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| Document Title: | Applied Research, Development, and Method Validation of Toolmark Imaging, Virtual Casing Comparison, and In-Lab Verification using a GelSight-Based Three Dimensional Imaging and Analysis System for Firearm Forensics |
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# 1 Project Purpose and Background

Over 80 years the field of toolmark examination has advanced to incorporate traditional comparison light microscopy, digital image 2D microscopy, and now 3D surface topography measurements. In January 2013, we began development of a 3D surface topography imaging and analysis system for firearm forensics based on the GelSight scanning technology and custom feature-based image comparison algorithms. The technology is capable of measuring a true 3D surface topography at micron-scale and matching these scans to indicate likelihood of common origin. Since 2013 we've developed the GelSight scanning technology to acquire and compare breech-face impressions and aperture shears, established a 01 confidence match function, completed numerous deployments with city, state, and federal crime labs, established best scanning practices, studied inter-operator scanning variability, adopted and promoted a cross-modality data format (X3P), and established proof-of-concept scan comparison across different scanning modalities (*e.g.*, GelSight vs Confocal). The research work described in this report took place in 2016. The work represents several critical next research steps towards developing a 3D surface topography analysis system tailored to the needs of the forensic community.

The research work was completed by Cadre Research Labs, a scientific computing contract research organization, working in collaboration with GelSight Inc, a company formed by the MIT researchers who developed the GelSight surface topography imaging technology. The two companies collaborate closely with Todd Weller, a firearms examiner previously of the Oakland Police Department. We continue to collaborate with colleagues at NIST, 2 Federal Crime Labs (including Mike Neel at the Atlanta ATF), Andy Smith (San Francisco PD), Nancy McCombs (DoJ Fresno Crime Lab), and Andrew Carriveau (Michigan State Police).

# 2 Project Design

The one year project had three aims. In Aim 1 we developed the ability to scan and compare Firing Pin Impressions (FPIs) which complements the scanner's ability to analyze breech-face impressions and aperture shears. Although firing pin impressions are less frequently used for casing comparisons, there are some situations in which firearms examiners find them extremely useful. In some cases, FPI similarity may allow an identification or elimination when it would otherwise be inconclusive. Beyond its use in database search and visualization, Cadre's technology can also be useful in verification and analysis (Aim 2). We investigated the use of our imaging and analysis technology in a live lab environment. Finally, we investigated Virtual Microscopy (VM), the use of measured 3D surface topographies as a substitute for physical casings (Aim 3). The ability to examine virtual casings allows easy inter-lab collaboration and consultation without requesting that the physical evidence be transferred. Virtual microscopy allows documentation of examiner annotations and eliminates set-to-set variability in proficiency testing. All 3 proposed aims were successfully completed during the project period.

# 3 Materials and Methods

Each of the three aims represent independent work and are discussed separately. Methods have been abbreviated to conform to the maximum page limit.

**Base Scanner**: The scan acquisition system [4] uses advanced three-dimensional imaging algorithms (*e.g.*, shape from shading and photometric stereo) and the retrographic sensor of Johnson and Adelson [2, 3] to measure an object's three dimensional surface topography. In contrast to confocal microscopy and focus-variation microscopy, the use of a painted elastomeric gel removes the influence of surface reflectivity on the measured topography. The scanner contains a linear xy-stage that allows fine positioning control. The setup contains an 18-megapixel digital camera with a 65mm macro lens (Fig 1E). A small-pistol primer (*e.g.*, 9mm) (breech-face impression, aperture shear, and firing pin impression) can be measured using a single frame (*i.e.*, without stitching multiple images) at approximately 1.4$\mu m$/pixel lateral resolution with submicron depth resolution. A custom designed casing holder secures the casing using its strong extractor groove (in a manner similar to a kinetic puller) (Fig 1D). GelSight utilizes a planar array of lights embedded around a central glass lightplate. The lightplate is held level with redesigned bilaterial supports (Fig 1B). A new lift stage mechanism was designed with an integrated force sensor (Fig 1C). The lift stage raises the casing holder into the gel and stops when a specific back-pressure is achieved. The ability to measure gel force allows consistent gel application and fine tuning of force when collecting firing pin impression scans. Development of this new lift mechanism and force sensor required both electrical and mechanical redesigns.

