Article

Deposition of Bloody Friction Ridge Impressions

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Abstract: To date, no experiments have been published measuring the cause and effect relationship of various deposition factors and the resultant appearance of the ridge detail in a bloody friction ridge impression. This study reports the effects of deposition pressure (at four categories of pressure: light, medium, heavy, and extreme), the effects of increasing volumes of human blood loaded onto a finger (from 10 µL to 100 µL), the effects of depositing impressions on a horizontal surface versus a vertical surface, and finally, the effects of allowing the blood to dry on the finger for a significant amount of time before depositing the impression (hereafter: predeposition waiting interval or PWI). Prior to testing these variables, a series of study design tests were also performed to optimize the conditions of the study. During these tests, we examined several other factors (such as the temperature of the blood, the ambient air temperature, the temperature of the skin) for their contribution to the appearance of the bloody impressions.

The trials showed that to produce identifiable impressions, relatively small amounts of blood were needed (10 to 20 µL). When impressions were deposited in a vertical position, increasing the deposition pressure produced more impressions of evidential value. Identifiable impressions were produced with larger volumes of blood when there was a significant PWI interval. After allowing some of the excess blood to dry on the finger, an identifiable impression was deposited.

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Perhaps the most startling revelation of the study was the determination that the currently accepted mechanism for the creation of a tonally reversed bloody impression (i.e., excessive pressure will cause blood to squeeze off the ridges and into the furrows) is false. The results showed that tonally reversed bloody impressions were created through one of two proposed mechanisms: (1) removal of excess blood preferentially from the ridges, followed by significant deposition pressure or (2) waiting a significant amount of time to allow blood on the ridges to dry, while leaving blood trapped and protected in the furrows still wet. Under this second mechanism, we produced tonally reversed bloody impressions with even the lightest of deposition pressure.

Introduction

After an extensive literature search, the author was not able to locate any published material, other than that published by Ashbaugh [1], that addresses the various distortions found in bloody fingermarks[1] that fingerprint examiners have come to understand through training, word-of-mouth, and experience. Even Ashbaugh only superficially treated the topic and gave a single example. Beyond this, no data can be found in the literature for quantitatively or qualitatively assessing the effects of various factors that can contribute to the appearance of a bloody fingermark. It is important to have a thorough understanding of the distortions that can be present in a bloody fingermark because the bloody fingermark can be among the most probative of evidence in a trial, especially when that fingermark is individualized to the defendant, is deposited with the victim's blood, and indicates a relative time frame for the deposition of that mark.

We did not attempt to determine which was first: blood on the finger to create the bloody fingermark or a clean finger impressed into blood on a surface. This question anecdotally arises with respect to some cases or possibly at the request of an attorney. Research reported by Huss et al. [3] explored this issue but found that they could not determine the order. Huss et al. also noted, "The quantity of blood on the finger will determine whether or not the print is [tonally] 'reversed'". We did not observe that volume had any effect on the production of

[1] The author is choosing the convention of using "fingermark" throughout the article rather than the lengthy "bloody friction ridge impression". The reasons for this nomenclature are discussed by Margot [2]. Also, although only bloody fingermarks were tested in the study, it seems reasonable to assume that there would not be differences in the results with respect to palms and soles, other than the obvious increase in surface area.

tonally reversed fingermarks (see Results and Discussion). Huss et al. did not discuss in their methods whether they controlled or measured deposition pressure and the amount of time waited between loading blood onto the finger and depositing a bloody fingermark. Perhaps it was one of these other factors that contributed to the production of their tonally reversed fingermarks.

Laber and Epstein [4] reported preliminary data for drying times for single drops of blood on various substrates, drying under three environmental conditions. Their "Condition 1" was most similar to conditions in this study; specifically, they measured drying times in a 75 °F (24 °C) room, with 44% relative humidity and minimal air circulation. For both nonporous surfaces (floor tile and glass), the drying times for a drop of blood (volume not provided) were 40 and 30 minutes, respectively. It is not known from their study what the temperature of the blood was before depositing on the surface. Brady et al. [5] also reported drying times under three environmental conditions for various bloodstains on two substrates (painted drywall and linoleum tile). For similar conditions to the present study [specifically, 72 °F (22 °C), 67% humidity], Brady et al. reported drying times for transfer swipe patterns[2] ranging from approximately 1.4 to 3 minutes on painted drywall and 1.5 to 7 minutes on linoleum tile. The parameters for blood volumes and blood temperatures were not reported by Brady et al. Other than these two studies, there was very little published data on blood drying times (though several sources reported to the author doing unpublished experiments in workshops and for case-specific bloodstain pattern analysis testing), and there were certainly no published studies for blood either drying on skin or drying times for bloody fingermarks.

[2] A swipe pattern is defined by the International Association of Bloodstain Pattern Analysts (IABPA) as the transfer of blood from movement of a bloodstained object onto an unstained surface [6]. Excepting the movement component, this mechanism is most similar to the deposition of bloody fingermarks in the present study. Specifically, the type of bloodstain pattern in our trials is what the IABPA defined as "transfer/contact pattern" (a bloodstain pattern created when a wet, bloody surface comes in contact with a second surface. A recognizable image of all or a portion of the original surface may be observed in the pattern.) [6] There were no published studies on drying times of transfer or contact patterns.

Materials and Methods

Bloody fingermarks were deposited, depending on the trial, on a horizontal or vertical surface. The substrate used in all reported trials was white poster board (Twinkote, C2S, .05, white). This poster board has a slightly glossy, mostly nonporous coating. Sheets of the poster board were cut to size and taped to a digital scale (Electroscale, model 438). In the horizontal trials, the board and scale were lying flat. In the vertical trials, the board and scale were tipped on end (Figure 1). We realize this is not the intended position for use of the digital scale, but the design was sufficiently functional to measure gross ranges of pressure applied to the scale.

In each trial, an amount of blood (dependent on the trial) was pipetted onto the finger (with a Rainin Classic Pipet, 10 to 100 µL, using Rainin 250 µL tips). The blood was then immediately spread as uniformly as possible with the pipette tip across the surface of the finger. Then, dependent on the trial, the donor waited between 0 sec (instantaneous deposition) and up to 4 minutes to deposit a bloody fingermark. The interval was measured with a digital stop watch, and this parameter is referred to in this paper as "predeposition waiting interval" or PWI. The blood was always applied to the fingerpad while the finger was held in a horizontal position. If there was a predeposition waiting interval, then the finger remained in a horizontal position during the interval for a horizontal trial. For a vertical deposition, the finger was placed in a vertical position during the predeposition waiting interval (Figure 2).

Between each trial, the remaining blood was washed from the finger and the skin was dried with a towel. Laber and Epstein [7] reported that wetting a surface with blood can affect bloodstain appearance and wetting capacity (the ability to "wet" the surface with a fluid) of materials.

