Preprint of article subsequently published:

Hicklin RA, Buscaglia J, Roberts MA (2013) Assessing the clarity of friction ridge impressions. Forensic Science International. 226(1):106-117. (http://dx.doi.org/10.1016/j.forsciint.2012.12.015)

Assessing the Clarity of Friction Ridge Impressions

Abstract: *The ability of friction ridge examiners to correctly discern and make use of the ridges and associated features in finger or palm impressions is limited by clarity. The clarity of an impression relates to the examiner's confidence that the presence, absence, and attributes of features can be correctly discerned. Despite the importance of clarity in the examination process, there have not previously been standard methods for assessing clarity in friction ridge impressions. We introduce a process for annotation, analysis, and interchange of friction ridge clarity information that can be applied to latent or exemplar impressions. This paper: 1) describes a method for evaluating the clarity of friction ridge impressions by using color-coded annotations that can be used by examiners or automated systems; 2) discusses algorithms for overall clarity metrics based on manual or automated clarity annotation; 3) defines a method of quantifying the correspondence of clarity when comparing a pair of friction ridge images, based on clarity annotation and resulting metrics. Different uses of this approach include examiner interchange of data, quality assurance, metrics, and as an aid in automated fingerprint matching.*

Keywords: fingermark | fingerprint quality | latent fingerprint | quality metrics | image quality

Introduction

Despite the importance of clarity in the latent print* examination process, there have not heretofore been standard methods for defining, annotating, and quantifying clarity in friction ridge impressions. Here we introduce a process for assessment, annotation, computation, and interchange of friction ridge clarity information, designed specifically for use in the analysis and comparison of friction ridge impressions.

The ability of latent print examiners to correctly discern and make use of the ridges and associated features in fingerprints or palmprints is limited by the clarity of the latent and exemplar prints. As a latent print examiner analyzes the details of a specific location within a friction ridge impression, a critical attribute constraining the value of those details is the clarity of ridge detail at that location and the immediately surrounding area. As clarity decreases, feature uncertainty increases; some features may not be discerned, image artifacts may be erroneously treated as features, and feature details may be misinterpreted. The clarity of a friction ridge impression refers to the fidelity with which anatomical details are represented in a two-dimensional impression *[5]*, and directly corresponds to an examiner's confidence that the presence, absence, and details of the anatomical friction ridge features in that area can be correctly discerned in that impression.

Clarity is unrelated to the quantity of features in an impression: the ability to discern the presence/absence and attributes of features is independent of the number of features present. For example, a high-clarity area may include no features, such as a clear open field of ridges that contains no minutiae. The term "clarity" is used here instead of "quality" to avoid ambiguity, since the latter term as used in biometrics and forensic science can take various meanings. Generally, latent print examiners define quality to be synonymous with clarity *[1]*, but some other uses of the term "quality" conflate multiple concepts, including not only clarity but also the quantity or distinctiveness of features *[6,7]*.

**Regarding the use of terminology — "latent print" is the preferred term in North America for a friction ridge impression from an unknown source, and "print" is used to refer generically to known or unknown impressions [1]. We recognize that outside of North America, the preferred term for an impression from an unknown source is "mark" or "trace," and that*

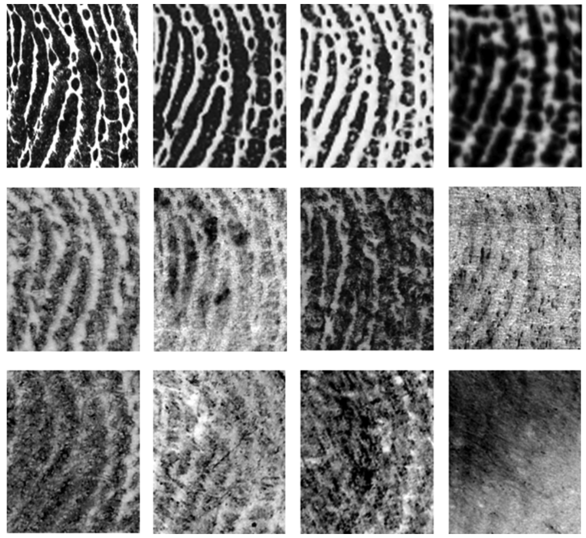


Figure 1: Twelve impressions of a specific area of friction ridge skin, showing the effects of varying clarity on the perception of features.

Figure 1 shows examples of how local variations in clarity determine how features are perceived. Detailed analysis of attributes such as ridge edge details or pores (level-3 features) requires the highest clarity. As clarity decreases, level-3 features become ambiguous, but the paths of individual ridges can still be accurately assessed, including the presence or absence of minutiae (level-2 features). As clarity decreases further, level-2 features become ambiguous, but the continuity and direction of ridge flow (level-1 features) can still be assessed. The lowest clarity does not permit assessing the continuity of ridge flow and, therefore, does not permit the differentiation of actual ridge features from impression-related artifacts such as slippage, smearing, or multiple impressions.

Local assessments of clarity are distinct from any assessments of the overall clarity of the entire impression, as shown in Figure 2. An overall assessment of the utility of an image may be a subjective human assessment, such as the commonly used informal “good”, “bad”, or “ugly” categories, or automatically calculated, such as the National Institute of Standards and Technology (NIST) Fingerprint Image Quality (NFIQ) metric *[7]*, which is widely used as a predictor of automated fingerprint identification system (AFIS) matcher scores for exemplar prints. Both human assessments and automatic calculations are directly or indirectly based in part on an aggregate of local clarity assessments, but necessarily cannot have the specificity of the local assessments. This local specificity is important when only a portion of an image, or individual features, are used in the analysis or comparison of images. Local and overall assessments of clarity both have distinct uses and should not be conflated.

Figure 2: Local clarity assessments are specific to individual areas, and would differ for the four indicated regions. An overall assessment of clarity based on an aggregate of all such local samples from the entire image would lose the detail that the clarity of specific regions in the print ranges from good to poor.

The prevailing method used in latent print examination is Analysis, Comparison, Evaluation, and Verification (ACE-V). *[5,8]* Each of the stages of ACE-V requires that the examiner assess and understand the implications of varying levels of clarity. During the *Analysis* phase, when a friction ridge image is initially assessed, the determination of whether the impression is of value for comparison (for potential individualization or exclusion) is based on the quantity and clarity of features. The *Comparison* phase consists of comparing features in two images to find corresponding and/or non-corresponding information. For complex comparisons, the availability, selection, and use of features during comparison is limited if local clarity makes individual features or their details indiscernible. Concerns are raised if poor clarity results in large gaps or discontinuous areas that prevent the accurate assessment of features in context with other features. During the *Evaluation* phase, a conclusion of individualization, exclusion, or inconclusive is made based on the quantity and distinctiveness of the features in common between the two images being compared, as limited by clarity. In making evaluation conclusions, clarity and the quantity of features are inversely proportional: as clarity decreases, an increasing number of features is necessary to make a conclusion of individualization or exclusion. *[5,9]* *Verification* is an independent repetition of the ACE process by another examiner. If verification results in a conclusion contrary to the initial examiner's conclusion, a dispute resolution process ensues. During dispute resolution, the differing conclusions are often based on differing assessments of clarity: disputes often revolve around differing interpretations of the presence, absence, or attributes of individual features, all of which are driven by clarity. *[e.g. 10]* In each stage in ACE-V, the examiner's decisions are determined in part by assessments of local image clarity for overlapping areas of comparison impressions.