**(Aim 1) Firing Pin Impression Scanning**: Firing Pin Impression (FPI) scanning requires both hardware and software changes. Several techniques were investigated. These included variations to scan acquisition (*e.g.*, depth from focus), gel material, and scanner design. The most successful approach includes a reformulation of the scanning gel and a new lightplate design which includes several out-of-plane (dome) lights (Fig 1A). The new gel is a hybrid gel that consists of a base substrate of standard firmness with a soft top layer (Fig 2A). The soft layer can more easily conform to the surface of the casing including the reaching of the bottom of the FPI. The dome lights are raised from the surface of the lightplate glass (Fig 2B). Their height allows them to better cast light into the depth of the FPI and minimizes shadow effects. Finally, FPI scanning requires more pressure to be applied between the casing and the gel than when scanning the breech-face impression (appx. 3x more force). It was necessary to design a mechanism both for applying and measuring that force. A new force sensor was built under the casing holder and a motorized lift mechanism was designed to raise the holder into the gel. To support this increased force, bilateral side supports were designed to secure both sides of the lightplate. The prior design where the lightplate was only supported on one side was not compatible with the increased force required. Taken together, these changes to the gel, lightplate lights, casing mount, lightplate supports, and software enable firing pin impression imaging.

**(Aim 1) Firing Pin Impression Data Processing**: The FPI is inherently a concave structure; however, the curved baseline depth of the impression is not considered relevant for comparison. The informative details are the toolmarks that lie on the curve. Even when imaged in 3D it can be very difficult to visualize the bottom of the FPI because it is physically impossible to position a light at a low enough angle to produce grazing light (the light would have to be lower than the plane of the breech-face impression (Fig 3A)). We developed a method to remove the FPI baseline thereby allowing a low-angle virtual light to cast grazing illumination (Fig 3B). Several methods were evaluated. Tried but not selected were (a) fitting a single paraboloid to the FPI shape and (b) LOWESS regression to fit a local baseline[1]. The paraboloid method left baseline artifacts in the flattened FPI. The LOWESS regression resulted in the removal of the baseline but was prohibitively slow. The best approach was a third method using a Fourier-based high-pass filter. The filter was applied to the firing pin impression. Several high-pass thresholds were considered (Fig 4). A cutoff of 850 microns was selected based on visual inspection and matching accuracy (see Results section below). The baseline corrected FPI maintains the informative microscopic toolmarks useful for comparison. We then developed a comparison algorithm capable of scoring the geometric similarity between two baseline corrected FPIs. Several approaches were considered including looking for explicit edges, rings, and ring defects; however, the best comparison algorithm is one built off our feature-based breech-face impression comparison algorithm. The method searches for informative geometric features by identifying patches of the measured surface topography with non-zero gradients (slopes) in both x and y.

**(Aim 1) Firing Pin Impression Dataset**: Most casings encountered in forensic practice do not have well-marked firing pin impression individual marks. FPI analysis is therefore only useful for select casings. In collaboration with Todd Weller we identified twelve 9mm firearms with well-marked FPIs and collected 36 test fires (3 per firearm). These casings constitute our core test set and were used during algorithm development and testing. These FPIs have a range of toolmark types (granular, concentric rings, and asymmetric defects). Baseline corrected versions of these casings are shown in Fig 5.

**(Aim 2) Validation Workstation Deployment and Data Collection**: A version two scanner (including the dome lights, force sensor, and bilateral lightplate supports) was deployed to Michael Neel in the Atlanta ATF office. During setup, Dr. Lilien gave a technology and training presentation to approximately ten individuals in the firearms and related groups. Dr. Lilien led a hands-on training session with the firearms group. Each participant collected a scan of a quality control casing and received instruction in the use of the software. Input was also solicited from another crime lab which has a version two scanner.