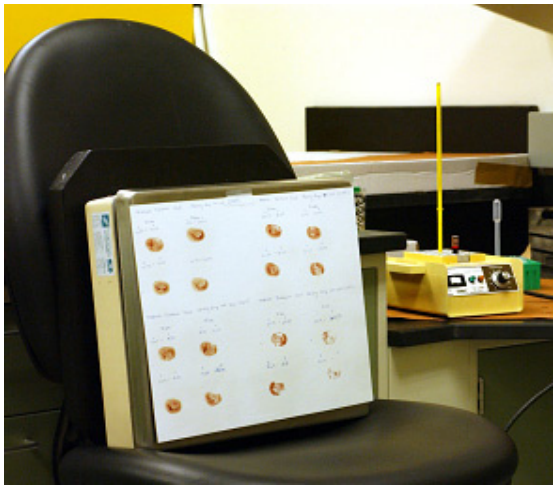


Figure 1

For vertical deposition trials, the scale was positioned vertically. For horizontal deposition trials, the scale was positioned "normally" in the position for intended use.

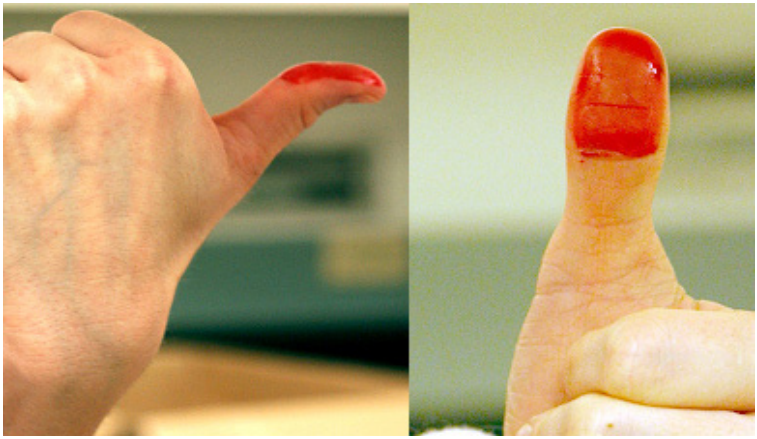


Figure 2

Finger position during PWI. For horizontal deposition trials, when there was a PWI > 0 seconds, the finger was held in a horizontal position (left image). For vertical deposition trials, where PWI > 0 seconds, the finger was held in a vertical position (right image).

Measuring Pressure Applied During the Deposition

We used four categories of pressures to express four ranges of pressure. Because pressure is dependent on area (pressure = force/area), the surface area of the finger contacting the surface must be considered. Prior to performing the study, inked impressions were taken from each donor at various levels of applied force. The mean surface area was calculated for each donor for the four categories of pressures. The pressure ranges are for the primary donors in the study. It should be noted that mean pressure differences among donors ranged from approximately 0 to 20%. Given the wide range of pressures defined for each category, this difference is fairly negligible. The forces, as measured on the scale, and the corresponding pressure ranges, given the surface area of the donors, were:

light pressure	=	0.8 to 1.5 lbs of force	=	1.6 to 3.6 lbs/in^2
medium pressure	=	2.0 to 6.0 lbs of force	=	3.7 to 12 lbs/in^2
heavy pressure	=	8.0 to 13 lbs of force	=	13 to 24 lbs/in^2
extreme pressure	=	18 to 25 lbs of force	=	27 to 43 lbs/in^2

Each donor aimed for a target value and stopped depressing the finger once the target value was observed on the digital LED of the scale. The donors, after much practice, became quite proficient at consistently reaching this target value during trials. The target values were 1, 4, 10, and 20 lbs of force for light, medium, heavy, and extreme pressures, respectively. Also, it should be noted that the extreme force category topped the scale at 25 lbs of force and actually began to cause some pain and discomfort to the donor. These trials were therefore somewhat limited unless significant differences were observed between heavy and extreme pressure values in the trials. This turned out not to be the case. There were minimal differences in the results between heavy and extreme pressures.

For this study, most of the trials were performed with three primary donors. The pressure ranges above reflect the pressures of these three donors, given the force measured and the finger surface area of these donors. One portion of the study did involve 10 donors, but pressure was not a critical factor in those trials.

Optimization Parameters

At the initial outset of the research, several factors were identified as potential variables to be controlled in the experimental trials. These factors included:

- Collection and storage of the blood
- Temperature of the blood to be deposited
- Surface skin temperature
- Ambient air temperature and air flow
- Ambient relative humidity

We conducted early trials to determine which of the above factors were significant and therefore needed to be optimized and controlled for the experimental trials.

Trained phlebotomists drew human blood from donors for use in the trials. Because the quality of ridge detail was to be evaluated, it was obviously important for the bloody fingermark donor to safely apply blood directly to his or her friction ridge skin. Therefore, the fingermark donors used their own blood for the trials.

We used relatively fresh blood in the trials. Ideally, fresh blood could have been used in each trial; however, for the sake of convenience, blood was drawn weekly during the trials. We did not observe any significant changes in ridge detail appearance over the approximate week for which the blood was used. The blood was stored in a purple top (anticoagulant) tube (10 mL BD Vacutainer brand glass collection tubes with K_3EDTA) in a refrigerator at approximately 43 °F (6 °C). Pex et al. [8] reported that the presence of anticoagulant, especially at the low volumes utilized in this study, does not significantly affect drying times.

Prior to each series of trials, the blood tubes were removed from the refrigerator and warmed gently in a heating block (Thermolyne Type 17600 Dri-Bath) to approximately 98 °F (37 °C). This temperature was chosen to coincide with freshly shed blood that would be most likely encountered at a crime scene. The temperature of the blood was found to affect drying times. For convenience and consistency, blood at 98 °F (37 °C) was used in all experimental trials.

The surface skin temperature of the fingermark donor was found to significantly affect not only the appearance of the friction ridge detail, but also the drying times for the blood drying on the surface of the finger. To control the skin temperature of the donor, the skin was either heated or cooled, using hot or cold water or warm air. The temperature of the skin was measured with a portable IR thermometer (Raytek MiniTemp MT2 with a reported accuracy of +/- 2 °C). The temperature of the donor's skin was difficult to control, but prior to an experimental series, the temperature of the fingermark donor's skin was brought within the range of 70 °F to 80 °F (21 °C to 27 °C). Because of heat transfer during the loading of blood on the finger, the surface skin temperature would change slightly. Figure 3 shows bloody fingermarks, each deposited in the horizontal position, at medium pressure, with 20 µL of blood, with a PWI of 50 seconds. It can be observed in Figure 3 that beginning at 80 °F (27 °C), and clearly evident at 90 °F (32 °C), the sweat pores in the ridges were open and actively sweating[3]. The sweat diluted the blood and gave a spotty, light-colored appearance to the ridge detail, but dark, contrasting-colored blood can be observed in the furrows and creases of the fingermark.

Another critical factor affecting drying times and the appearance of friction ridge detail was the ambient air temperature. Figure 4 shows bloody fingermarks, each deposited in the horizontal position, at medium pressure, with 20 µL of blood, after 60 seconds of drying time on the finger for a range of ambient air temperatures [17 °F to 30 °F (63 °C to 86 °C)]. The experimental trials were conducted in an area where there was minimal airflow through the room. It was observed in early trials that significant airflow across the finger drastically affected drying times. We kept the airflow to a minimum during the trials and maintained the ambient air temperature between 70 °F to 75 °F (21 °C to 24 °C). Airflow was kept to a minimum by performing all trials in a sequestered room, away from air vents, windows, and open passages.

