To Ross Gardner
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ARTICLES

THE DIRECTIONAL ANALYSIS OF BLOODSTAIN PATTERNS THEORY AND EXPERIMENTAL VALIDATION

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ABSTRACT

Directional Analysis of bloodstain patterns is a mathematical procedure developed by the author that is based on the string method. It finds the directions in space (virtual strings) that point from the bloodstains to a spot directly above the location of the blood source. When viewed from above, the virtual strings are seen to converge onto the source position. When viewed from the side, the virtual strings provide an upper limit for the probable height of the blood source.

The theory relies only on the well-known physical laws of motion, the resolution of a velocity into its three components and simple trigonometry, and does not depend on unknown quantities such as droplet sizes and droplet speeds. This procedure has a solid basis in physics and mathematics, and satisfies the criterion of sound scientific methodology for bloodstain evidence specified by the courts. Digital cameras are used for gathering the evidence and the analysis is carried out with a computer.

The second part of this paper will describe a laboratory experiment that validates "Directional Analysis" both in theory and in practice.

RÉSUMÉ

L'analyse directionnelle des patrons de projections de sang est une procédure mathématique décrite par l'auteur qui repose sur la méthode des cordes. Cette méthode détermine les directions dans l'espace (cordes virtuelles) de points qui originent des gouttes de sang à un site se trouvant directement au dessus de la source de sang. Lorsque l'on observe la scène à vol d'oiseau, les cordes virtuelles convergent vers la position de la source. Lorsque l'on observe la scène de côté, les cordes virtuelles renseignent sur la limite supérieure de la hauteur probable de la source de sang.

La théorie repose entièrement sur les lois bien connues du mouvement, la résolution de la vélocité dans ses trois composantes et de simple trigonométrie. Elle n'est pas dépendante des quantité inconnues tel que la dimensions et la vitesse des gouttes. Cette procédure possède des bases solides de physique et de mathématique et répond aux critères de la méthodologie scientifique prescrite par la cour. Les caméras numériques sont utilisées pour la collecte des données et l'analyse se fait par ordinateur.

La seconde partie de cet article décrit une expérience de laboratoire pour la validation théorique et pratique de "l'analyse directionnelle".

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INTRODUCTION

Figure 1 shows the tracks of two blood droplets, viewed from above, moving from the source location S to the impact points P and P' on a wall. The tracks meet the wall with the acute angles beta and beta prime (β, β') degrees. These tracks are the projections onto the floor of the flight paths of the droplets. Although the flight paths will have downward curvature due to both gravity and air resistance, the projections are straight lines that extend from point P and P' on the wall back to point S at the source position. In principle only two such tracks are needed to pinpoint the horizontal location of the source because the two tracks will intersect one another at the source location S.

The theory described below explains how to compute the top view of the PS track for each bloodstain on the wall in order to locate the position S of the blood source. This procedure will be known as the "Directional Analysis" of a bloodstain pattern and makes use of virtual strings that are drawn by a computer[2].

In the second part of this paper, a laboratory experiment will be described that creates a bloodstain pattern and uses Directional Analysis to locate the blood source with good accuracy.

Properties of the Flight Paths

Figure 2 is a side view of the flight paths of the two blood droplets depicted in Figure 1.

This view reveals the familiar parabolic shapes of the tracks due to the force of gravity. The gravitational force equals the weight of the droplet and is always directed downward. Another weaker force that acts on the moving droplets is the air resistance. The magnitude or strength of the air resistance force depends on the size and speed of the blood droplets. Its direction is exactly opposite to the direction of motion thus lowering the speed of the droplet. Its main effect is to reduce the distance traveled by small droplets. Under the action of these two forces, the flight paths are always confined to unique vertical planes that include the source S and the bloodstains P and P' i.e. the top view of the paths are the straight lines SP and SP' as seen in Figure 1. We need not concern ourselves further regarding the nature of these two forces because, remarkably, they do not appear anywhere in the formulation of Directional Analysis as described here.

Directional Analysis uses the measured values of the impact angle α of the blood droplet and the glancing angle γ of the bloodstain to compute the direction of the droplet at the **instant before** impact. A virtual string having this direction is then assigned to the bloodstain. The main object of this theoretical discussion is to show how to calculate these virtual string directions, display them in three dimensions, and then explain how they can be used to locate the source of the blood (1).

The Angles α and γ

The angle alpha (α) refers to the impacting blood droplet and the angle gamma (γ) refers to the resulting bloodstain. Alpha is called the impact angle of the blood droplet and its value ranges from close to zero degrees for a very oblique impact, to a maximum of 90 degrees for case when the blood droplet's direction is perpendicular to the wall. The value of α is estimated by using the empirical relationship sin (α) = W/L, where W and L are the width and length of an ellipse that is carefully fitted to the shape of the stain. Note that when W = L for a circle, α has a value of 90 degrees i.e. sin(90) = 1.

Gamma (γ) is called the glancing angle or the directionality angle of the bloodstain and ranges from zero to 360 degrees. It is the angle measured on the wall, between the main axis of the bloodstain and a reference direction. In this work the reference direction is the vertical direction. A blood droplet impacting with the wall while moving straight up will produce a stain with a γ value

2. Directional Analysis is performed by BackTrack/Images and BackTrack/Win, computer programs distributed by Forensic Computing of Ottawa Inc., www.bloodspattersoftware.com.

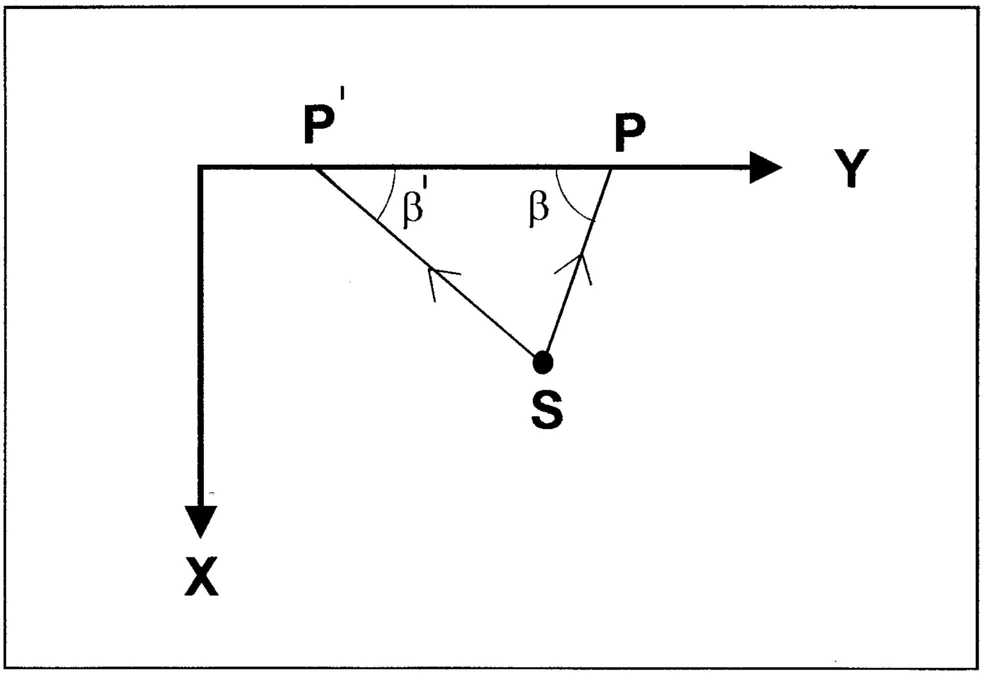

Figure 1. The top view of two flight paths from the blood source to bloodstains at the points P and P'.