**(Aim 3) Virtual Microscopy Software Development**: We created an extended version of our X3P viewer software to allow virtual microscopy of cartridge casings. This Virtual Microscopy Viewer (VMV) software provides an easy interface for side-by-side comparison of casings. First, the user selects a folder of casing scans for batch loading (Fig 6A). By clicking on the different scan names the user can pull up any pair of casings for comparison (Fig 6B). Next, the user interacts with the visualizations using the same functionality as our other viewer software. The user can adjust virtual light position, rotate and translate the casings, and save high resolution images of the current view. The software provides locked and unlocked viewing modes. A toggleable enhanced contrast mode was added to bring out additional surface detail. Finally, users can paint casing surfaces with a color annotation to indicate regions of geometric similarity and dissimilarity (Fig 6C). These color annotations can be saved and loaded for review.

**(Aim 3) Virtual Microscopy AFTE Workshop**: We ran a Virtual Microscopy workshop at the May 2016 national AFTE meeting. See details below.

**(Aim 3) Virtual Microscopy Test Set Creation**: Three proficiency-style test sets were created in collaboration with Todd Weller and Richie Hockensmith (Collaborative Testing Services). One of the tests utilized 38 special caliber casings and two tests utilized 9mm casings. All casings were scanned using our hardware and the scans were preloaded onto participating computers.

**(Aim 3) Virtual Microscopy Examiner Study**: We conducted a study to evaluate the feasibility of using virtual microscopy for cartridge casing examination. We created a training tutorial containing figures and step-by-step instructions on how to use each function of the VMV software. Each participant (both in the AFTE workshop and the VM study) worked through the training tutorial prior to participating in the proficiency-style tests. We solicited volunteer participation from all US crime labs via announcements at conference presentations and the online AFTE forums. Fifteen labs received approval to participate. The study had 56 participants (46 trained examiners and 10 trainees). Three labs wished to keep their participation anonymous, the other 12 labs are listed in Table 1. Note that the listing of these labs does not imply endorsement. We are grateful to all participants and participating labs. To eliminate the computer and display as a variable, three identical laptops were sent around to the different labs[1]. Each computer was loaded with the study data, each lab had a unique login, and each individual had a unique participant code. Participants recorded their findings on an electronic worksheet and saved their annotations to disk. A script was created to allow each lab's point of contact to package their results and upload them to our server. Conclusions were reported using the AFTE range of conclusions (Fig 7).

# 4 Results and Analysis

**(Aim 1) Firing Pin Impression Imaging**: The firing pin impression test set was scanned using soft-top gel, dome lighting, and the new lightplate assembly with integrated force sensor. FPI topographies were cropped and baseline corrected using a high-pass threshold of 850 microns. The baseline corrected scans (one casing from each firearm) are shown in Figure 5.

**(Aim 1) Firing Pin Impression Analysis**: The baseline corrected scans were compared using a variant of the feature-based comparison algorithm originally developed for the breech-face impression. The results of an all-vs-all comparison using only the FPIs is shown in Table 2. Despite this test being a small closed-world study, the matching results are promising. The top-ranked result was correct for all 36 casings. The KM and KNM distributions are as expected with the majority of KM scoring higher than the KNM with an overlapping region for less identifiable casings. At a score threshold of 80, there are 27 of 36 (75%) KM with score >80 and 0 of 1188 (0%) KNM with score >80. Algorithm generated heatmaps and alignments are shown in Fig 8.

Before algorithmic analysis was performed, Mr. Weller visually compared the baseline corrected FPI scans. He rated each firearm on a scale 0-4 relating to an examiner's ability to make an identification (0: insufficient for comparison, 4: well marked for ID). Firearms identified by Mr. Weller as more weakly marked tended to be more difficult for the algorithm (see Table 2 caption for detail).

Although the FPI analysis was conducted on a small set, the results are promising. They demonstrate that similar to other toolmark comparisons, it's unlikely to observe KNM with high similarity (0/1188)

[1]Two labs used their own hardware. We verified that their computers met our display requirements. The performance of these labs was at least as good as the labs that used our laptops. There were no identification errors reported by these two labs.

while some (but not all) KM have recognizable characteristics. The FPI score would never be used alone. When combined with similarity scores for the breech-face impression and aperture shear, it could become a useful part of the overall comparison score. We are currently investigating this.