James [9] reported that ambient relative humidity influences drying times; however, no data was cited. Pex et. al [8] reported

[3] As a note of interest, the author has found that raising the skin temperature to induce the opening of the pores is an excellent way to obtain pore detail when taking inked fingerprints. Several sets of inked exemplars may need to be taken, and the earliest inked fingerprints, taken immediately after warming the hands under hot water and quickly drying, will often be "too sweaty". However, as the pores constrict during cooling, they will be very visible and subsequent exemplars will capture this detail.

that relative humidity had a negligible effect on drying times of single blood droplets within the first 15 minutes of drying. Given the small volumes of blood utilized in our experiment and the relatively short drying times (under 5 minutes), we did not consider this factor to any serious degree. Also, during the period of time in which the experimental trials were performed (fall and winter in Minnesota), the relative humidity ranged from 20% to 50% in a climate-controlled environment, but the exact humidity was not recorded on a daily basis before each experimental trial. It would have been very difficult, if not impossible, to precisely control the relative humidity of the testing environment for each experimental trial.

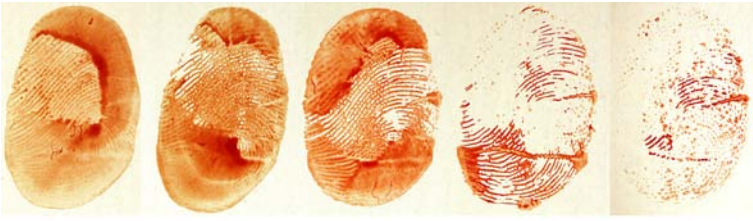


Figure 3

Variation in appearance and drying times for increasing skin temperatures. These impressions were deposited in the horizontal position, at medium pressure, with 20 µL of blood, with a PWI = 50 seconds. At higher skin temperatures, the blood dried faster and evidence of sweat can be seen diluting the blood.

Figure 4

Variation in appearance and drying times for increasing air temperatures. These impressions were deposited in the horizontal position, at medium pressure, with 20 µL of blood, with a PWI = 60 seconds.

Results and Discussion

Volume of Blood and Deposition Pressure

In these trials, we varied the volumes of blood loaded on the finger surface. Trials began at 10 µL of blood and continued through 100 µL. We started with the 10 µL volume because volumes lower than 10 µL did not completely cover the fingerpad surface area. We applied a series of volumes (10, 20, 30, 40, 50, 70, and 100 µL) for fingermarks deposited at light, medium, high, and extreme pressures and deposited immediately (PWI = 0 seconds) on a horizontal surface. The trials were then repeated for a vertical surface. A minimum of eight impressions were made for each series (i.e., eight trials at 10 µL, light pressure, immediately on a horizontal surface; eight trials at 20 µL, light pressure, immediately on a horizontal surface, and so on through all four ranges of pressure and both positions). In total, there were over 500 trials for this part of the study.

After allowing the bloody fingermarks to dry, they were evaluated by the author. The author found Schiffer's use of categorizing the mark as either "exploitable" or "identifiable" very useful [10]. The bloody fingermarks were subjectively assessed for evidentiary value based on the training, experience, and opinion of the author. Generally speaking, the author determined that the mark was "exploitable" if a minimum of 5 distinct features (typically these were minutiae, but in some instances included creases) were observed and some general ridge flow assessment could be made. This left the door open for a mark to potentially be used for exclusionary purposes. Afterwards, the author assessed the "exploitable" marks to determine whether they were "identifiable". A determination, based on the quantity and quality of ridge details observed, was made by the author for each impression.

Table 1 and Table 2, for the horizontal and vertical positions, respectively, show the percentage of bloody fingermarks (out of the minimum of 8 trials per set of variables) that were deemed "exploitable". The values in parentheses represent the percentage of the total marks in the series that were deemed "identifiable".

	Volumes of Blood (in µL)						
	10	20	30	40	50	70	100
Pressure							
Light	100% (50%)	50% (38%)	12% (0%)	0%	0%	0%	0%
Medium	100% (71%)	44% (0%)	0%	0%	0%	0%	0%
Heavy	100% (75%)	68% (12%)	12% (0%)	0%	0%	0%	0%
Extreme	100% (68%)	50% (12%)	0%	0%	0%	0%	0%

Table 1

Percentage of bloody fingermarks deemed "exploitable" or "identifiable" for horizontal depositions. Values in parentheses represent percentage of marks that were identifiable.

	Volumes of Blood (µL)						
	10	20	30	40	50	70	100
Pressure							
Light	100% (75%)	12% (0%)	0%	0%	0%	0%	0%
Medium	100% (88%)	50% (12%)	0%	0%	0%	0%	0%
Heavy	100% (100%)	100% (50%)	12% (0%)	0%	0%	0%	0%
Extreme	100% (100%)	100% (50%)	25% (0%)	0%	0%	0%	0%

Table 2

Percentage of bloody fingermarks deemed "exploitable" or "identifiable" for vertical depositions. Values in parentheses represent percentage of marks that were identifiable.

Three conclusions can be drawn from Tables 1 and 2:

1) More fingermarks of value were found at higher pressures for the vertically deposited marks.

2) In general, more fingermarks of value were found under the vertical surface condition than under the horizontal surface condition.

3) There is a maximum loading volume of blood for the finger, that once reached, no further exploitable ridge detail was produced.

With respect to the first conclusion from Tables 1 and 2, it can be observed, especially for the 20 µL and 30 µL columns in Table 2, that at heavy and extreme pressures, there was a higher percentage of fingermarks deemed "exploitable". There is also a trend of an increasing percentage of "identifiable" finger-

marks for these higher pressures. This effect may be due to an excess of blood being squeezed away from the center of the pad. This hypothesis can be tested by observing contact under similar conditions through glass. Slow-motion video capture may illuminate the truth of this hypothesized mechanism.

Secondly, the effect of increased pressure is clearly stronger in the vertical deposition versus the horizontal deposition. Comparatively, between horizontal deposition and vertical deposition, there were more fingermarks of any evidentiary value for corresponding pressures. This observation can be explained by the simple fact that when the finger was held in a vertical position, blood loaded onto the finger migrated towards the finger joint because of gravity. This migration began instantly, but is obviously dictated by the viscosity of blood[4]. Although deposition was instantaneous in these trials after loading the blood, there was still some migration of the blood. Therefore, at the time of contact, there were areas of the fingerpad that had a lower volume of blood in a vertically deposited fingermark than the volume of blood distributed across the fingerpad in a horizontally deposited fingermark, even though both positional conditions began with equal amounts of blood. This effect was clearly observed when predeposition waiting intervals were increased, allowing for significant migration (this is discussed in more detail later in this paper).

Finally, there was a maximum loading capacity of blood on the finger. In Tables 1 and 2, this donor was never able to produce exploitable ridge detail above 30 µL of blood loaded onto the thumb. We assumed that this loading maximum was based on surface area of the fingerpad. We explored this possibility with 10 donors. The 10 donors were selected representing a range from small adult, female fingers to very large adult, male fingers. The average surface area for point of contact on the fingerpad ranged from 3.0 cm^2 (0.46 in^2) to 5.7 cm^2 (0.88 in^2) for these 10 donors. It was observed that, even for the donor bearing the largest fingers that we could find (out of approximately 100 laboratory employees), we rarely produced exploitable ridge detail above 40 µL of blood applied to the fingerpad. The maximum volume of blood for the average-sized donor in our trials (4.1 cm^2 /0.64 in^2) was approximately 20 µL

[4] The relative viscosity of blood at 37 °C is approximately four times that of water, but the viscosity varies considerably with the amount of hematocrit (red blood cell fraction), rate of flow, and the temperature of the blood [11].