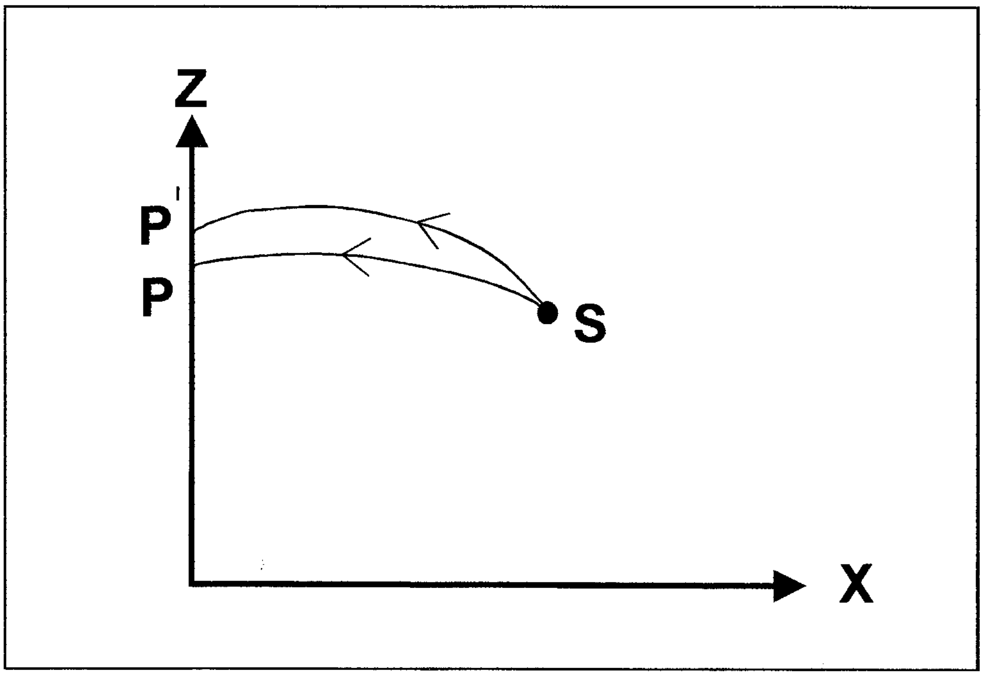

Figure 2. The side view of the same flight paths shown in Figure 1.

of zero or 360 degrees. A bloodstain from a blood droplet impacting with the wall while moving straight down will have a γ value of 180 degrees measured in the clockwise sense.

Top View of the Virtual Strings

The String Angle (β) as a Function of Alpha and Gamma

Figure 3 shows a bloodstain on a wall represented by the YZ plane. It has a glancing angle γ of about 30 degrees. Also shown are the impact velocity vector V and its three components, V_x, V_y, and V_z. V_x is the projection of V onto the direction of the X-axis, V_y is the projection of V onto the direction of the Y-axis, and V_z is the projection of V on to the direction of the Z-axis. The velocity vector V and its three components are drawn with a convenient scale to show the three interlocking right angle triangles and their relationship to the three impact angles α, β and γ.

It can be seen that

$$\tan(\beta) = V_x / V_y,$$
$$\tan(\alpha) = V_x / \sqrt{\left(V_y^2 + V_z^2\right)},$$
$$\sin(\gamma) = V_y / \sqrt{\left(V_y^2 + V_z^2\right)}$$

where the theorem of Pythagoras has been used for the length of the hypotenuse in the triangle containing the angle γ. After dividing the latter two equations, the square root factor cancels and we are left with

$$\tan(\alpha) / \sin(\gamma) = V_x / V_y.$$

Now referring to the first equation we get the relationship

$$\tan(\beta) = \tan(\alpha) / \sin(\gamma),$$

or

$$\boldsymbol{\beta = \arctan\{\tan(\alpha) / \sin(\gamma)\}} \qquad \textbf{(1).}$$

Except for certain cases discussed below, the β angle associated with each bloodstain can be calculated by substituting the measured values of α and γ into this formula.

It is important to realize that the relationship between α, β, and γ does not depend on the forces acting on the moving droplets. Therefore, it is quite independent of the sizes and speeds of the blood droplets. Therein lies the power of Directional Analysis, because the sizes and speeds are generally unknown quantities.

The angle β is the acute angle between the flight path SP and the wall when seen from above (Figure 1). Therefore, we can simulate the flight paths by having the computer draw the top view of virtual strings originating at the positions of the bloodstains with the appropriate angles for β. Given accurate values for α and γ, these virtual strings will pass directly over the source of the blood (Figure 4a).

Taking into account the unavoidable errors of measurement, the virtual strings will not converge onto a point but rather on a region of space that we can assume contains the source location.

Special Cases when Computing β from the Measured Values of α and γ

When α is equal to its maximum value of 90 degrees, tan (90) is infinite and equation (1) cannot be used. However, the direction of the impacting blood droplet is clearly perpendicular to the wall and, hence, we conclude that β = 90 degrees and this bloodstain does not have a γ value because the bloodstain will be circular in shape (α = 90 degrees).

Another problem occurs with equation (1) when the value of the denominator, sin (γ), equals zero. This is true when γ = 0 or 180 degrees, which are two valid γ values. However, for these two values of γ, we can see from geometrical considerations that the tracks of the blood droplets, viewed from above, are perpendicular to the wall and once again we conclude that β = 90 degrees.

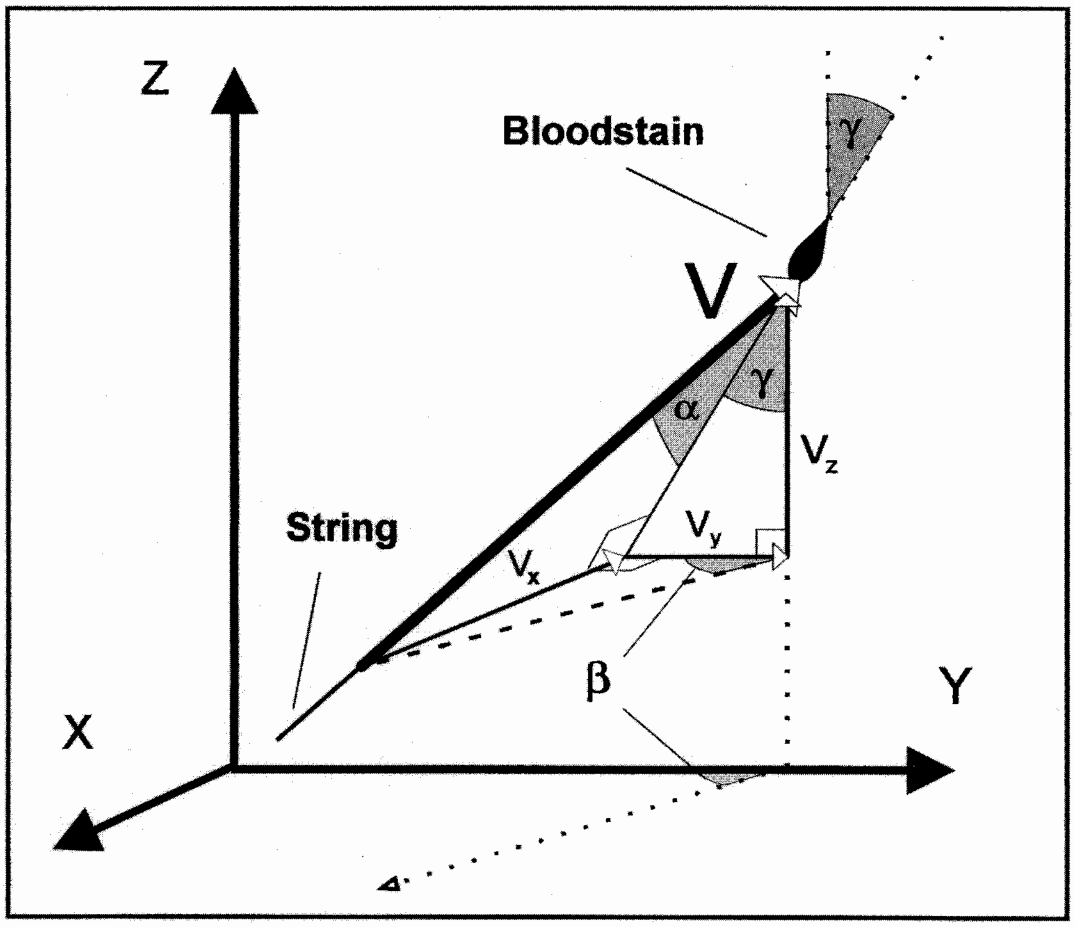

Figure 3. The impact velocity vector **V** is shown in relation to its three components, V_x, V_y, and V_z and the virtual string. The three interlocking right triangles containing the three angles α, β, and γ are also shown.