Background: Latent Quality Survey

The method described here was developed based on the findings from our previous survey of latent print examiners, described in detail in *[3]*. In that study, 86 latent print examiners assessed the local and overall clarity of latent prints and exemplar fingerprint images. Out of a total pool of 1090 fingerprints, each examiner reviewed approximately 70 fingerprint images, resulting in a total of 5245 image reviews. For each image, each examiner used a custom software application to annotate areas within each impression to indicate the degree of confidence in level-1 features (ridge flow), level-2 features (presence, absence, and location of minutiae), and level-3 features (ridge edge, ridge shape, and pore detail). In addition, the examiners provided an overall assessment of each image by indicating whether the image was of value for individualization and/or exclusion, and by indicating the overall difficulty anticipated in performing a comparison using the image (assuming sufficient quality and overlapping area in the exemplar print).

One of the results of the Latent Quality Survey was the development of a simplified graphical means of defining clarity in terms of examiner confidence with a specified color-coding scheme. These "clarity maps" provide an intuitive visual depiction of friction ridge clarity, as shown in Figure 3.

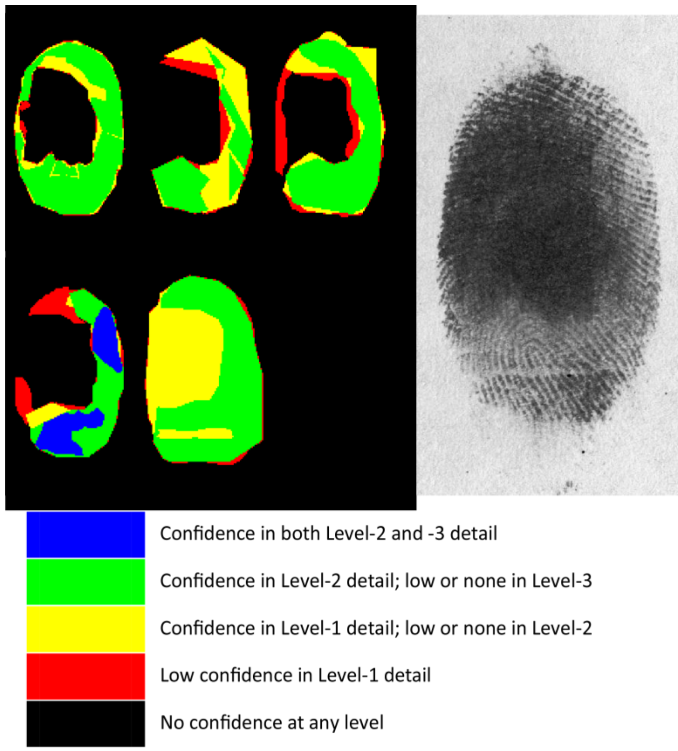


Figure 3: Clarity maps indicating examiner confidence derived from the latent quality survey results, showing typical variation among five different examiners. Figure duplicated from [8] with permission.

The interexaminer variation in annotation seen in Figure 3 was typical: although all of the examiners annotated the same basic areas, they frequently assigned different degrees of confidence to the features found in the area. The differences in annotation among examiners correlated to the examiners' assessment of the value and difficulty of the images: examiners who indicated lower confidence or smaller areas of confidence were more likely to assess a given impression as difficult than examiners who indicated higher confidence or larger areas of confidence. Analysis of the Latent Quality Survey results showed the extent of consistency between examiners in value determinations; the relationships between the overall perceived quality of an impression and the size of clear ridge detail; and the relationships between quality, size, and correct pattern classification. Analysis of the relationships between the sizes of local clarity regions and examiner assessments of value and difficulty revealed information useful for the development of guidelines, metrics, and software tools for assessing the quality of friction ridge impressions.

Approach: Latent Quality Assessment Software (LQAS)

The data and findings from the Latent Quality Survey were used as the basis for further analyses of latent print clarity. In turn, these analyses led to the development of prototype Latent Quality Assessment Software (LQAS), shown in Figure 4. LQAS was designed as a proof-of-concept interactive tool for the evaluation of clarity, with the following functionality:

- Manual definition of clarity maps using a painting interface (discussed below under *The process of assessing clarity*);
- Automated definition of clarity maps based on image processing algorithms (Not discussed here; to be described in a separate paper);
- A variety of functions to process clarity maps, resulting in aggregate clarity measures and calculation of an overall clarity (OC) metric (see *Algorithms for aggregating clarity maps*);
- Annotation of corresponding points, providing a method for overlapping impression areas, and calculation of clarity metrics in the overlapping areas (see *Corresponding clarity for comparisons*).

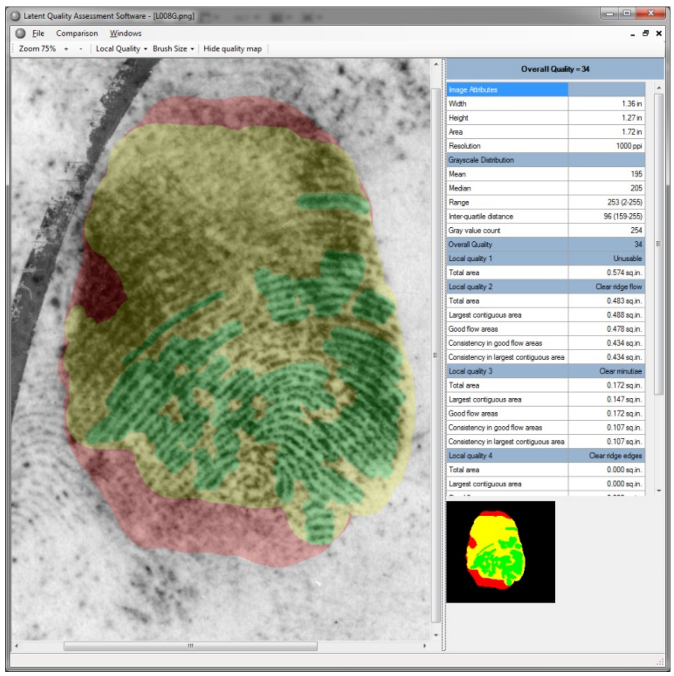


Figure 4: Screenshot of the graphical user interface for prototype Latent Quality Assessment Software (LQAS).