(Figure 5). Therefore, for optimal ridge detail in bloody fingermarks, approximately 10 µL of blood should be used to produce high-quality bloody fingermarks *when deposition is immediate*. Less than 10 µL proved to not adequately cover the surface of the finger and more than 10 µL approached loading maxima, depending on the surface area and size of the finger. However, 10 µL of blood dried very rapidly (generally less than 45 seconds). So if deposition is not immediate, 20 µL should be considered, depending on the amount of time between loading and deposition.

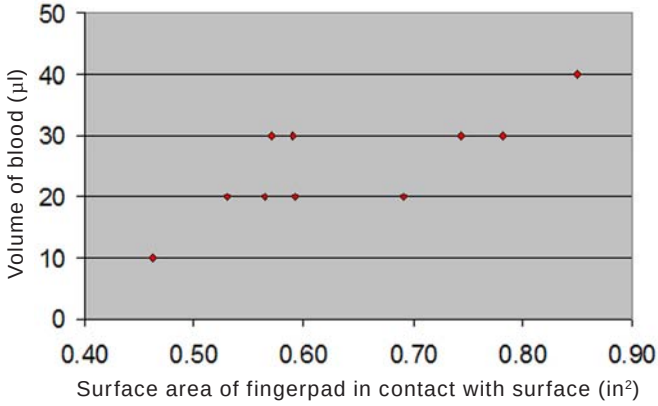


Figure 5

Maximum volume of blood for which "exploitable" ridge detail was observed.

The imperfect trend in Figure 5 suggests that although surface area is related to the maximum loading capacity to the finger, one must also consider that the friction ridge skin system on the finger is not smooth. Furrow width and ridge height most likely contributed to the maximum loading capacity of the finger. In other words, surface area (2-dimensional) may not be the ideal measurement for the relationship, but rather maximum volume (3-dimensional), including the loading capacity of the furrows and height of the ridges when depressed during deposition. This would entail further study and measurement of ridge heights, volume estimates, and so forth of the donors.

Qualitatively, the horizontal and the vertical conditions were very distinguishable, especially at larger volumes. The horizontal impressions bore a mostly uniform distribution of blood in the impression, with centralized pooling at larger volumes. The vertical impressions bore an uneven distribution (splotchy areas of pooling) at lower volumes of blood and a very distinct pooling at the bottom of the impression, clearly from the gravitational migration of the blood downward (Figure 6).

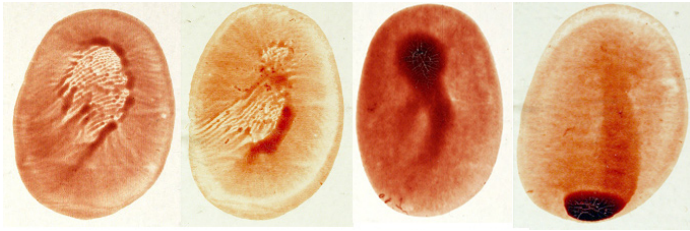
At approximately 40 µL, the blood pooled at the sides of the fingerpad and in the creases because of the fluidity of blood (Figure 7). At lower volumes, this effect was not observed and the blood was evenly distributed across the epidermal ridges and in the furrows. Essentially, beginning around 40 µL, the furrows have been completely filled with blood, and the excess blood pools at the edges of the fingerpad. Also, no participant in the trials could maintain 100 µL on the thumb without the blood dripping off (Figure 7).

Predeposition Waiting Interval (PWI)

In the previous trials exhibited by the data in Table 1 and Table 2, all impressions were made immediately after the blood was loaded onto the fingerpad. In all of the those trials, the time from loading to deposition was less than 5 seconds. Essentially, it took a few seconds to uniformly spread the blood across the friction ridges with the applicator and then position the finger for deposition.

For the next series of trials, the donor waited varying intervals of time, which were measured by a digital stopwatch, before making the bloody fingermark. Thus, the blood was allowed to dry for a time before making an impression. Airflow was kept to a minimum across the surface of the digit, and ambient temperature was maintained between 70 to 75 °F (21 to 24 °C).

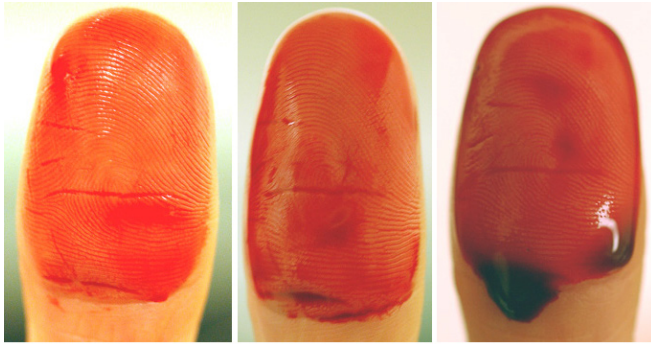
For these experiments, fingermarks were first deposited on a horizontal surface and then the trials were repeated on vertical surfaces. As previously noted, for the horizontal position trials, the fingerpad was kept in the horizontal position during the PWI; for the vertical position trials, the fingerpad was kept in the vertical position during the PWI. This represented two extremes of positions for the digit during the PWI. Obviously, this is probably not realistic in a crime scene setting, as the perpetrator will not maintain his or her fingers in a single, rigid position.



20 µl horizontal | 20 µl vertical | 50 µl horizontal | 50 µl vertical

Figure 6

Qualitative comparison of bloody fingermarks deposited in a horizontal versus vertical position. At the 20 µL volume, in the vertical position, blood is pooling toward the bottom of the mark. This effect is more pronounced at 50 µL.



20 µl | 40 µl | 100 µl

Figure 7

Three volumes of blood on the finger. Beginning at 40 µL of blood, excess blood pooled at the sides of the finger. At 100 µL, the excess blood dripped off the finger.

For the PWI trials, impressions were made only at three pressures (light, medium, and heavy) because significant differences were not observed in previous trials between heavy and extreme pressures (and because of the physical discomfort experienced by the donors at extreme deposition pressure). Impressions were made at 10, 20, 40, 70, and 100 µL volumes, because these volumes represented an increasing range of volumes, without redundancy. A minimum of four impressions were made for each set of variables tested (pressure, volume, horizontal or vertical position, and PWI). An example of the variables tested for each trial would therefore be 10 µL at light pressure, horizontal position after a PWI of 10 seconds. The PWI times were chosen based on early trial results during a study design phase. After the impressions were completed, the author assessed their evidentiary value. Table 3 shows the results for the range of PWI times in which identifiable marks were observed. The range of times would naturally be extended for exploitable marks.

Three conclusions can be drawn from Table 3:

1) The PWI maxima were generally lower for the vertical positioning of the finger than for the horizontal positioning of the finger.

2) At higher volumes of blood where no ridge detail was previously observed in the fingermarks, there was typically a PWI window where identifiable fingermarks were observed; eventually, a maximum PWI time was reached and no ridge detail was observed because the blood had dried on the finger.

3) Increasing the pressure during deposition tended to cause a shift in the PWI times where identifiable fingermarks were observed; this shift tended toward longer interval times and later maxima.