In Figure 4a the string on the right has a gamma value between 0 and 180 degrees and the sin (γ) factor is positive. The string on the left has a gamma value between 180 and 360 degrees and the sin (γ) factor is negative. With the negative sin (γ) factor, the solutions of equation (1) are (180 - β) or (- β). We must choose the former solution, which is the positive one, in order to get the correct direction of the virtual string. This means that the slopes of the virtual strings appropriate for these gamma values are now pointing left to right. This is consistent with blood droplets striking the wall with gamma values between 180 and 360 degrees (See Figure 4a).

Side View of the Virtual Strings

The String Angle (β_s) as a Function of Alpha and Gamma

Figure 4b shows the side view of the two virtual strings. This is the projection of the virtual strings (or impact velocities) onto the ZX plane. This projection of a virtual string meets the wall with the angle β_s. It can be shown by a similar argument to the one above that

$$\tan(\beta_s) = \tan(\alpha) / \cos(\gamma) \qquad (2).$$

Again, this relationship is seen to be independent of droplet sizes and speeds.

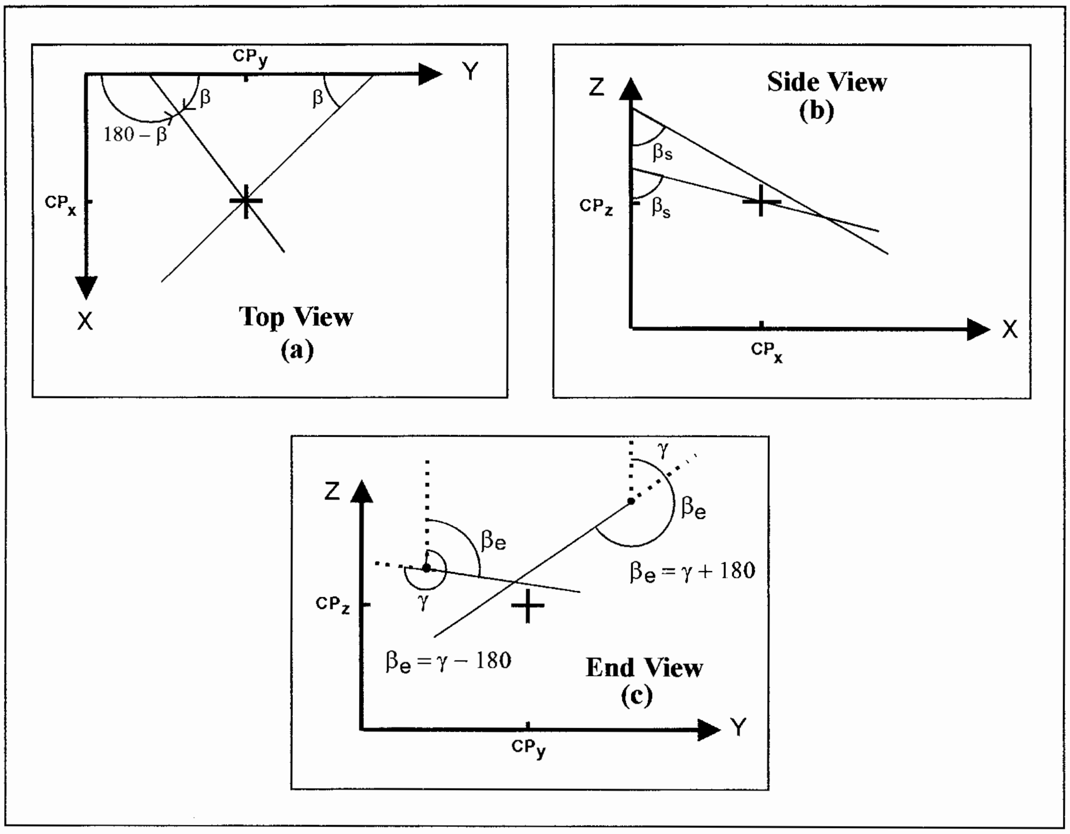

Figure 4. Three different views of the same two virtual strings, illustrating the three angles β, β_s, and β_e. The cross marks the convergent point coordinates CP_x, CP_y, and CP_z.

Special Cases when Computing β_s from the Measured Values of α and γ

As in the case of the β angle, β_s equals 90 degrees when α is 90 degrees and the γ values lose their significance (circular stains). In this formula, the denominator is cos (γ) rather than sin (γ), therefore, it becomes zero when γ = 90 and 270 degrees. Equation (2) cannot be evaluated when there is a zero in the denominator. However, again from geometrical considerations, we can conclude that the value of β_s is 90 degrees in both cases.

Figure 4b shows two downward-pointing strings. The upper string has a gamma value between 0 and 90 degrees. The lower string has a gamma value between 270 and 360 degrees. The cos (γ) factor is positive in both cases.

When the values of gamma lie between 90 and 270 degrees, the cos (γ) factor is negative and the solutions of equation (2) are (180 - β_s) or (- β_s). We must choose the former solution, which is the positive one, in order to get the correct slope of the virtual string. This means that the directions of the virtual strings appropriate for these gamma values are now pointing upward. This is consistent with downward-moving blood droplets striking the wall producing what are known as called gravity stains.

End View of the Virtual Strings

The String Angle (β_e) as a Function of Gamma

Figure 4c shows the end view of the same two virtual strings. This is the projection of the virtual strings (or impact velocities) onto the ZY plane. The strings originate at the positions of the bloodstains and make an angle β_e with the vertical, given by equations (3a) and (3b). From Figure 4c we see that for γ between 0 and 180 degrees:

$$\beta_e = \gamma + 180 \qquad \textbf{(3a)}$$

and for γ between 180 and 360 degrees:

$$\beta_e = \gamma - 180 \qquad \textbf{(3b).}$$

MATERIALS AND METHODS

A bloodstain pattern was produced in the laboratory by striking a 10 mL pool of blood with a hammer. The target was a 4 by 8 ft. sheet of white paper fastened to the wall 100 centimeters above the floor. The blood source was located 60 centimeters in front of the target, 114 centimeters from the left edge of the target and 94 centimeters above the floor. All the bloodstains that appear in this paper belong to this pattern.

From the bloodstain pattern, six bloodstains that appeared to result from fast upward-moving blood droplets were selected. Three of the stains were located to the left of the blood source, and the other three were located to the right. These six stains were individually photographed close up, along with a millimeter scale and a vertical mark inscribed on the scale (for the gamma measurement). The digital camera was a Sony Mavica model MVC_FD91 that conveniently saves the images on 3.5" diskettes with a jpeg format.

The six images were analyzed by BackTrack/Images using the method of fitting ellipses to measure the impact angles (α) and the glancing angles (γ) for each stain. These two angles define a direction in 3D space that is the direction of the virtual string for the bloodstain (it is also the direction of the blood droplet at the instant of impact).

The data file produced by BackTrack/Images was then read into BackTrack/Win for the virtual string analysis that locates the position of the blood source.