The process of assessing clarity

During analysis of an impression, comparison of two impressions, or verification of another examiner's comparison, latent print examiners generally follow a series of conscious or unconscious steps when assessing each feature. Consequently, the analysis of clarity can be reduced to a series of assessments: of the presence of friction ridge information, the continuity of overall ridge flow, the continuity of the paths of individual ridges, and the discernibility of features within individual ridges. Figure 5 shows this decision process as a series of yes or no questions, resulting in a color-coded categorization of local clarity (LocC).

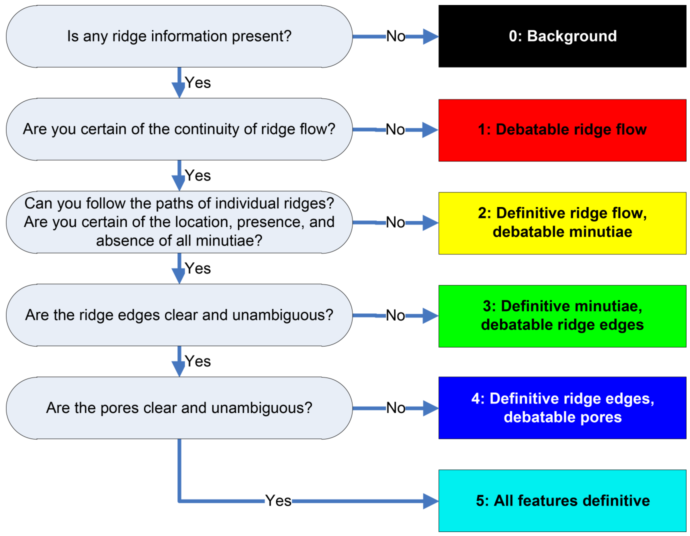


Figure 5: Decision process for the assessment of local clarity (LocC) as used in clarity maps (from [9]).

Clarity maps provide a person (or software program) reviewing the image a standard, straightforward means of assessing the size and degree of clarity within various portions of the image. While the exemplar in Figure 6 can be described in words, the clarity map immediately conveys that the examiner found two areas (colored red) without continuity of ridge flow, and larger areas (colored yellow) in which minutiae and individual ridge paths are debatable and may therefore potentially contain false or missed features. Different examiners may differ in their assessments of images: this approach provides a means of indicating what a given examiner sees in an image; comparison of maps between multiple examiners can be used to depict the extent of (dis)agreement in their assessments.

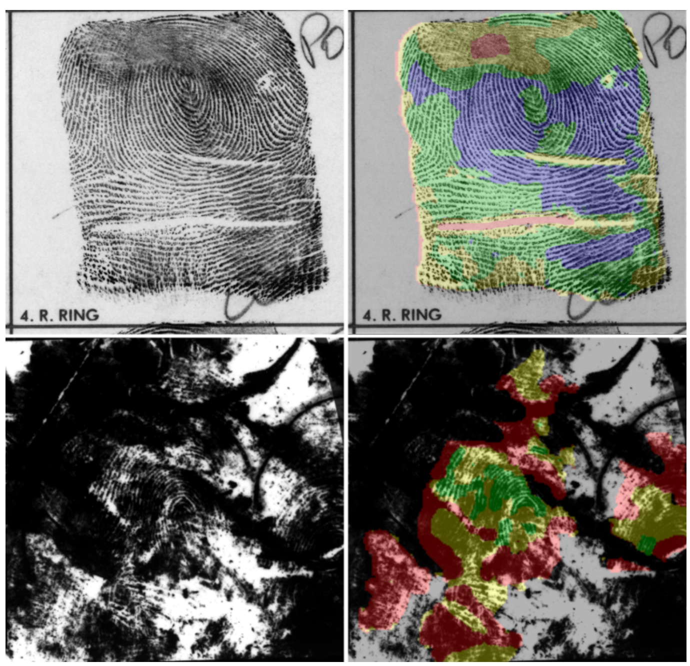


Figure 6: Examples of clarity maps: (top) for an inked exemplar; (bottom) for a latent image with multiple discontinuous areas.

The value of an image depends upon the size and continuity of the clarity map areas. Clarity maps are particularly important for images with extensive discontinuities: the small separations of debatable ridge flow (red) are key, because those define the problem areas that can cast doubt on comparison decisions. The latent print in Figure 6 is complex, containing multiple impressions, slippage, and double taps; the associated clarity map indicates an examiner's assessment of the areas that contain continuous ridge flow, and literally depicting the areas that should be treated with caution in performing comparisons (often referred to as "red flags").

Analysis of clarity maps can be rapid and effective: when viewed at thumbnail size, dozens of images can be reviewed at a glance, as shown in Figure 7. Much of the assessment of the overall utility of the image can be reduced to analyses of these clarity maps: ideal images have large blue or green areas, whereas poor images have little green or blue, and notable gaps, discontinuities, holes, or concavities. When multiple clarity maps are available for a single impression, disagreements among examiners in analysis are immediately apparent; for example, in Figure 3, examiners did not concur on the continuity of the area in the center of the impression, or the usability of the ridge detail at the top and left of the impression.

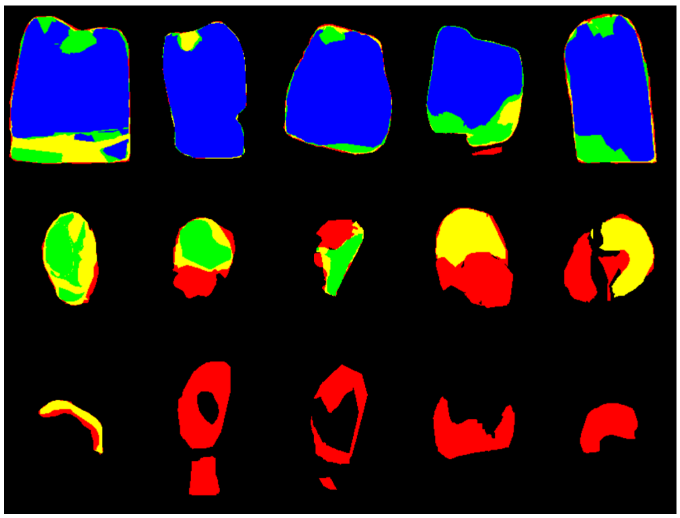


Figure 7: Clarity maps shown at thumbnail size; all images are the same scale. The top row includes exemplars rated "very easy" by examiners; the second row are latents rated "Difficult" or "Very difficult" by examiners; the third row are latents rated "of no value" by examiners.