As an example, examining the Medium Pressure column in Table 3, PWIs are reported for five volumes (10, 20, 40, 70, and 100 µL). At the lowest volume, 10 µL, identifiable marks were observed at the immediate deposition time (PWI = 0 seconds). Identifiable marks were observed for up to 50 seconds PWI when the finger was held in the horizontal position, but only for up to 30 seconds PWI when the finger was held in the vertical position. After these maximum times, the blood had dried on the finger and no visible fingermarks were deposited. In most trials,

the maximum PWI times are lower for the vertical position than for the horizontal position. This is due to the migration of blood on the finger and thus a lower volume of blood to dry in the PWI time. There were instances of variability as one might expect when trying to control for several factors (skin temperature, air temperature, etc.).

	Volumes of Blood (µL)				
	10	20	40	70	100
Pressure					
Light	H: 0-30 sec V: 0-25 sec	H: 30-60 sec V: 20-50 sec	H: 60-100 sec V: 60-100 sec	H: 80-160 sec V: 60-180 sec	H: 80 sec only V: 100-160 sec
Medium	H: 0-50 sec V: 0-30 sec	H: 30-90 sec V: 20-80 sec	H: 80-160 sec V: 40-100 sec	H: 80-220 sec V: 60-160 sec	H: 80 sec only V: 80-160 sec
Heavy	H: 0-55 sec V: 0-40 sec	H: 30-100 sec V: 30-100 sec	H: 80-160 sec V: 60-140 sec	H: 80 sec only V: 80-140 sec	H: no identifiable marks observed for any interval V: 60-160 sec

H = Horizontal position during PWI and at deposition
V = Vertical position during PWI and at deposition

Table 3

Range of PWI times in which identifiable bloody fingermarks were observed.

Continuing with the data in the Table 3, Medium Pressure column, it can be observed that when the volume of blood is increased to 20 µL, no identifiable marks were observed during an immediate deposition time (PWI = 0 seconds) in the horizontal position. But as the blood dried, identifiable fingermarks began to appear at 30 seconds and then were observed for the next minute or so. At 80 to 90 seconds PWI, as seen in Table 3, the blood was nearly dry and fewer identifiable marks were observed. After 90 seconds, as can be observed in Figure 8, minimal ridge detail was observed (still exploitable), until approximately 120 seconds, and no ridge detail was observed at all (Figure 8). This trend was observed as the blood volumes were increased to 40 µL, 70 µL, and 100 µL. Whereas previously, no donor could deposit a fingermark with ridge detail at 70 µL when the fingermark was deposited immediately, after holding the finger in a horizontal position for 80 seconds, ridge detail could then be observed in the fingermarks. After 220 seconds, the blood had dried on the finger and no identifiable fingermarks were observed.

With respect to the effect of pressure on the PWI times, there was a shift toward longer time intervals. As an example, in the 20 µL volume row in Table 3, identifiable marks were found (for horizontal positioning) between 30 to 60 seconds PWI for light pressure (a 30-second window), 30 to 90 seconds PWI for medium pressure (a 60-second window), and 30 to 100 seconds for heavy pressure (a 70-second window). The maximum times are steadily increasing (60, 90, and 100 seconds for light, medium, and heavy pressures, respectively). This trend was more consistent for the first three volumes (10, 20, and 40 µL), but was less consistent and less pronounced for the largest volumes (70 and 100 µL).

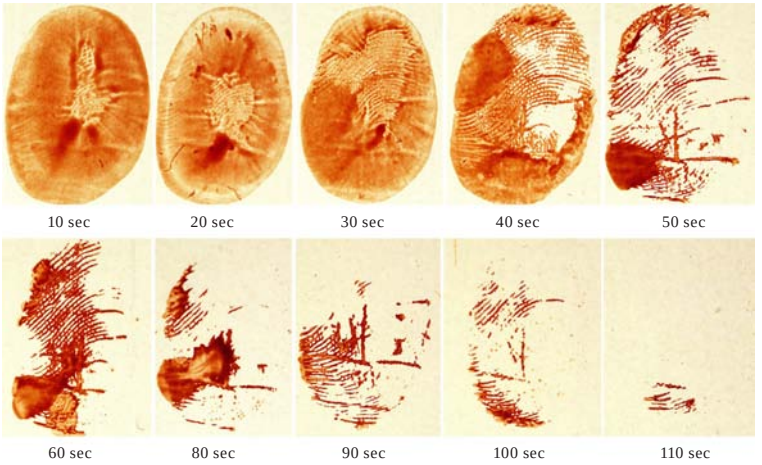


Figure 8

PWI series from 10 seconds to 110 seconds. All fingermarks were made with 20 µL of blood, at medium pressure, on a horizontal surface. No ridge detail at all was observed at 120 seconds (not shown above).

We observed that in the PWI trials, somewhere between 3 and 4 minutes of PWI time, regardless of the volume of blood, the blood on the finger was nearly dry. We explored this further. We performed a series of trials where as much blood as possible was loaded on the fingers. We did not keep the fingers in one consistent position, but rather allowed a free range of movement, and then observed ridge detail produced at 1-minute intervals. Again, we found similar results: the blood was nearly dry at 3 to 4 minutes PWI and at 5 minutes, no ridge detail was observed (Figure 9). Obviously, at smaller volumes of blood, the blood dried much sooner (1 to 2 minutes). This could be a useful fact to the crime scene investigator at the scene of a crime. We did not perform these types of trials with blood that had cooled or at cooler ambient air temperatures. It is expected that cooler blood or a cooler ambient temperature would increase this maximum drying time of blood on the fingers, but we did not explore to what extent this window might be extended.

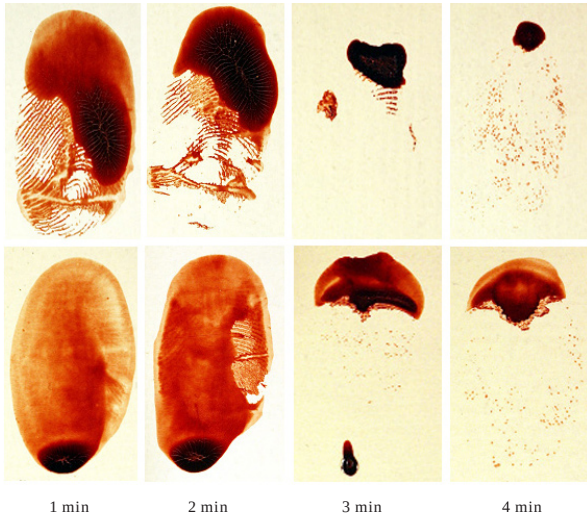


Figure 9

Maximum volume of blood loaded onto thumb. The maximum possible amount of blood was loaded onto the thumb and then fingermarks were made at extended PWI times, under medium pressure for horizontal position (top row) and vertical position (bottom row). No ridge detail was observed at the 5-minute mark (image not shown).