**(Aim 2) Validation Workstation Deployment and Analysis**: Several features were identified as being useful in support of incident analysis and blind verification. In this report, we use the term 'incident' to refer to a criminal case or lab case to avoid confusion between criminal case and cartridge case. The first new feature relates to our lightbox viewing mode. The lightbox is similar to the virtual microscopy viewer in that any two casings can be displayed side-by-side forming a virtual comparison microscope. Within our main software the two selected casings were automatically compared to each other, scored, and oriented per the best algorithm-based alignment. To remove unwanted influence from the algorithm it's important to hide this information from the user when the user is performing blind verification. We added an option to hide match scores and alignment in the lightbox. Second, when analyzing an incident it is useful to compare all the casings to each other. We found that the 'intra-incident' search was very useful. The intra-incident search compares all casings associated with an incident to each other. Third, we received positive feedback from our heatmap visualization mode where algorithm identified regions of geometric similarity are highlighted in blue (Fig 9 top). This helps an examiner understand the basis for the algorithm score. Finally, we added the ability to export report documents. That is, when viewing a casing or pair of casings the user can export a Word document with metadata (Fig 9 bottom) that can be read and edited in Microsoft Word and added to a lab's traditional information management system.

**(Aim 3) Virtual Microscopy Test Sets**: Three test sets were created for the AFTE workshop and Virtual Microscopy study. VM study sets were named CCTS1 and CCTS2 standing for Cadre-CTS. Screenshots of the casings involved in the VM study are shown in Figures 10-12. Some casings have strong, yet partial, aperture shears. Analysis of these shears required alignment of the casings under the center dividing line (Figure 13). The AFTE test set has no aperture shear and more subtle surface features. Therefore, successful analysis of the three test sets required proficiency with the VMV software and scan fidelity with respect to the measured surface topography.

**(Aim 3) Virtual Microscopy AFTE Workshop**: The workshop was attended at full capacity (25 attendees). The workshop included presentations by Ryan Lilien (Cadre), Erich Smith (FBI Firearms and Toolmark Unit), Todd Weller (Oakland Police Department), and Michael Stocker (NIST). In addition to presentation, we brought a number of laptop computers and split the attendees into groups of two or three. Each group worked through a training tutorial and then informally completed the AFTE virtual proficiency test. During the workshop, attendees also had access to a Leeds comparison scope. Participants were able to examine the same samples on the traditional microscope and the VM software. At the conclusion of the event participants completed an online feedback form. All received responses appear in the Supplementary Materials section below. Overall, feedback indicated that the workshop was well received. Participants found the software easy and intuitive to use. Participants liked the ability to position a virtual light as their favorite feature. While most participants found the software easy to use some participants had initial awkwardness manipulating the 3D scans. This is understandable given the limited time participants had with the software. It often takes time to gain fluency with the manipulation of 3D objects on a computer screen (just as it takes time to learn to operate a comparison scope).

**(Aim 3) Virtual Microscopy Examiner Study**: Fifteen sites and 56 participants took part in our study. Each participant completed two separate proficiency tests with each test being similar in structure to a standard CTS style test. The inclusion of both trained examiners and trainees allowed us to study the performance of both groups. To our knowledge this is the largest virtual microscopy study performed to date. The study was blind in that examiners did not know the true source of the casings. Each examiner completed study worksheets and saved their individual casing annotations. Examiners were asked to follow the AFTE range of conclusions (Fig. 7). Any conclusion of 'inconclusive' A, B, or C was counted as simply 'inconclusive' in the results table. We thought it unreasonable to ask every participant to annotate all 21 casing pairs for each test (7 casings results in 21 unique pairs). We therefore asked participants to annotate at least one identification and one elimination. This resulted in different participants annotating different pairs; however, most individuals annotated Item 1 and we were able to obtain a number of informative Annotation Image Maps (see below). In hindsight we would have explicitly specified four pairs of casings to annotate. We may also ask examiners to mark only those regions used in reaching their conclusion rather than any identified regions of similarity or difference.

We produced a series of color **Annotation Image Maps** to illustrate the regions of similarity and dissimilarity identified by the participants. 'Combined' maps show a density map of annotations for a single casing by combining the annotations from multiple individuals (*e.g.*, Fig 15). Regions of the surface that were not annotated by any examiner are uncolored; annotated regions appear in color. The colors range from blue to red and indicate the percent of annotations for the specified casing that had the area marked. For example, if 40 participants annotated casing X and if only 3 of the 40 participants marked a specific part of the casing surface than that area would be a dark blue. If 35 of the 40 participants had marked the region it would appear orange-red. The color bar is shown on the top of some of the image maps.