RESULTS

The Method of Ellipses for Measuring the Impact angle (α)

We begin by demonstrating the validity of using ellipses to determine the impact angles, α. Rearranging the formula for β that was derived in equation (1), and solving for α we get

$$\alpha = \arctan\{ \tan(\beta) \sin(\gamma) \} \qquad \textbf{(4).}$$

Beta (β) is the angle that the plane of the flight path makes with the target surface (Figure 1). Beta can be computed from the geometry of the source-target setup. Figure 5 shows that the α angle for a particular bloodstain is given by

$$\beta = \arctan\{ X_b / (Y_s - Y_b)\} \qquad \textbf{(5),}$$

where X_b and Y_b are the X and Y coordinates of the location of the blood source, and Y_s is the Y coordinate of the particular stain.

Gamma (γ) is the glancing angle of the bloodstain and it is determined by direct measurement. Therefore, the impact angle (α) of any bloodstain on the target can be computed using equation (4).

Consider a particular bloodstain. The angle β for this bloodstain is computed using equation (5). The glancing angle γ is measured using BackTrack/Images. The value of the impact angle α is then calculated by substituting for β and γ into equation (4). An ellipse with a width W equal to the width of the bloodstain and a length L given by the empirical relationship L = W sin(α) is then superimposed onto the image of the bloodstain.

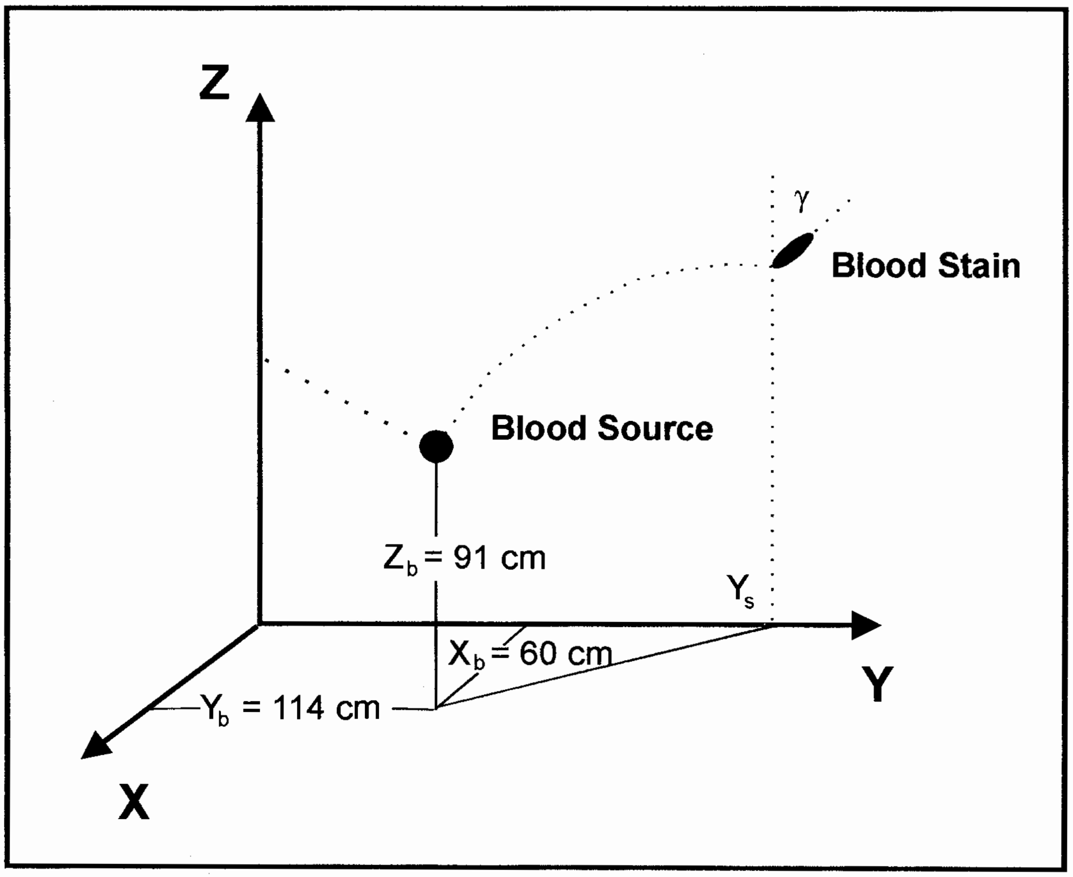

Figure 5. The geometry of the source-target set-up.

Figures 6, 7, and 8 show some typical bloodstains with the ellipses superimposed on to the stains. Alphac values are the impact angles using equation (4). The gamma values were measured with the program BackTrack/Images.

DISCUSSION

Top View: A relationship, given by equation (1), has been derived that uses measured values of the impact angle α and the glancing angle γ, to compute β, the angle between the target wall and the flight plane of a blood droplet that impacts with the wall. By working with the top view of the scene (See Figure 4a), one can draw lines (virtual strings) that start at the position of each bloodstain and back track along each flight path to pass directly over the position of the blood source (CPx, Cpy).

By selecting a number of bloodstains and drawing the corresponding virtual strings for each bloodstain one can expect to get a converging pattern of strings that allows one to compute the horizontal position of the blood source with an accuracy that depends only on the precision of the α and γ measurements.

Side View: A similar relationship, given by equation (2), has been derived for the acute angles β_s, that the virtual strings make with the wall when viewed from the side (See Figure 4b). Under normal conditions the laws of physics require that all the virtual strings, when correctly drawn, pass directly over the source of the blood (CPx, Cpy, CPz). The height of the strings at the source position will vary depending on the curvature of the flight path at the instant of impact. This curvature

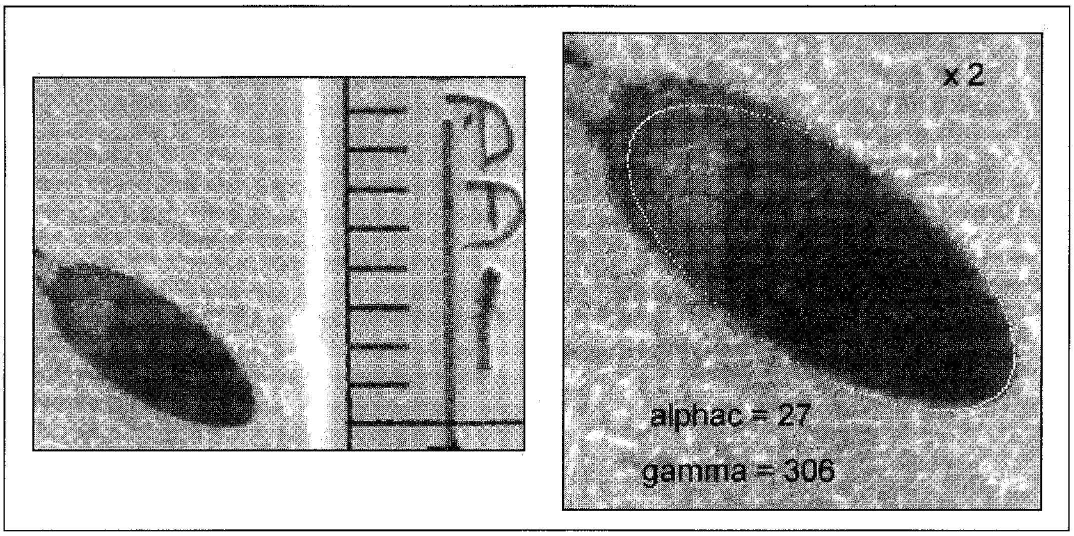

Figure 6. On the left is the image obtained with the Mavica digital camera. On the right is the same bloodstain showing the ~~14~~ 27 degree ellipse superimposed.