PWI and Levels of Detail

One aspect that was examined, though not directly reported here, was an assessment of the presence of level 1 detail (L1D), level 2 detail (L2D), level 3 detail (L3D), and "accidental" or "occasional features" (specifically, creases and wrinkles in this study)[5]. Although only identifiable fingermarks were reported for the PWI windows in Table 3, there was a shift in times, depending on which level of detail was examined. In the majority of marks, creases and wrinkles were the first observable features in the PWI window and often the last visible features in the window. L1D was discernible after occasional features appeared. This was then followed by L2D, which much of the reported PWI values were based on. Finally, there was a very short (if present at all) interval in which clear L3D was observed. Generally, blood was not a good matrix for capturing L3D shapes of ridges, but in some trials, the undried blood in the pores facilitated location of the pores. Ashbaugh reported:

> The heavy viscosity of the matrix often causes a piling-up effect when the finger is lifted, similar to when taffy is pulled. When contact between the substrate and the matrix is broken, the resulting settling down of the matrix can create what appears to be strong third level detail. Many false artifacts can be created in this situation. [12]

We noted a similar effect. Though Ashbaugh suggested that this is due to the viscosity of the blood, the "piling effect" can more likely be attributed to a combination of the physical properties of viscosity and cohesion (the affinity for similar molecules to be attracted to one another and resist physical separation, as opposed to adhesion, which is the attraction of one type of substance to another type of substance). Wonder [13] explained this phenomenon well with respect to the hematocrit component of blood and demonstrated this effect with photographic examples.

As a general model, we observed the following scheme, as depicted in Figure 10.

Illustrative of this flowchart scheme, the images in Figure 8 demonstrate this progression of the appearance of the three levels of detail.

[5] Other authors and sources have defined the levels of detail and they need not be addressed here.

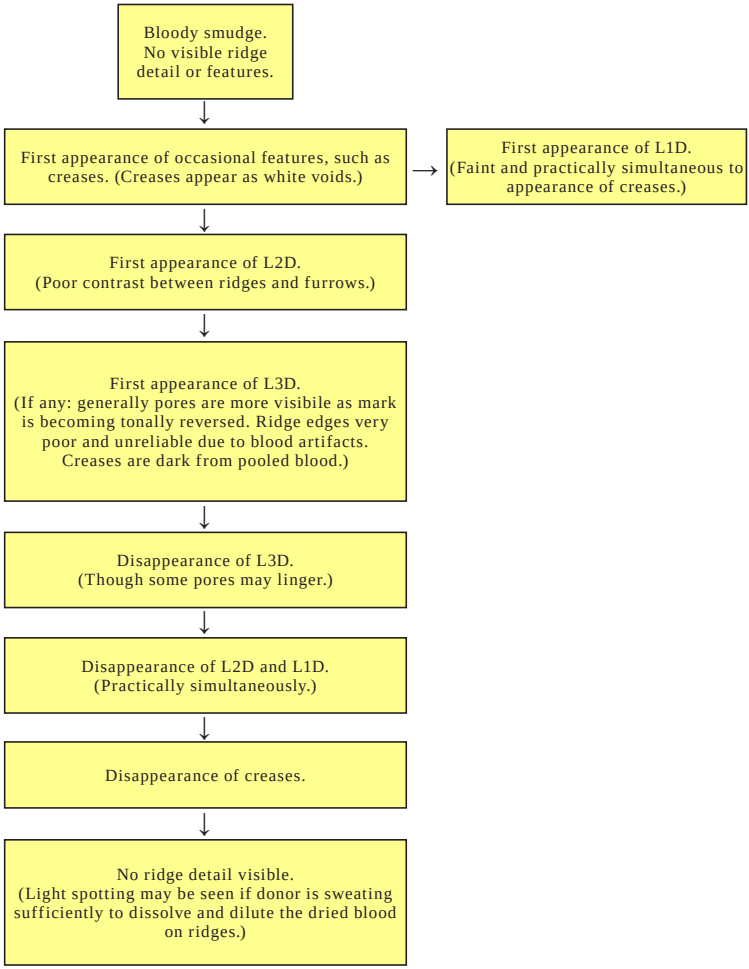


Figure 10

Flowchart representing appearance of various characteristics in a bloody fingermark PWI time series.

Use of Chemical Reagents for Enhancement of Bloody Fingermarks

Two general classes of reagents for the enhancement of ridge detail in blood exist: heme reacting reagents (e.g., leucomalachite green [14]; leucocrystal violet [15]; diaminobenzidine [16]); and general protein stains (e.g., amido black and coomassie brilliant blue [17]). None of these reagents were used in this study. Use of these reagents could drastically affect the results. For example, ridge detail may be observed beyond the 3- to 4-minute maxima that were reported in this study. This may occur where trace amounts of blood were deposited, but were not visible to the naked eye. Additionally, identifiable fingermarks may be viewed for shorter PWIs or for larger volumes of blood, where use of the reagent may remove some of the excess blood and increase contrast between the ridge and furrows. It is highly recommended that future studies address this issue, given the extensive use of these reagents at crime scenes.

Pressure and Tonally Reversed Ridges

Normally, the friction ridges in an impression reflect the color of the development medium (black ridges when black fingerprint powder is used or white ridges when white fingerprint powder is used) or the friction ridges are the color of the matrix which compose the fingermark (black ridges when deposited with fingerprint ink or dark red ridges when deposited with blood). Occasionally, the friction ridges in an impression are found to be the opposite color of what is expected (e.g., friction ridges are white, while black fingerprint powder developed the furrows black). This is known as a tonal reversal (or sometimes referred to as "inverted ridges") [18]. Ashbaugh also described this effect as a "reversal":

> This type of print appears to change ridge color halfway through the print when it is developed. These prints are sometimes referred to as reversals .... [19]

Calling this phenomenon a "reversal" can be confusing, because a "reversal" can also refer to a left-right "image reversal" [20]. An image reversal can be observed when using a rubber or gelatin lifter or a silicon-based type casting material (e.g., Mikrosil) to lift a powder-developed fingermark. The author prefers the specificity of the nomenclature suggested by Triplett (i.e., tonal reversal).

The tonal reversal effect can be explained by various mechanisms. Tonally reversed impressions can occur when the development medium has a greater affinity for the substrate than an affinity for the matrix or components found on the ridges. An example of this can be seen when a latent fingermark is visualized with cyanoacrylate (ridges are white) and then black powder is applied to further visualize the fingermark. The expectation is that the ridges will develop black. On occasion (for instance, when the substrate is a plastic bag), the black powder may preferentially adhere to the bag rather than to the cyanoacrylate-developed ridges. Thus a fingermark is developed where the furrows are black and the ridges are white.

Another mechanism that has been used to explain the phenomenon of tonal reversals is by the application of excessive pressure during deposition. Ashbaugh described the phenomenon as follows:

> In situations where there is extreme pressure the ridges can be flattened against the substrate to such a degree that the matrix is pushed to each side of the ridge, resulting in a hollow ridge appearance upon development. [21]

An example of this is shown in Figure 11. The left-most image in Figure 11 is an inked thumbprint that was produced with a normal amount of ink (Ace Brand Black Fingerprint Ink), medium pressure, on white poster board. The ridges are black and the furrows are white in this ink fingerprint deposited under normal conditions. The next two images to the right were produced with extreme pressure, the first with a normal amount of ink, the second with excess ink. Both images are tonally reversed - - the ridges are white and the furrows are black. The right-most image is a visualized latent fingermark that was produced by loading excess sebaceous material onto the finger and then depositing on white poster board with extreme pressure. The mark was visualized with black magnetic powder (Sirchie brand). Again, a tonally reversed fingermark was created. Therefore, the accepted mechanism for producing tonally reversed fingermarks when the matrix is highly viscous, such as ink or sebaceous residue or grease, appears to be valid.