It is critical to note that the clarity maps are not contingent on minutiae or other features. A clarity map can be used in conjunction with marked features to indicate degrees of confidence in specific features. For example, minutiae in a yellow area are not definitive; minutiae in a green area are definitive but with little or no associated ridge edge detail; and minutiae and ridge edges in a blue area are definitive but with little or no associated pore detail (level-3 detail). Clarity maps can indicate distinctions between the definitive absence of features and the lack of discernible features: a green area without any marked minutiae indicates an open field of ridges (definitive absence of minutiae), whereas a yellow area without any marked minutiae indicates an ambiguous area that may contain undetected minutiae.

The decision process and LocalClarity (LocC) categories defined in Figure 5 and implemented in LQAS built upon findings from the Latent Quality Survey *[3]*, and were further refined based on iterative feedback from users of LQAS. The LocC definitions specifically refer to "ridge flow" instead of "level-1 detail", and "ridge edge features" and "pores" instead of "level-3" detail, based on findings from the Latent Quality Survey that the working definitions of "level-1" and "level-3" detail vary among examiners. The development of LQAS and assessment of its usability resulted in replacing the polygon/lasso interface used in the Latent Quality Survey with a paintbrush approach that was simpler and more intuitive for examiners to use, in which the clarity map colors are painted as a transparent overlay on the friction ridge impression. One effect of changing from a polygon-based representation to a painting interface was that the resulting representation of the clarity map required consideration of the sampling frequency used. It rapidly became clear that sampling clarity maps at the resolution of the original image[†] provided an excessive amount of detail, and made comparing the clarity maps cumbersome because the resulting sizes were dependent on the original images' resolutions. As a result of experimentation during the development of LQAS, we concluded that sampling was most effective at a frequency of 0.008 inches[‡] (0.2 mm); aliasing is limited since this is less than the Nyquist rate for ridge frequency for most of the population.[§] Lower sampling frequencies were blocky and imprecise because the frequency was too close to the ridge frequency itself, resulting in interference and not permitting individual ridge paths to be followed. Higher sampling frequencies increased storage space and processing time and were not found to provide any notable benefit. The resulting clarity maps have an effective resolution of 125ppi (4.9ppmm), regardless of the resolution of the original image.

The clarity maps that were developed in this study and are described here have been incorporated into the Extended Feature Set (EFS) in the American National Standards Institute/ National Institute of Standards and Technology (ANSI/NIST) 2011 standard "Data Format for the Interchange of Fingerprint, Facial & Other Biometric Information" *[11]*, which is used for the exchange of biometric and forensic information by law enforcement and other agencies in over 100 countries. The EFS revisions to the ANSI/NIST standard are the result of a process started in 2005 to define a standard means of representing features as used by latent print examiners, with the oversight of a broad spectrum of representatives from law enforcement and forensic agencies, the fingerprint community, academia, and senior engineers from each of the major automated fingerprint identification system (AFIS) vendors. EFS clarity maps have been implemented in the FBI's Universal Latent Workstation (ULW), which can be used for editing, viewing, or exchange of clarity annotation.

Two recent publications propose methods for the annotation of latent prints in casework using color-coding to indicate clarity or confidence in features: GYRO *[12]* and Laird *[13]* color-code both minutiae and ridge tracings. The approach discussed here and implemented in EFS encompasses the features of these approaches, but also incorporates them into a formal machine-readable standard, and uses this as a basis for algorithms to quantify clarity. The clarity maps are not contingent on specific minutiae; this permits defining the areas that do not contain minutiae, differentiating between open fields of ridges and ambiguous areas, when the clarity maps are used in combination with minutia annotation. While the GYRO and Laird use of color-coding ridge tracings does provide a means of differentiating among areas without minutiae, the clarity map approach provides a means to define clarity for those areas where a definitive ridge tracing cannot be determined, and can be accomplished much more rapidly than requiring ridge tracing.

Algorithms for aggregating clarity maps

Assessing the overall clarity of an impression requires the aggregation of local clarity data over the image. While the size of the area for each local clarity value is correlated to overall assessments of an image *[3]*, both visual assessments and machine learning analysis showed that area alone was ineffective as an overall assessment of a fingerprint image. Aggregation methods need to address not just size, but also the consistency of the data, accounting for factors such as gaps, discontinuities, or concavities. Such methods of aggregating local clarity values are necessary not just for overall assessments of clarity, but also for automated region of interest estimation.

Algorithms for aggregating local clarity

Ideal impressions have large areas of high clarity that are generally convex and without gaps. The utility of a given location in an impression is not limited to the clarity at that point, but is also based on contiguity of ridge flow, and therefore depends

[†] *The fingerprint images used in the latent quality survey were digitized and meet FBI image capture specifications at a resolution of 1000 pixels per inch (ppi; 39.37 pixels per mm (ppmm)) for latent prints, and 500 ppi (19.69 ppmm) for exemplars.*

[‡] *American units are cited here in cases such as resolution or decision thresholds when they are the primary units and the metric equivalents are rounded.*

[§] *The mean peak-to-peak ridge distance varies by source. Based on experience with criminal databases, the distance used here is 0.56mm; Ashbaugh reports distances of 0.48mm for males and 0.43mm for females [5].*

on the clarity of the neighboring regions. This section describes the derivation of *OverallConsistency*, which is a weighted measurement of the area within a clarity map in which all LocC values are greater than or equal to a specified LocC; OverallConsistency is the primary component used in the calculation of our Overall Clarity metric. In OverallConsistency, locations are weighted more heavily if they are in large continuous areas, and away from gaps and edges. For example, a clarity map with a single large elliptical area of green (LocC=3) will have a much higher OverallConsistency value than a clarity map with the same total amount of green in discontinuous, irregular areas. The algorithms described here are all derivations of a clarity map, which may have been marked by a human examiner, generated automatically, or edited by a human based on an automated map.

Discussion of these algorithms uses the following terminology:

- Sampling point (SP): a specific location within an impression, with points sampled at 125 ppi (4.9 ppmm).
- SPmetric: a numeric value calculated at a specific sampling point
- Map: two-dimensional matrix of SPmetrics.
- Clarity map: a map consisting of LocC sampling points quantized to the values defined in Figure 5, ranging from LocC=0 (black, background) through LocC=5 (aqua, all features definitive).