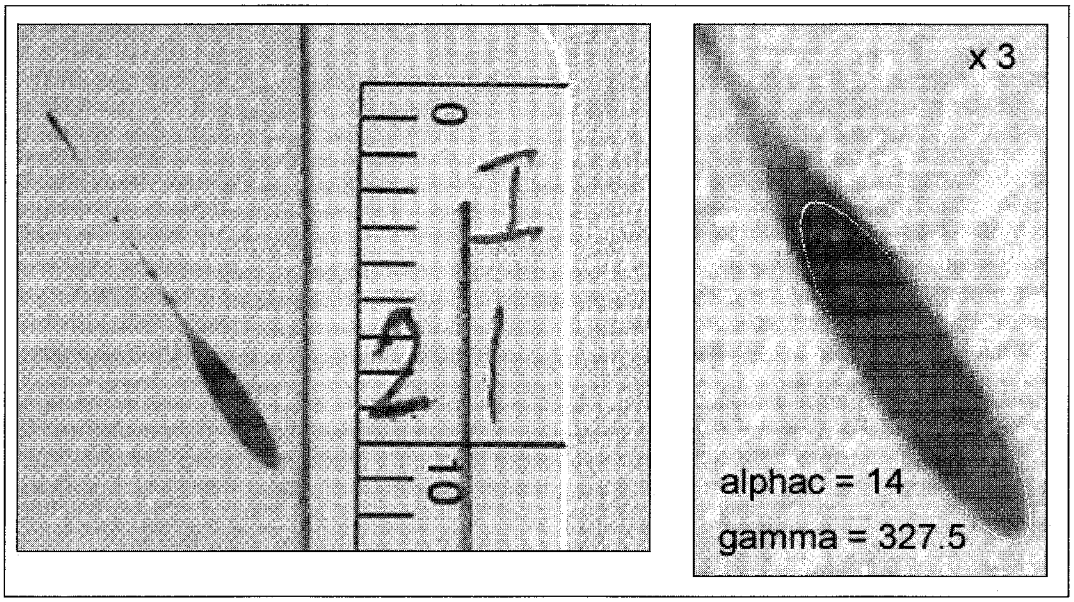

Figure 7. On the left is the image obtained with the Mavica digital camera. On the right is the same bloodstain showing the ~~27~~ 14 degree ellipse superimposed.

cannot be computed because it depends on the speed and size of the droplets, which are unknown quantities. Therefore, the best one can do here is to estimate an upper limit for the height of the source (CPz).

In the example shown in Figure 4b this upper limit is assumed to be where the lower string intersects with the CPx position. In a more realistic situation, one would be advised to average a number of intersections of suitable strings. This is done with the reasonable expectation that the average is likely to be more accurate.

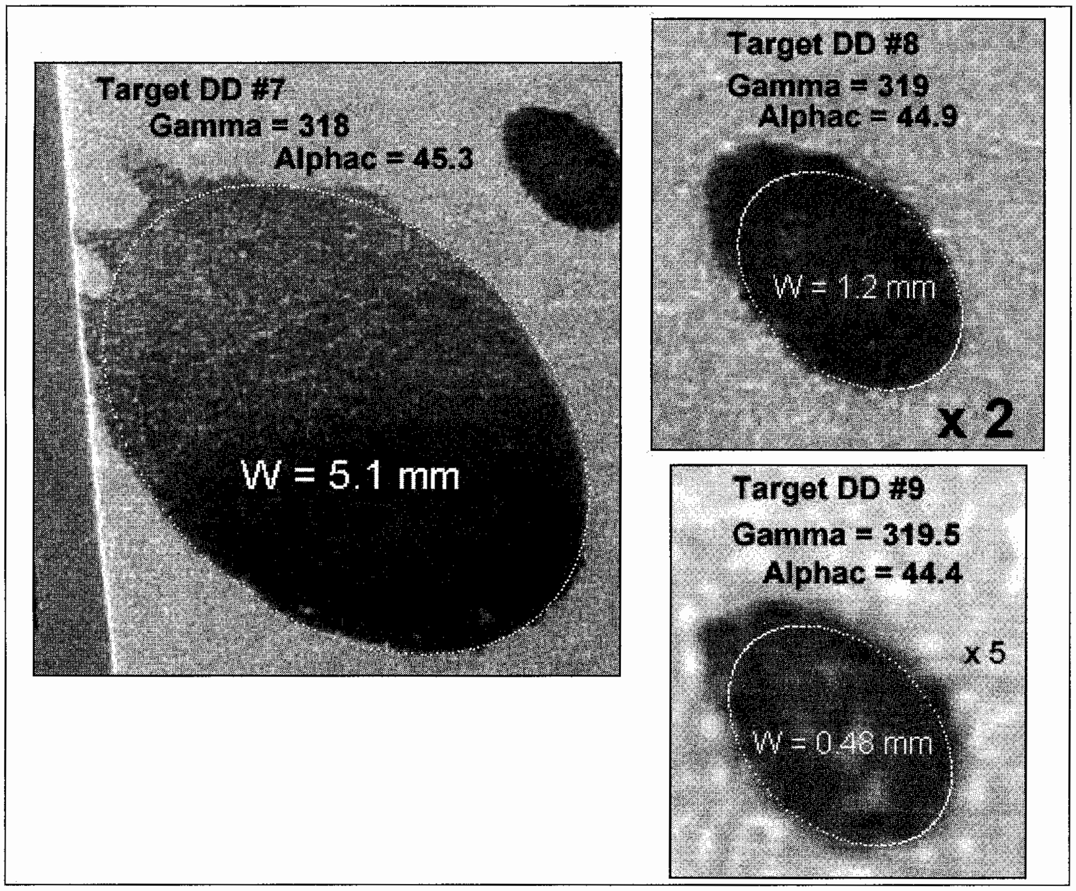

Figure 8. A group of stains having α values of about 45 degrees. The three stains range in size by a factor of 5.

End View: In this view, the virtual string directions depend on the gamma values as shown in Figure 4c and by equations (3a) and (3b). There often appears to be a convergence pattern for the strings. Because this pattern is easily constructed, by drawing lines on the wall, it has received the most attention in the past. This two-dimensional convergence is often mistakenly identified as the three-dimensional convergence projected onto the wall. This is not the case because the flight paths do not project onto the wall as virtual strings. Indeed, the virtual strings are tangent to the projected flight path only at one point, the impact point of the blood droplet.

With significant curvature of the flight paths, the 2D convergences created by lines drawn on the wall guided by the bloodstains, are not reliable. Each 2D point of convergence is displaced horizontally, from its true position on the wall by an amount that depends on the unknown curvature of each flight path. Only the top view analysis of the virtual strings can yield a point of convergence that is unbiased by the curvatures of the flight paths[3].

Discussion of The Method of Ellipses

The images in Figures 6, 7, and 8 were captured from the BackTrack/Images program. Each stain has an ellipse superimposed onto the stain. The ellipse has a width, W, equal to the width of the

3 See www.bloodspattersoftware.com for more on the problem with the Tangent Method when it is applied to bloodstain patterns found on walls.