However, when the matrix is less viscous and more fluidlike, the mechanism did not produce tonally reversed fingermarks. It has been the author's personal experience that the mechanism of extreme pressure is commonly used to explain tonally reversed ridges in bloody fingermarks. In a bloody fingermark, the tonally reversed ridges will appear as white, and the furrows will appear as the color of the blood (or the color of a chemical enhancer, such as amido black, if applied). The mechanism to explain a tonally reversed bloody fingermark, as explained to the author during training (and erroneously propagated by the author as a trainer!), was that pressure will force the blood off the friction ridges and into the furrows during deposition, causing the tonal reversal. Thus there is a direct correlation to increasing pressure and the likelihood of a tonal reversal. *This is definitely not the case*. Figure 12 clearly shows with increasing pressure from left to right in series, there was no drastic change in the appearance of the ridges and only minimal tonal reversal was observed. (There were slight exceptions. For example in Figure 12, in the "heavy pressure" fingermark, in a small area on the left side of the mark, there is a tonal reversal shift from dark ridges to white ridges). The absence of tonally reversed bloody fingermarks under excessive pressures was repeated time and time again in the study much to our surprise, because it is such a widely held belief.

Nonetheless, we found a way to consistently produce a tonal reversal, and even under the lightest of pressure. We discovered that we could produce tonally reversed bloody fingermarks whenever there was a significant PWI time before deposition. Figure 13 clearly demonstrates this effect for three pressures: light, medium, and heavy.

Returning now to Figure 8, one can observe the point in the series where the tonal reversal occurred for these conditions. Figure 8 shows a series of bloody fingermarks deposited in the horizontal position, with 20 µL of blood, at medium pressure. Each image in the series shows a fingermark deposited under these conditions, but with an increasing PWI time. It is shown in Figure 8 that when the fingermarks were deposited with a PWI of 10 seconds to 20 seconds, there was no evidence of a tonal reversal. The first signs of tonally reversed ridges appeared at 30 seconds PWI in the area halfway toward the tip (at the 12 o'clock position). At 40 seconds and each subsequent PWI time, a clear tonal reversal can be observed in each image. The PWI time was the critical factor for creating a tonal reversal, not pressure.

Ink
Medium Pressure

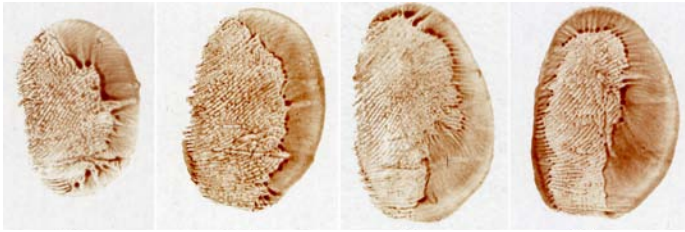
Ink
Extreme Pressure

Excessive Ink
Extreme Pressure

Excess Sebum
Extreme Pressure

Figure 11

Ink and sebum matrix fingermarks demonstrating tonal reversal with excessive pressure.



Light Pressure

Medium Pressure

Heavy Pressure

Extreme Pressure

Figure 12

Increasing deposition pressure did not produce tonally reversed bloody fingermarks.

Light Pressure

Medium Pressure

Heavy Pressure

Figure 13

Tonally reversed fingermarks produced at three deposition pressures. These bloody fingermarks were produced with 20 µL of blood, each deposited at different deposition pressures, in a vertical position, at PWI = 50 seconds. A consistent tonal reversal is present in each fingermark.

Blood accumulating on the friction ridges will dry at a faster rate than the blood accumulating in the furrows. There is most likely a larger volume of blood trapped in the furrows and any volume of blood will be more protected from drying effects by the neighboring ridges. A slightly modified alternative to this explanation rather than initially different volumes of blood in the furrows than on the ridges is that because of the fluidity of the blood and the effect of gravity, blood on the ridges will flow down from the ridges into the furrows during the PWI time. So though initially there may not have been a different volume of blood on the ridges than the volume of blood in the furrows, there is a differential that accumulates over time as the blood migrates from the ridges into the furrows. Once in the furrows, the blood is sufficiently protected and the neighboring ridges act to sequester the blood from drying forces. A graphic is provided in Figure 14 to illustrate this possible mechanism. The author did not perform additional experiments to test this mechanism and recommends further research.

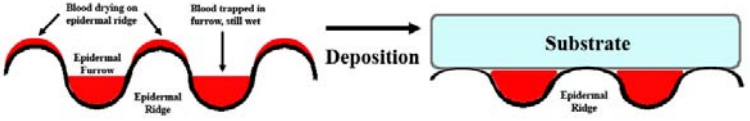


Figure 14

Proposed mechanism for tonally reversed fingermarks after significant PWI times. When deposition occurs, the blood is dry on the epidermal ridge and the epidermal ridges are depressed sufficiently to access still wet blood trapped in the furrows.

Depletion Series

A depletion series is where the donor makes several impressions in a row, with each subsequent impression providing less matrix for reactivity. This scheme is excellent for testing the sensitivity of a chemical. In our previous trials, we did not do any depletion series. Based on comments and suggestions made by Wilkinson [22] after seeing preliminary results, two follow-up tests were conducted.

In the first test series, approximately 100 µL of blood was loaded onto the finger and immediately a depletion series of four impressions was made at light pressure. Each touch physi-

cally removed blood from the ridges through transfer. After four impressions, test fingermarks were made at light, medium, heavy, and extreme pressures. Minimal tonal reversal occurred (Figures 15a and 15b).

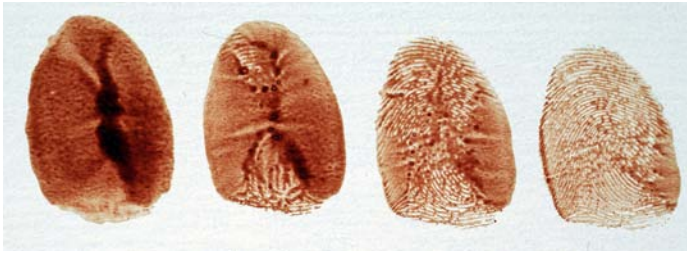
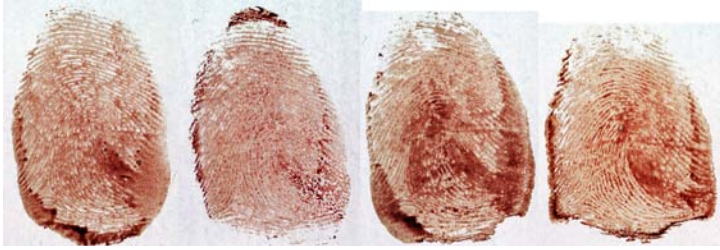


Figure 15a

Depletion series of four sequential fingermark depositions at light pressure.



Light Pressure Medium Pressure Heavy Pressure Extreme Pressure

Figure 15b

Varying deposition pressures after a depletion series of four fingermarks.

The first four depositions in the series were all made at light pressure to gradually remove blood from the ridges. The fifth impression of each series (shown above) was made at varying degrees of pressure. There is actually evidence of slight tonal reversal at each of the four pressures. However, there are no obvious differences from one extreme pressure to the other with respect to the appearance of the ridge detail in these fingermarks.