We define a *consistency* operation as a transformation of a clarity map, resulting in a map in which SPs are deprecated within approximately 3 ridges of gaps, discontinuities and edges. Consistency, given a LocC map and a specified LocC value, measures at each SP the proportion of the surrounding area greater than or equal to LocC, with the surrounding area defined as 17x17 SPs (11.9 mm^2, or approx. 6.2x6.2 ridges assuming an average peak-to-peak ridge distance of 0.56 mm). Our consistency metric is a measurement of variability as a probability.[**]

When calculating areas in LocC maps based on either automated or manual clarity annotation, we found that there were frequently small holes or gaps in the maps that were clearly artifacts of the annotation, such as when an examiner would annotate two adjoining areas and leave small gaps. By performing open then close operations[††] *[14]* (*OpenClose*) for LocC=2 (yellow) with a distance of 2 SPs, a map of the areas of usable ridge flow is transformed to ignore small[‡‡] gaps, and protrusions and isthmuses for use in calculating contiguous areas. The purpose for this is to ensure that (for example) an area is not considered contiguous if it is only connected by a thin isthmus. Our use of OpenClose is balanced by the use of the consistency operation: we determine contiguous areas using the expansive definition of OpenClose but the final calculations are based on consistency measures within those contiguous areas.

We define the following overall metrics:

- *Total area*: the total size of all regions in a clarity map in which all LocC values are greater than or equal to the specified LocC. The size of an area is a count of SPs that meet the specified criteria (24.2 SPs per mm^2). For example, TotalArea(1) is the size in mm^2 of the all areas in a clarity map with LocC=1 (red) or better.
- *Good flow area (GFA)*: the total area for a specified LocC, ignoring areas small enough to be inconsequential. The algorithm uses OpenClose to omit minor gaps or protrusions, and then all regions of any shape smaller than 2.0 mm^2 are omitted (equivalent to a square ~2.5 ridges in each direction). For example, GFA(3) is the size in mm^2 of all areas in a clarity map with LocC=3 (green) or better, omitting trivial areas. If a clarity map only contains large regions for the specified LocC without small gaps or protrusions, GFA and TotalArea are identical.
- *Largest contiguous area (LCA)*: the total area of the single largest connected region in a clarity map in which all LocC values are greater than or equal to the specified LocC. If a clarity map only contains a single connected region for the specified LocC, LCA and GFA are identical. The algorithm uses OpenClose to omit minor gaps.

[**] *This could also be quantified in terms of Shannon entropy: for probability P, entropy = P log(1/P).*

†† Open and close are standard image processing morphological operations. An opening operation is erosion followed by dilation, which removes thin regions and small protrusions, as well as smoothing edges. A closing operation is dilation followed by erosion, which removes small gaps, holes, and concavities, as well as smoothing edges.

[‡‡] *Gaps, protrusions, and isthmuses less than 1.0mm (±2 SPs, approx. 1.8 ridges) are ignored.*

- *ConsistencyInGFA:* a derivation of GFA in which the size of each area is calculated not as the count of SPs, but as the sum of the consistencies for each point in the area. This is a weighted measurement of area in which locations near edges or holes are downweighted, with the result that irregular areas will have lower values than an elliptical area of the same size.
- *ConsistencyInLCA:* calculated as is ConsistencyInGFA, but is limited to the largest contiguous area.
- *OverallConsistency* is an average of ConsistencyInLCA and ConsistencyInGFA, resulting in an increased weight for the largest continuous area.

Calculation of overall clarity metrics

The goal in deriving an overall clarity (OC) metric was to develop a repeatable monotonic value that corresponded to human examiner assessments of the value and difficulty of an image, given a clarity map created by a human examiner or by software. We determined that in order for an overall clarity metric to be useful to latent print examiners, it needed to employ a single scale for both latents and exemplars representing the value and difficulty of the impression. The desired result was to have a single value between zero and 100 that was monotonic with respect to the human examiner overall clarity assessments. The scale was primarily based on the size and consistency of the areas of definitive minutiae (LocC ≥ 3, green or better), and the highest clarity values were limited to impressions with large areas of both definitive minutiae and clear ridge edges (LocC ≥ 4, blue or better).[§§]

The Latent Quality Survey *[3]* results provided a useful but imperfect basis for training an overall clarity algorithm. During that survey, the examiners provided assessments of the value and difficulty of each image, as summarized in Table 1. When using the value and difficulty assessments from the survey, the median assessment for each impression was used; 612 images that had five or more examiner reviews were used to limit variation in the medians. The value and difficulty assessments from the survey were clearly affected by factors such as whether the image was a latent or exemplar print, or the number of minutiae visible in the image. Since these assessments did not directly correspond to our goals for an overall clarity metric, they could not be used in a standard machine learning process as training and test data. Instead, these assessments were used to define a heuristic algorithm as part of a feedback loop using analysis with recursive partitioning, analysis of the images, and development or enhancement of aggregation algorithms.

<table>
<tr><th></th><th></th><th>Value</th><th>Difficulty</th></tr>
<tr><td rowspan="7">Overall value and difficulty</td><td>0</td><td colspan="2">Unusable</td></tr>
<tr><td>1</td><td colspan="2">Useful for exclusion only</td></tr>
<tr><td>2</td><td rowspan="5">Useful for individualization and exclusion</td><td>Very Difficult</td></tr>
<tr><td>3</td><td>Difficult</td></tr>
<tr><td>4</td><td>Moderate</td></tr>
<tr><td>5</td><td>Easy</td></tr>
<tr><td>6</td><td>Very Easy</td></tr>
</table>

Table 1: Human-assessed overall value and difficulty as defined in the latent quality survey [8]

Table 2 describes the overall clarity algorithm. Distinct portions of the scale were assigned to images of no value, or of value for exclusion only. The bulk of the calculations are based on OverallConsistency. The "exclusion only" range is calculated based on the OverallConsistency of yellow regions in a range from 0 to 0.7 in^2 (451.6 mm^2). The "of value for comparison" range is based on a weighted average of green and blue regions to increase weight for regions with level-3 detail: given that OverallConsistency(3) is assessed on areas of green or better, and OverallConsistency(4) is assessed on areas of blue or better, then OverallConsistency(3,4) = 2*OverallConsistency(3) + OverallConsistency(4), with the result that blue areas are considered 1.5 times as valuable as green areas. The OC ranges are associated with specific sizes of OverallConsistency(3,4),

[§§] *In the overall clarity calculation, LocC=5 (clear pores) are treated the same as LocC=4, (clear ridge edge, debatable pores). This treatment is based on both the data and consultations with latent print examiners, neither of which indicated that they should be treated differently.*

so that a size of 0.1 in^2 (5.1 mm^2) results in OC=40, 0.2 in^2 (10.2 mm^2) results in OC=60, 0.4 in^2 (20.3 mm^2) results in OC=80, and 0.7 in^2 (35.6 mm^2) results in OC=90. OC values above 95 are reserved for images that have at least some blue areas marked.