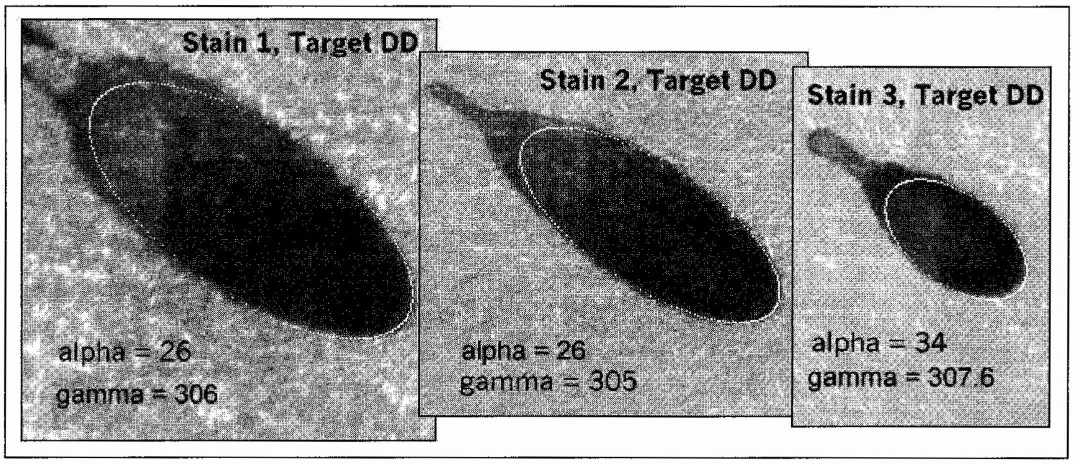

Figure 9. Stains 1, 2, and 3 with their ellipses and their α and γ values.

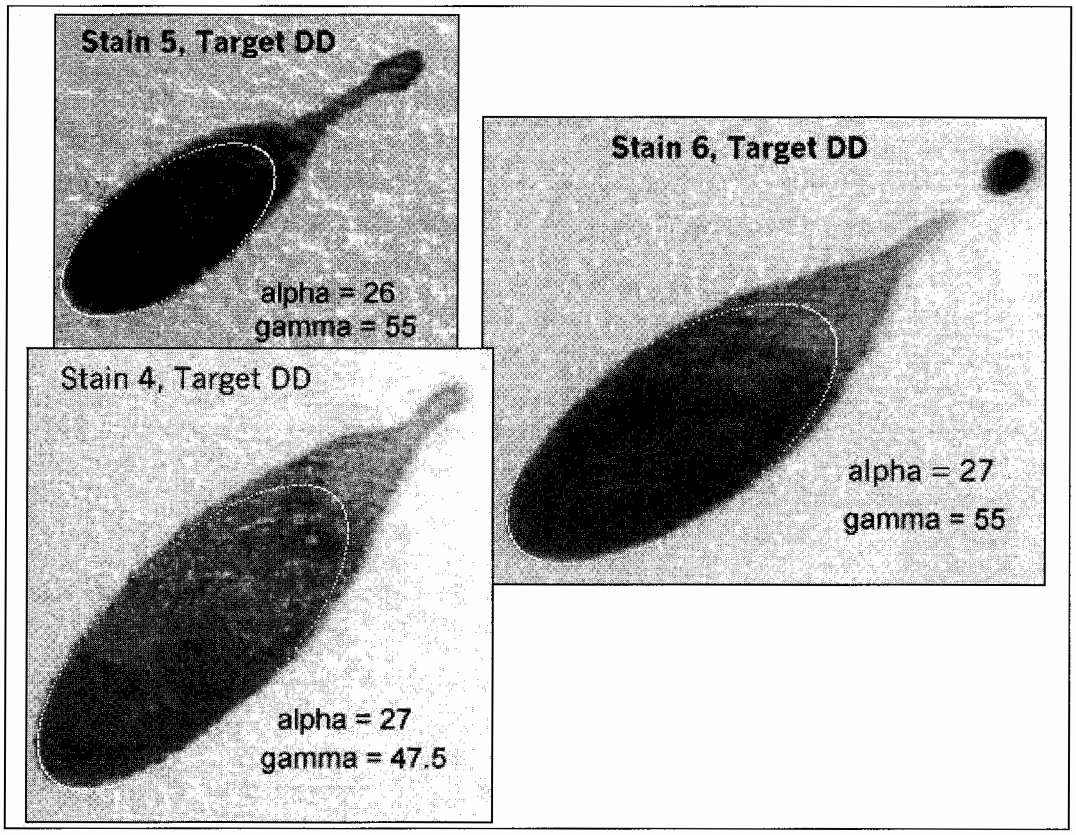

Figure 10. Stains 4, 5, and 6 with their ellipses and their α and γ values.

stain at the widest point and a length, L, given by L = W / sin(alphac) where alphac is the *computed* impact angle for that stain. Therefore, the lengths of the above ellipses have been computed from the known values of the impact angles (alphac) and can be used as reference templates for finding the best fit of ellipses for unknown cases.

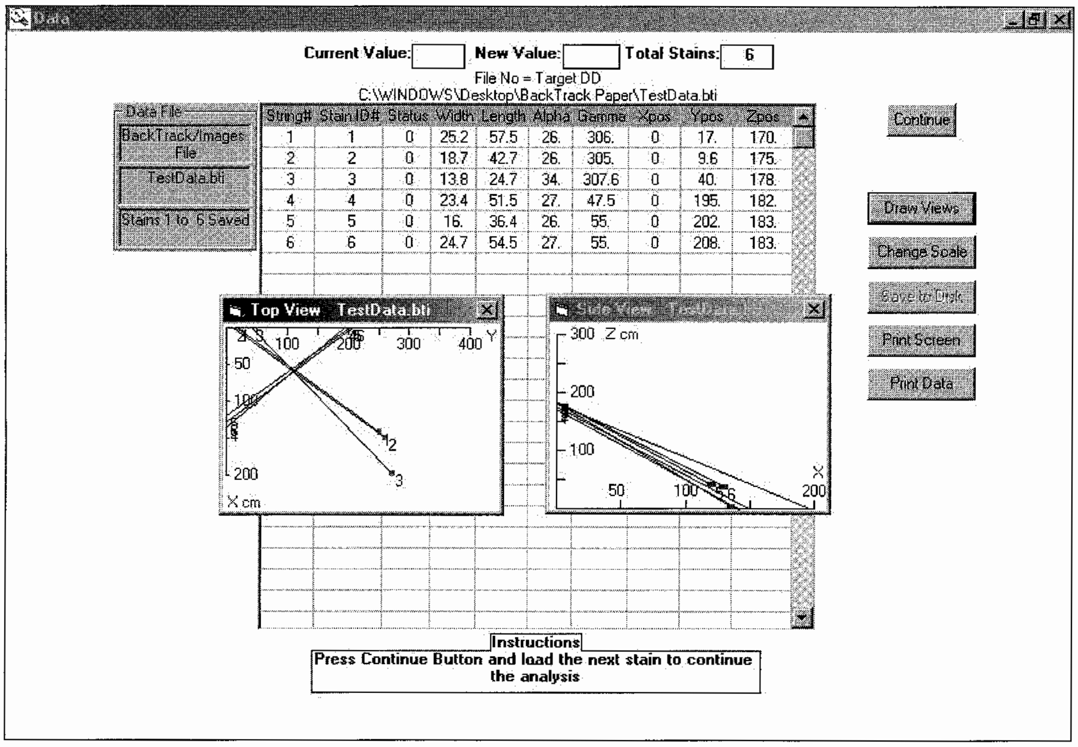

Figure 11. The BackTrack/Images screen that summarizes the analysis of the six stains.

From the reasonable fits of the ellipses to the stains shown in Figures 6, 7, and 8, it is concluded that "fitting the ellipse" can be used as a reliable method for measuring the impact angles of bloodstains.

The length of the ellipse is the most critical factor for determining the value of the impact angle. One would normally superimpose an ellipse that has the same width as the stain and then adjust the trial values of the impact angle α until the "fit" resembles the appropriate template. The value of α that yields the best fit is then accepted as the best estimate of the impact angle.

The Directional Analysis of Six Bloodstains

Figures 6 and 7 show typical arrangements of the stain, the mm scale, and the inscribed vertical line. Figures 9 and 10 show the stains 1 to 6 with ellipses fitted to the stains. Also shown on the images are the values of the glancing angle, γ, and the impact angle, α, appropriate for each ellipse. These values were obtained by matching the width of the ellipse to the stain and then finding the alpha value that gives the best fit for the ellipse, as described above.

