30.5cm	*Maximum errors reported*
Le & Liscio (2019)	FARO Zone 3D	2ml, sheep's blood	1	2 walls	Impact rig	Undefined	100cm	3cm	12cm	24cm	*Maximum errors reported*
Orr et al (2019)	Sherlock	2ml, sheep's blood	1	1 wall, white paper	Impact device	Undefined	29cm	4.7cm	0.1cm	6.6cm	*Maximum errors reported*
Camana et al (2020)	AnTraGoS	Undefined amount, swine blood	1	1 wall, poster board sheets	Cylinder, impact rig	Upward/Downward	124cm	1.0cm	N/A	3.0cm	*Average errors. Z is distance from target wall.*
Esaias et al (2020)	FARO Zone 3D	15ml, bovine blood	1	1 wall	Rubber mallet	Undefined	71.5cm	No data	17.3cm	6.3cm	*Y as distance from target wall*
Santoro (2020)	Leica Map360	2ml, sheep's blood	1	2 orthogonal walls, white cardboard	Plastic mallet	Undefined	11.7cm	3.8cm	0.1cm	2.3cm	*Z as distance from target wall, Y as height*
Santoro (2020)	Leica Map360	2ml, sheep's blood	1	2 orthogonal walls, box object, white cardboard	Plastic mallet	Undefined	59.6cm	2.8cm	4.3cm	1.7cm	*Z as distance from target wall, Y as height*
Santoro (2020)	Leica Map360	2ml, sheep's blood	1	2 orthogonal walls, slanted ceiling, white cardboard	Plastic mallet	Undefined	66.8cm	2.7cm	3.0cm	3.1cm	*Z as distance from target wall, Y as height*

Table 3: AO software experimental study parameters

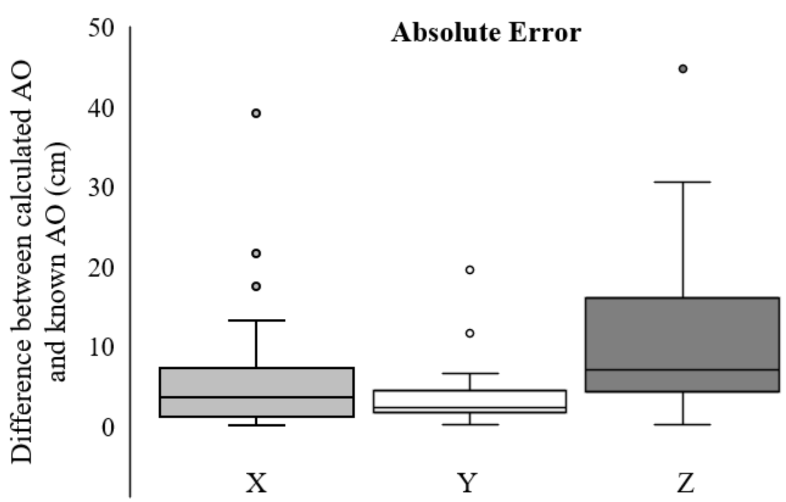

Figure 5: Absolute errors for x, y, z axes

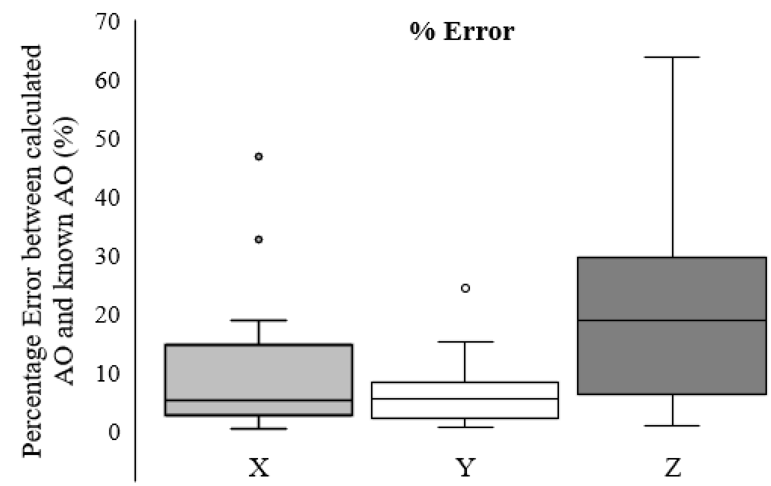

Figure 6: % error for each axis

Conclusion

The initial purpose of this review was to identify all available software for digital AO analysis in order to provide BPA experts with a comprehensive awareness of all available technologies, and their limitations. It is unlikely that every available paper has been collected by this review's systematic search process and some in-house validation testing may not be publicly available. Based only upon peer-reviewed evidence in the public domain, this review suggests that BPA software have not undergone validation testing extensive enough to ensure a robust and reliable application in a forensic investigation. The software has been validated to achieve certain levels of accuracy under very strictly controlled test conditions. However, no published research has proven the conditions in which the software may begin to perform poorly; a requirement for validation as outlined in ANSI/ASB Standard 072. Extensive testing should include creating patterns from distances greater than 1m from the target surface, with various substrates or mock crime scene scenarios. The software must be tested to the point of failure, where AOs cannot be reasonably and reliably identified, and the errors quantified, in order to comply with relevant forensic guidelines. Police and forensic service providers may have conducted additional in-house validation tests that are not publicly available. If these results were to be subjected to peer-review processes and published, forensic standards for validation would be satisfied (Legal Information Institute, 2021; ASB, 2019). Many of the software identified in this review rely upon a straight-line trajectory principle determined by the size of elliptical bloodstains. Thus, extensive validation of one of these software could validate similar software. To this effect, this review strongly recommends that any datasets created during the validation of one or more software should be made available to other researchers to conduct their own experiments, either with a separate software or for the purpose of proving the reproducibility of results.

The review found a lack of published evidence of investigative applications. However, repeated assertions were made within the literature that these software were commonly employed in law enforcement (De Bruin et al, 2011). The documentation of these software being applied in cases may encourage other investigators to adopt the same techniques, without the requisite validation literature having been published to ensure the evidence is later suitable for court.

A number of validation papers referred to differing tolerances for error. Bevel and Gardner (2008) were cited three times in the literature for an AO accuracy standard (Le & Liscio, 2016; Le & Liscio, 2019; Santoro, 2020). A single literature standard for accuracy may be defined by future researchers. In addition to more extensive validation research, future work could also search and examine court records in order to analyse the impact of AO software in criminal justice systems.

Declarations of Interest

The authors declare that they have no conflict of interest.

Author Contributions

Patrick H Home: Study conceptualisation, data collection, data analysis, manuscript writing.

Dr. Danielle Norman: Study conceptualization, academic input, manuscript editing.

Prof. Mark A Williams: Study conceptualization, manuscript proofing.

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