Overall Clarity *from*	Overall Clarity *to*	Value	Description	Calculation
0		No value	Reserved for completely blank image	$If\ GrayscaleRange = 0\ then\ OC = 0\ else$
1		No value	Unusable: No ridge information	$If\ TotalArea(1) = 0\ then\ OC = 1\ else$
2	9	No value	Unusable: No usable ridge flow	$If\ OvConsist(2) = 0\ then\ OC = \min\left[\left(\frac{TotalArea(1)}{0.7}\right) * 7 + 2, 9\right]\ else$
10	19	Exclusion only	Only ridge flow can be used	$If\ OvConsist(3,4) \leq 0.01\ then\ OC = \min\left[\left(\frac{OvConsist(2)}{0.7}\right) * 9 + 10,\ 19\right]\ else$
20	99	Of value for comparison	Continuous value ranging from very difficult to ideal	$If\ OvConsist(3,4) \leq 0.1\ then\ OC = \left(\frac{OvConsist(3,4) - 0.01}{0.09}\right) * 20 + 20\ else$ $If\ OvConsist(3,4) \leq 0.2\ then\ OC = \left(\frac{OvConsist(3,4) - 0.1}{0.1}\right) * 20 + 40\ else$ $If\ OvConsist(3,4) \leq 0.4\ then\ OC = \left(\frac{OvConsist(3,4) - 0.2}{0.2}\right) * 20 + 60\ else$ $If\ OvConsist(3,4) \leq 0.7\ then\ OC = \left(\frac{OvConsist(3,4) - 0.4}{0.3}\right) * 10 + 80\ else$ $If\ OvConsist(4) \leq 0.1\ then\ OC = \min\left[\left(\frac{OvConsist(3,4) - 0.7}{0.8}\right) * 5 + 90, 95\right]\ else$ $If\ OvConsist(4) > 0.1\ then\ OC = \min\left[\left(\frac{OvConsist(3,4) - 0.7}{0.8}\right) * 9 + 90, 99\right]$

Table 2: Description of the overall clarity algorithm

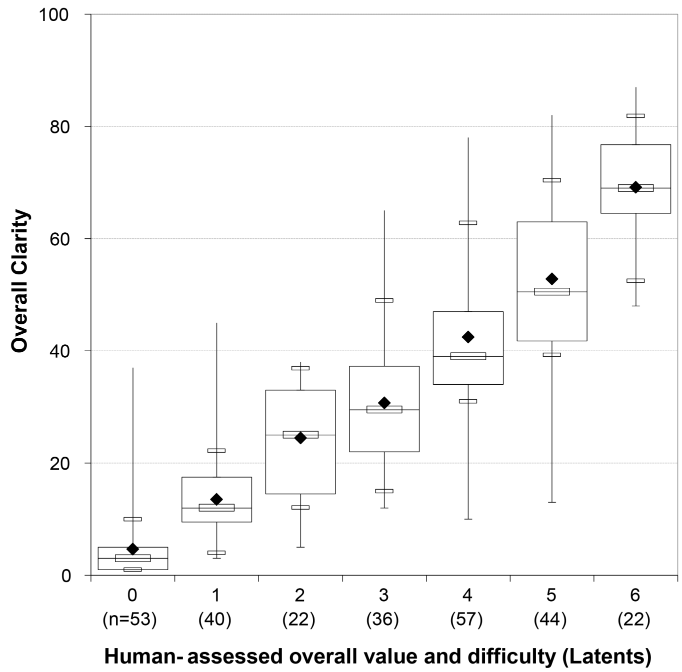
Evaluation of the Overall Clarity Metric

We evaluated the effectiveness of our Overall Clarity metric by comparison with human examiner assessments of the value and difficulty of 545 latent and 545 exemplar fingerprints, collected as part of the Latent Quality Survey *[3]*. Table 3 and Figure 8 summarize the relationship between human-assessed overall value/difficulty and Overall Clarity (based on the median examiner annotation from the Latent Quality Survey). The result is a scale in which Overall Clarity generally ranges from 1 to 10 for "no value" latents, 5 to 20 for "value for exclusion only" latents, 10 to 50 for very difficult or difficult latents, and 40 to 80 for easy or very easy latents. The goal of monotonicity with respect to the human examiners' assessments was achieved: the result was an R^2 of 0.76 for latent prints, and 0.84 for exemplars; correlation of 0.87 for latent prints, and 0.92 for exemplars. Note that the relationship with latent prints is very clearly monotonic, but exemplars are more erratic, due to the limited numbers in all of the bins below 5 (Easy). When compared against the informal "good, bad, ugly" scale used in the NIST SD-27 dataset *[15]*, the median Overall Clarity was 14 for "ugly" prints, 35 for "bad" prints, and 49 for "good" prints; see *[3]* for comparisons of human-assessed overall value/difficulty and good/bad/ugly assessments.

Overall Clarity (OC) *from*	Overall Clarity (OC) *to*	Mean human-assessed overall value and difficulty (0-6) Exemplars	Mean human-assessed overall value and difficulty (0-6) Latents	% of Exemplars *(n=304)*	% of Latents *(n=308)*
0	0				
1	1	0.00	0.00	1.7%	5.8%
2	9	0.00	0.31	1.0%	13.0%
10	19		1.65	-	15.3%
20	40	3.24	2.98	5.6%	26.0%
40	60	4.61	4.30	6.3%	22.7%
60	80	5.61	5.06	10.2%	14.0%
80	90	5.88	5.45	28.4%	3.2%
90	95	5.98		7.6%	-
95	99	6.00		39.3%	-

Table 3: Comparison of human examiner value and difficulty assessments with OC

While the Overall Clarity metric correlates to the examiners' informal, subjective assessment of difficulty, the Overall Clarity metric is more repeatable and reproducible; it is precise, more amenable to analysis, and provides a standard means of communicating assessments of clarity.



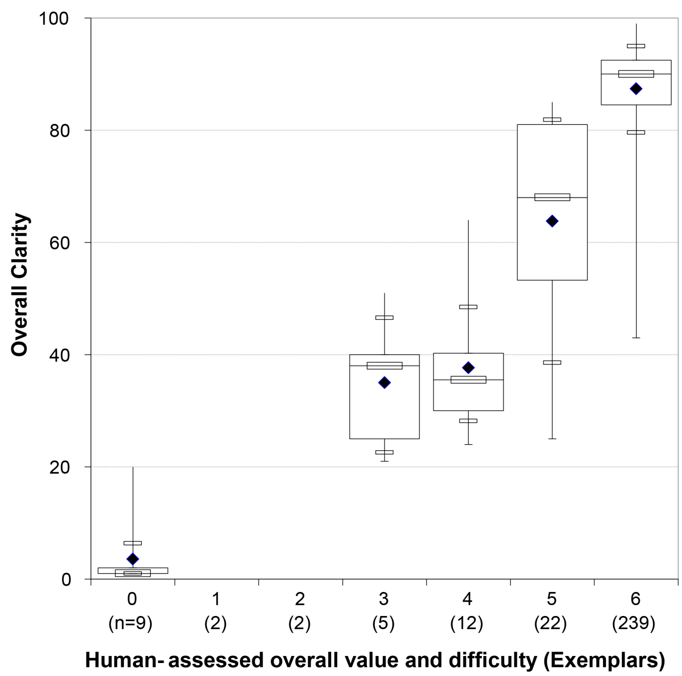


Figure 8: Comparison of human examiner value and difficulty assessments with OC for latent and exemplar images (excluding images with fewer than 5 examiners, fractional human-assessed medians, and bins with fewer than 5 examples).