Figure 11 shows the BackTrack/Images screen that summarizes the preliminary analysis of the 6 stains. The parameters are listed in a spreadsheet format. Each row defines the virtual string that belongs to the stain number specified in column 2. These parameters are contained in the file "TestData.bti". The width and length of each ellipse are given in units of 0.1 mm.

Also shown for convenience are sketches of the Top View and Side View of the virtual strings. The bloodstain pattern is assumed to be on Y-Z plane. The laws of physics dictate that each virtual string should pass directly over the source position of the blood. The top view of the virtual strings shows them converging onto a region with the approximate coordinates X = 60 cm and Y = 110 cm. This region must contain the location of the blood source. The side view of the virtual strings will yield an upper limit for the height of the source.

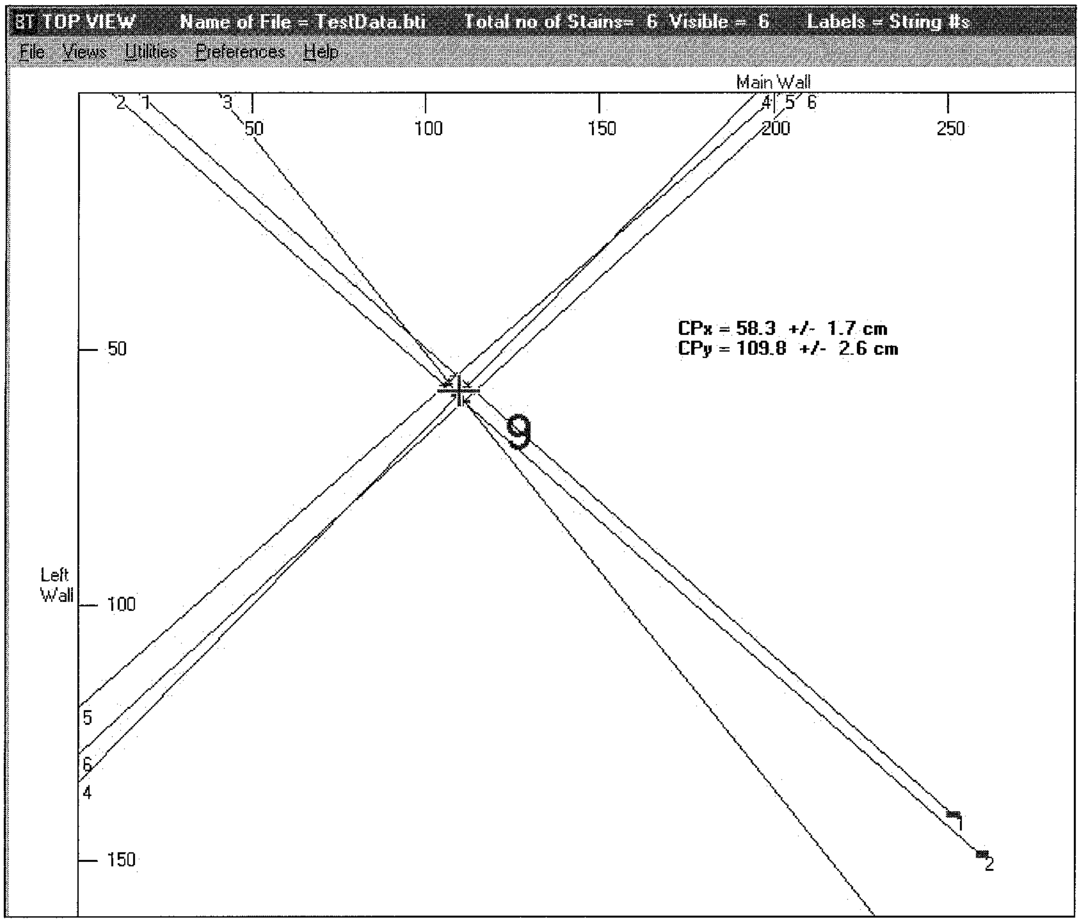

Figure 12. BackTrack screen, top view of the virtual strings after executing the Auto-Cpxy command.

The next step in the analysis is to read this file "TestData.bti" into the program BackTrack/Win and then perform the Auto CPxy command.

Figure 12 shows the screen of BackTrack/Win just after "TestData.bti" was loaded and the Auto CPxy command executed. One can see a good convergence of the virtual strings. There are 9 intersections that were used to compute an average X intersection given by CPx = 58.3 ± 1.7 cm and an average Y intersection given by CPy = 109.8 ± 2.6 cm. Rounding we get

CPx = 58 ± 2 cm [60 cm ± 2 cm]

CPy = 110 ± 3 cm [114 cm ± 2 cm].

The ± values are the standard deviations. The values in the square brackets are the measured or true values for the location of the source that was a circular pool of blood with a diameter of 4 cm. Thus we see that the CPx and CPy measurements agree very well with the true values.

Figure 13 shows the side view of the virtual strings projected onto the X-Z plane just after performing the Manual CPz routine. The vertical line marks the CPx position at 58.3 cm. Ideally, each virtual string should pass directly over the position of the blood source. Therefore, to take into account experimental errors and the fact that all intersections of the virtual strings have equal