In the second test series, the procedure above was repeated, but this time with a depletion series of eight impressions at light pressure. By the last impression in the depletion series, there was very little blood matrix remaining on the ridges. After the eighth impression, test fingermarks were made at light, medium, heavy, and extreme pressures. Tonal reversals were observed consistently at heavy and extreme pressures, there was some evidence of the tonal reversal beginning to occur at medium pressure, and none occurred at light pressure (Figures 16a and 16b).

A comparison of the ridge detail in Figures 8, 15b, and 16b reveals distinct differences in the appearance of the ridge detail. Though all show varying degrees of tonal reversals, they were created by different mechanisms and the distortion is noticeably different. The tonally reversed fingermarks are much more consistent and uniform when they were produced by the PWI mechanism. The amount of blood is relatively uniform, the furrows are uniform width, the creases are clear, and there is sharp contrast between the ridges and furrows. In the tonally reversed fingermarks produced by depletion series, followed by excess pressure, there is noticeably more blood transferred to the substrate. There is a lack of contrast between ridges and furrows because of the larger volume of blood used and the areas of tonal reversal are not consistent and uniform throughout. Also, note that in the second mechanism, where excess pressure is necessary to produce the tonal reversal, there is an absence of creases. In contrast, the tonally reversed fingermarks produced by the PWI mechanism at lighter pressures have predominant creases appearing in the fingermarks.

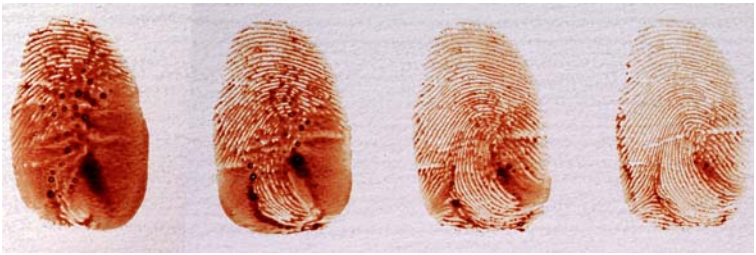


Figure 16a

Depletion series of eight sequential fingermark depositions at light pressure. The last four depositions in a depletion series of eight depositions are shown.

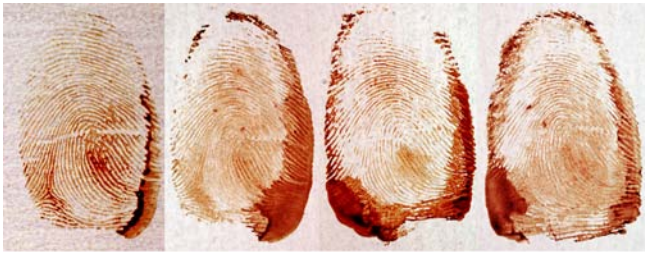


Figure 16b

Varying deposition pressures after a depletion series of eight fingermarks. There is no tonal reversal for the light deposition pressure and there is evidence of a slight tonal reversal for the medium deposition pressure. There is a clear and consistent tonal reversal for heavy and extreme depostion pressures.

Based on these results, the author contends that tonal reversals in bloody fingermarks are predominantly produced by one of two mechanisms:

1) Blood is first physically removed from the ridges through transfer and then the donor applies significant deposition pressure when producing a bloody fingermark. Blood trapped in the furrows and not removed by transfer will then be visible in the fingermark if deposited with significant pressure, sufficient to depress the ridges.

2) There is a significant predeposition waiting interval (PWI) time, such that blood on the ridges has sufficiently dried, while blood trapped and protected in the furrows is still wet. The fingermark donor will be able to deposit a tonally reversed mark with even the lightest of pressure.

Obviously, a combination of the two proposed mechanisms can occur as well. What is clear is that the currently accepted mechanism is false. Significant pressure causing the blood to "squeeze off the ridges" and into the furrows is not the dominant mechanism. Although this may be true for more viscous substances (waxy sebaceous materials or black fingerprint ink), the relatively lower viscosity of blood, compared to these substances, does not aid in the creation of a tonally reversed bloody fingermark.

Conclusions

The following conclusions were drawn from the experimental trials:

- Blood dries on a finger fairly quickly. At maximum loading capacity, the blood dried in 3 to 4 minutes, such that no visible ridge detail would be deposited. At the lowest volumes, the blood dried within 30 to 60 seconds.

- If more pressure was used when blood on the finger was nearly dry, more ridge detail could be deposited.

- Air temperature, airflow, temperature of the blood, and temperature of the skin all were critical ambient conditions that drastically affected drying times and the appearance of the ridge detail.

- The volume of blood on the finger at the time of deposition was a critical factor for the likelihood of depositing ridge detail in the fingermark. For most donors in the study, 10 to 20 µL was optimum when deposition was to be immediate. Beyond that volume, most donors left only a bloody smudge with no visible ridge detail. At volumes below 10 µL, donors left ridge detail in the fingermark, but the blood incompletely covered the finger.

- At lower volumes of blood (10 to 20 µL), higher deposition pressure produced more identifiable impressions than lower deposition pressure for vertically deposited fingermarks. After 30 µL, there was no difference; the pressure factor was negligible compared to the volume factor.

- At higher volumes of blood, identifiable bloody fingermarks were produced by waiting a minute or two before producing the mark. At these higher volumes of blood, no ridge detail was produced when the deposition had been immediate.

- Tonal reversals were not consistently observed with increasing deposition pressure as expected. Two other mechanisms have been proposed to explain tonal reversals based on our data and observations:

    - If sufficient time is allowed for blood on the ridges to dry, while blood trapped in the furrows is still wet, and then a fingermark is deposited, a tonally reversed fingermark can be produced with even the lightest of pressure (Figure 14).

    - If blood is preferentially removed from the ridges (for example, by touching other surfaces) and then a fingermark is deposited with excessive pressure, then a tonally reversed fingermark can be produced (Figure 16b).

- The appearance of the ridge detail produced by these two mechanisms will look drastically different from each other.

In general, there is a need for systematic study of distortion mechanisms and the resulting appearance of ridge detail. Examiners constantly observe distortions in fingermarks and infer the cause of the distortion. When this present research was begun, we had many assumptions about distortion in a blood matrix. Some of those assumptions proved false. This research held many surprises for us and the author believes more quantitative and qualitative data are needed regarding the study of distortion mechanisms.

Future Research Recommendations

Although the author has proposed theoretical mechanisms for the production of tonally reversed fingermarks in blood, these hypotheses should be further tested. As a suggestion, the author recommends that video through glass or high-speed video may be an effective way to study the deposition process for bloody fingermarks and other relevant matrices. This would allow for in-depth study of the mechanism, while comparing the distortion effects in the resultant fingermarks. Additionally, Ashbaugh's comments about the "tackiness" of blood and the potential for false artifacts, especially in the third level detail of ridge shapes, must be explored further. Again, video would be an effective way to observe these effects and compare to the resultant ridge detail.

Lamentably, we conducted all of our tests on a single surface type. These experiments should be conducted on various types of surfaces in future studies. Care should be taken to include at least some metal surfaces, where heat conduction could be integral to drying times. Both porous and nonporous surface effects should be examined.

Lastly, as stated previously, additional work should be performed with various blood-enhancing chemical stains to determine how this critical step would affect the parameters tested in this study.

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