Corresponding clarity for comparisons

Local and overall clarity measures for a single impression do not directly address how clarity affects the comparison of two impressions. A clear area in one impression is irrelevant if there is no corresponding area available in the other impression, or if the clarity of a corresponding area is substantially lower. When comparing corresponding areas in two impressions, the area of lower clarity limits the comparison. For example, in Figure 9, there are large areas in each image that cannot be used for comparison because there is no corresponding area available; a comparison cannot take full advantage of the incipient ridges in the blue area in the center image, because of the lower clarity of the corresponding area in the left image. The area and clarity of corresponding regions can be depicted in a *corresponding clarity map* that combines the clarity maps for each of the individual impressions: in Figure 9, the corresponding clarity map is the result of transforming and superimposing the clarity maps for the two impressions, and selecting the lesser LocC value at each sampling point.

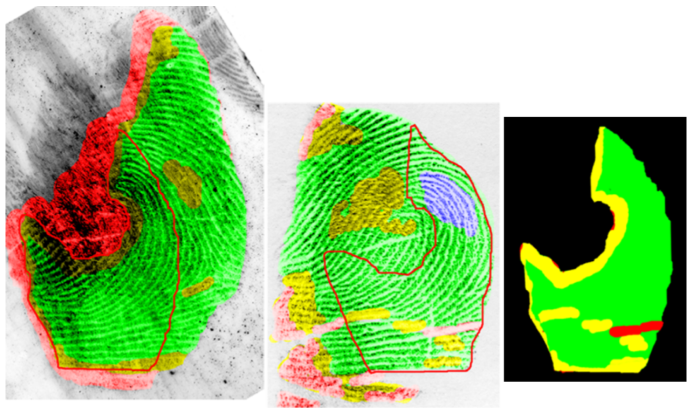


Figure 9: Example of the effect of clarity in a comparison. The outlines indicate the corresponding regions of interest in the two fingerprints. The corresponding clarity map on the right combines the clarity maps for the two fingerprints at each sampling point.

The process of calculating a corresponding clarity map requires a transformation of the two constituent clarity maps so that they are in the same Cartesian space. The clarity map for one impression (generally the latent print) must be transformed so that it can overlay the clarity map for the other impression. This process requires the marking of registration points for the two images, as shown in Figure 10. The transformation of the clarity maps so that they can be superimposed can be accomplished through various warping methods. Affine or projective transformations can be used for impressions that have minimal relative distortion; greater levels of distortion require more sophisticated approaches, such as thin-plate spline transformations. After the transformation, the clarity maps can be superimposed, and a corresponding clarity map created by taking the lesser value from each sampling point of the two clarity maps. Once a corresponding clarity map is defined, it can be processed as any other clarity map, resulting in *corresponding overall clarity* metrics.

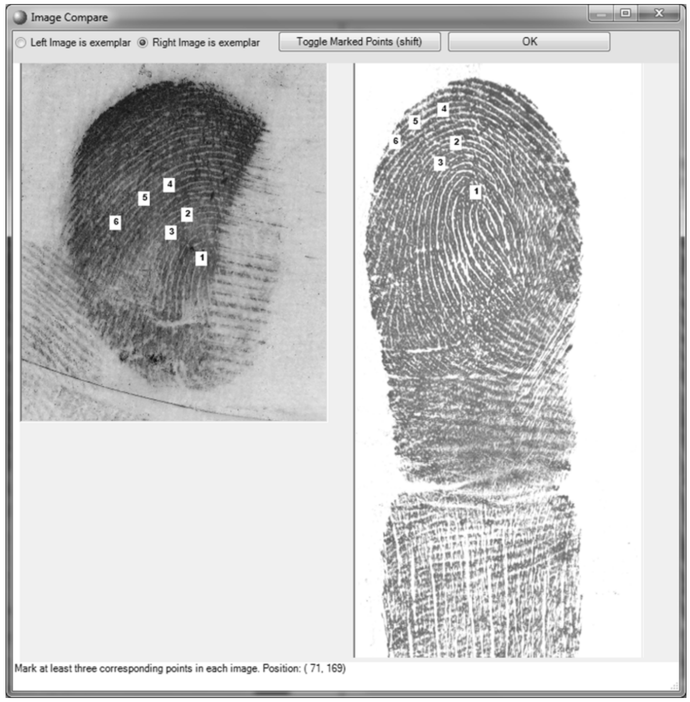


Figure 10: Example of the LQAS registration point user interface for marking corresponding points between and exemplar and latent print.

Figure 11 shows an example of how the latent print's clarity map is transformed and superimposed on the exemplar's clarity map to create a corresponding clarity map. The resulting overall clarity metrics provide a sophisticated means to quantify the complexity of a comparison. Corresponding clarity maps may be of operational interest for documenting comparisons; corresponding clarity metrics may be appropriate for use in quality assurance processes, such as in flagging complex comparisons that require additional review.

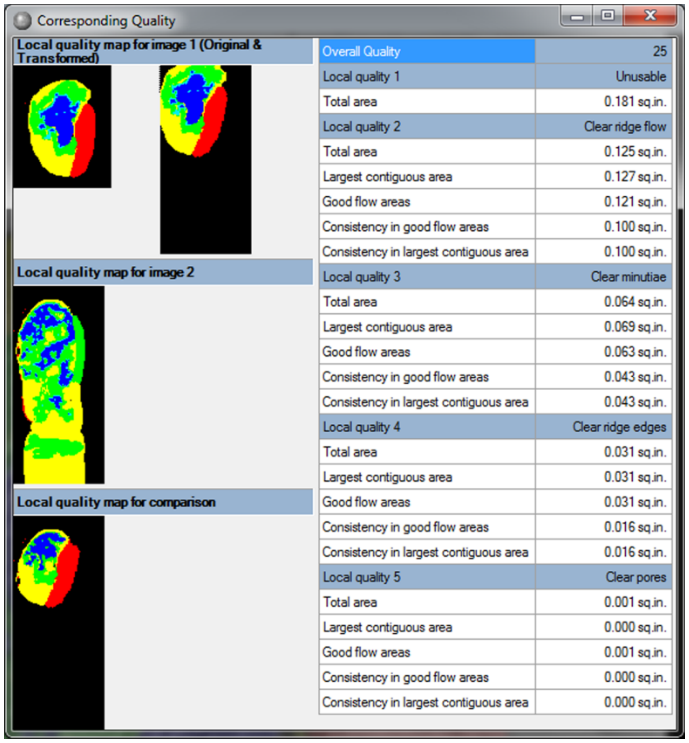


Figure 11: Example of the how the clarity map for a latent print (top left) is transformed and superimposed over an exemplar's clarity map (center left) to create a corresponding clarity map (bottom left), with resultant aggregate and overall clarity metrics (right) calculated based on the corresponding clarity map.