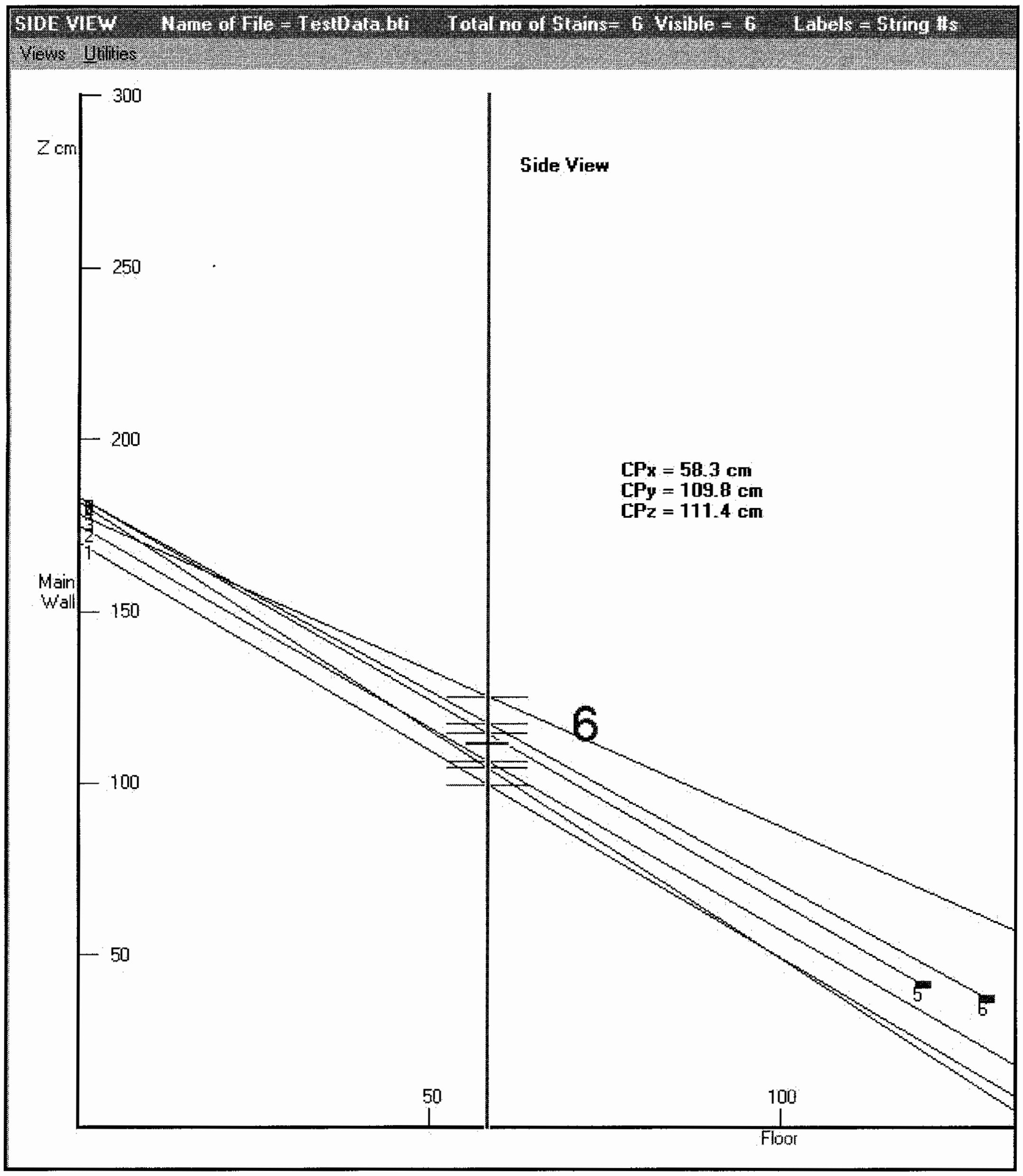

Figure 13. The side view of the virtual strings after carrying out the Manual CPz routine.

weight, we average the six intersections of the virtual strings with the CPx position. This average works out to be CPz = 111.4 cm.

This value for the height of the blood source is **an upper limit only**; an upper limit because the laws of physics, which require that each virtual string must pass directly over the source position, cannot estimate the amount of the clearance distance between the virtual string and the blood source. This is due to the fact that the actual flight paths cannot be calculated when the sizes and speeds of the blood droplets are unknown. The best that we can do, lacking this knowledge, is to estimate an upper limit for the value of CPz . However, we can state with confidence that the ver-

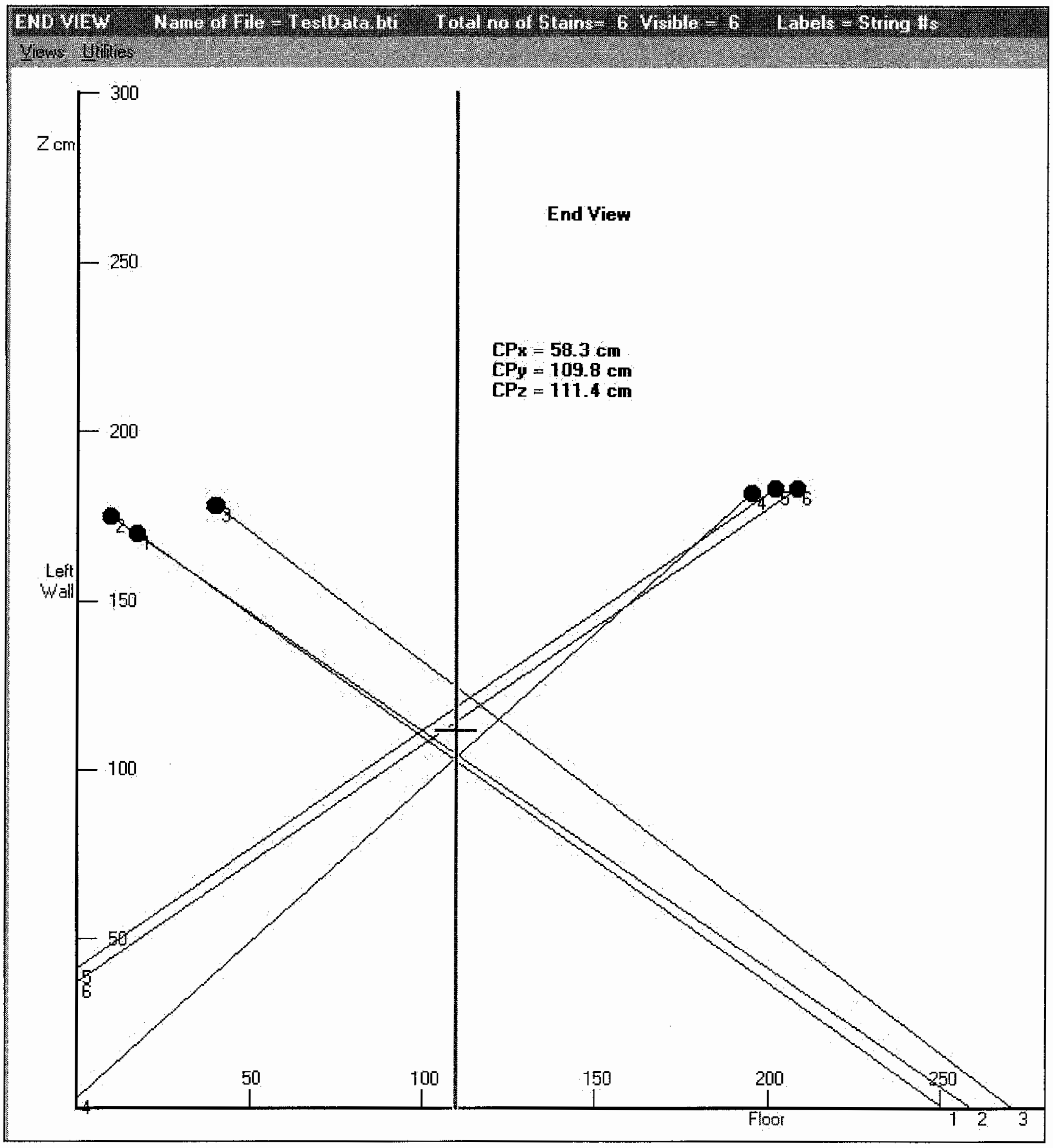

Figure 14. The end view showing the location of the bloodstains and their virtual strings.

tical position of the blood source must located somewhere below the value of 114 cm. The true value for the height of the blood source was measured to be CPz (true) = 95 cm.

Figure 14 shows the end view of the six bloodstains. The circles represent the bloodstains on the main wall or the Y-Z plane. The lines attached to the bloodstains are the projections of the virtual strings onto the main wall. The actual flight paths of the blood droplets are unknown and cannot be projected onto the Y-Z plane. However, we do know that they would be curved, concave downward and tangent to the virtual strings at the impact point. Thus the directions of the virtual strings, as seen from the end view, depend on the unknown curvatures of the flight paths. This means that the virtual string projections onto the Y-Z plane (sometimes called the 2D convergence) generally have false convergent patterns, false because the convergence can be displaced in the horizontal Y-direction by an unknown amount when the flight paths have substantial curvatures. Using 2D con-

TABLE 1

Blood Source

	Experiment Results Cm	*True Values* cm
X- position (CPx)	58 ± 2	60 ± 2
Y-position (CPy)	110 ± 3	114 ± 2
Z-position (CPz)	111 (upper limit)	95 ± 1

vergence patterns for locating the Y and Z coordinates of the source (the tangent method) should be avoided because of the possibility of large systematic errors that will be unknown to the investigator.

Fortunately this problem does not exist with the top view projections of the virtual strings since the flight paths project as straight lines. Under normal conditions the projected virtual strings will converge onto the location of the blood source regardless of the curvature of the flight paths.

CONCLUSIONS

The second part of this paper describes the method of ellipses for measuring the impact angle and shows how to carry out the Directional Analysis of a bloodstain pattern produced in the laboratory. Six bloodstains were selected for fast upward movement of the corresponding blood droplets. They were also selected for optimum placement i.e. 3 from the left side of the blood source and 3 from the right. The number of stains was limited to six only for simplicity. In general, a larger number would be preferable.

The results of the analysis are summarized in Table 1. There is excellent agreement between the measured position of the blood source and the true position. This good agreement validates the theory of virtual strings described here. It also validates the method of ellipses developed by the author for measuring the impact angles of the blood droplets.

ACKNOWLEDGEMENTS

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