Discussion and Conclusions

This paper describes a method for evaluating the local clarity of friction ridge impressions using standard color-coded annotation. Our approach has been formally defined and incorporated into the ANSI/NIST 2011 standard *[11]*, which is the standard format used internationally for transmission of forensic friction ridge data, and implemented in the FBI's Universal Latent Workstation. We build upon this definition for clarity annotation, and discuss algorithms for overall clarity metrics that aggregate the information in clarity annotation. The metrics we present are based on the size, continuity, and variability of the areas defined in the clarity maps, and can be based on either manual or automated clarity annotation. We also demonstrate how clarity annotation and metrics can be used to quantify the correspondence of clarity when a pair of friction ridge images is compared.

The definition of clarity maps in an international standard provides a reliable, commonly defined means for interchange of assessments of clarity and confidence in features made during the analysis or comparison stages of friction ridge examination. Clarity maps may be used in standardizing how examiners make value decisions, documentation, communication among examiners, resolution of conflicts between examiners, and as a means of rapid visual assessment of impressions. Clarity maps and resulting metrics could be useful for assessing the effectiveness of latent print development techniques, currently based on examiners' subjective assessment of the quality of the developed prints. Corresponding clarity may be used for documentation or presentation of comparison determinations, or as a tool for use in quality assurance processes, so that comparisons with low corresponding clarity that result in individualization determinations can be flagged for additional quality assurance review.

Our clarity model can be used as an aid in automated fingerprint matching. Clarity maps provide a means for examiners and automated systems to communicate confidence levels associated with feature annotation. Human-marked clarity maps included with minutiae in searches of an AFIS can be used by the AFIS to determine which minutiae are definitive, as well as to determine which unannotated areas are open fields of ridges. Feature-by-feature confidence information provides the means for an AFIS to make exclusions based on contradictory features. Automatically-generated clarity maps can be used as a tool in processing latent prints to be searched in an AFIS: overall clarity metrics based on automated clarity maps may be used as a means to flag the impressions of sufficient clarity to be processed as image-only searches, without manual examiner annotation of features.

Ultimately, clarity metrics can be combined with metrics based on the quantity of features to produce objective and repeatable value determinations for latent prints, as well as standardized assessments of the complexity of an image comparison.

Acknowledgements

This is publication number 12-06 of the Laboratory Division of the Federal Bureau of Investigation (FBI). The views expressed are those of the authors and do not necessarily reflect the official policy or position of the FBI or the U.S. Government. Portions of these results, including some figures, were first presented in 2008 at the International Association for Identification Educational Conference in Lexington, Kentucky. This research was conducted under a contract award to Noblis, Inc. from the Federal Bureau of Investigation Laboratory; additional funding was provided to Noblis by the FBI Biometric Center of Excellence to prepare this manuscript for publication. We thank William Fellner, Mark Burge, Brad Ulery, George Kiebuzinski, Harold Korves, Michael Beachler, Calvin Yeung, Ted Unnikumaran, Matthew Monaco, Larry Pantzer, David Vera, Matthew Schwarz, Stephen Meagher, and the Committee to Define an Extended Fingerprint Feature Set (CDEFFS) for their assistance and insights.

References

1 Scientific Working Group on Friction Ridge Analysis, Study and Technology; Standard terminology of friction ridge examination, ver.3.0 (2011). (http://swgfast.org/documents/terminology/110323_Standard-Terminology_3.0.pdf)

2 B.T. Ulery, R.A. Hicklin, J. Buscaglia, M.A. Roberts Accuracy and reliability of forensic latent fingerprint decisions. Proceedings of the National Academy of Science USA 108:19 (2011) 7733-7738. (http://www.pnas.org/content/108/19/7733.full.pdf)

3 R.A. Hicklin, et al; Latent fingerprint quality: a survey of examiners; J. Forensic Identification, 61:4 (2011) 385-418.

4 B.T. Ulery, R.A. Hicklin, J. Buscaglia, M.A. Roberts, Repeatability and Reproducibility of Decisions by Latent Fingerprint Examiners. PLoS ONE 7:3 (2012). (http://www.plosone.org/article/info:doi/10.1371/journal.pone.0032800)

5 D. Ashbaugh; Quantitative-Qualitative Friction Ridge Analysis: an Introduction to Basic and Advanced Ridgeology; CRC Press, 1999.

6 R.A. Hicklin, C.L. Reedy; Implications of the IDENT/IAFIS Image Quality Study for Visa Fingerprint Processing; Noblis, (2002). (http://www.noblis.org/MissionAreas/nsi/ThoughtLeadership/IdentityDiscovery_Management/Documents/NIST%20IQS%20Final.pdf)

7 E. Tabassi, C.L. Wilson, C.I. Watson; Fingerprint Image Quality, NIST Interagency Report 7151; National Institute of Standards and Technology, Gaithersburg, MD (2004). (ftp://sequoyah.nist.gov/pub/nist_internal_reports/ir_7151/ir_7151.pdf)

8 R.A. Huber; Expert Witness; Criminal Law Quarterly 2 (1959) 276-296.

9 J. Vanderkolk; Forensic Comparative Science: Qualitative Quantitative Source Determination of Unique Impressions, Images, and Objects; Academic Press, 2009.

10 Office of the Inspector General; A review of the FBI's Handling of the Brandon Mayfield case; U.S. Department of Justice, Washington D.C. (2006).

11 National Institute of Standards; American National Standard for Information Systems: Data format for the interchange of fingerprint, facial & other biometric information, ANSI/NIST-ITL 1-2011; 2011. (http://fingerprint.nist.gov/standard)

12 G. Langenburg, C. Champod; The GYRO system – A recommended approach to more transparent documentation; J. Forensic Identification, 61:4 (2011) 373-384.

13 A. Laird, K. Lindgren; Analysis of fingerprints using a color-coding protocol; J. Forensic Identification, 61:2 (2011) 147-154.

14 R.C. Gonzalez, R.E. Woods; Digital Image Processing, 3rd edition, Prentice Hall, 2007.

15 NIST Special Database 27: Fingerprint Minutiae from Latent and Matching Ten-print Images. (http://www.nist.gov/ts/msd/srd/nistsd27.cfm)