'Individual' maps show the parts of a single casing surface marked by a single participant (*e.g.*, Fig 17). All marked regions of an individual image map appear light blue. Participants could annotate the surface as being either 'similar' or 'different'; therefore, we have Similarity Maps and Difference Maps each of which contain only marks of the respective type. Note that scans are displayed in their canonical orientations for the annotation image maps; however, the scans were initially presented to participants in a random orientation (as scanned).

**CCTS Test Set 1**: 56 participants completed CCTS1 as part of the VM study. A single firearm (Taurus PT 24/7 9mm; PMC ammunition) was used to test fire the three casings of Item 1 and the individual test fires of Items 2-5. The results for all participants are shown in Fig 14. 100% of examiners and 100% of trainees made all correct identifications. Overall, no mistakes were made by trained examiners or trainees. Annotation Maps are shown in Figures 15-17. Fig 15 and Fig 16 (top) show that most individuals used the aperture shear to make the identification. Closeups of the surface areas marked appear in Fig 16 (bottom). Examination of each participant's annotations when comparing Items 1-1 and 2-1 (match) are shown in Fig 17. These images represent an expansion of the maps at the top of Fig 16. They show that 25 of 26 participants which annotated this pair of casings marked the aperture shear as being similar. Approximately half marked regions of the breech-face impression. Because we didn't ask participants to mark all regions of similarity it's unclear if examiners didn't recognize the similarity on the breech-face impression or if they only marked the aperture shear because the shear was sufficient for them to reach an identification conclusion. Wording changes to address this are proposed below.

**CCTS Test Set 2**: 56 participants completed CCTS2 as part of the VM study. A single firearm (Ruger P95DC 9mm; PMC ammunition) was used to test fire the three casings of Item 1 and the individual test fires of Items 3 and 5. A second different firearm (Ruger P85 MK II 9mm; PMC ammunition) was used to fire the casings of Items 2 and 4. The results for all participants are shown in Fig 18. 100% of examiners made all correct identifications. 0% of examiners made false identifications. 13% of examiners are not permitted to eliminate on individual characteristics (therefore their conclusions of inconclusive are valid). Overall, no mistakes were made by trained examiners. Among the trainees, one trainee made false identifications between Item 1 and 2 and Item 1 and 4. One trainee was not able to make an identification between Item 1 and 3 and listed the comparison as inconclusive (no annotation map was provided).

Annotation Maps are shown in Figures 19-22. Fig 19 shows that most individuals used aperture shear to make the identifications. Closeups of the surface areas marked appear in Fig 19 (bottom). Two regions of breech-face impression similarity were marked by most participants. Examination of each participant's annotations when comparing Items 1 and 3 (match) are shown in Fig 20. These images represent an expansion of the maps at the top of Fig 19. They show that 9 of 15 participants which annotated this pair of casings marked the aperture shear as being similar; 12 individuals marked the 10 o'clock breech-face impression marks as similar. Approximately half of the participants indicated breech-face impression similarity at 5 o'clock.

Items 1 and 2 are from different firearms. The annotation maps for these items are shown in Fig 21. The difference maps show that differences in aperture shear and a 10 o'clock breech-face impression patch were the most frequently marked. The 10 o'clock breech-face impression patch is the same region identified as being similar in identifications to Item 1 (Fig 19 top). Therefore, we can conclude that this patch was used to make correct identifications and eliminations when comparing to Item 1. While one examiner marked a small similar patch at 8 o'clock they still correctly marked the pair as an elimination.

The availability of the annotation maps allows us to examine the false identifications made by trainee L8K3R (Fig 22). Unfortunately, very little similarity is indicated in these maps and thus it is difficult to infer the reason that a false identification was made. A 'best' alignment between the aperture shears of Item 1 and 2 is shown in Fig 22 (right). The shears are quite different. The availability of the annotation maps would allow an instructor to discuss this comparison with the trainee to focus on the specific area.

Finally, although we did not ask for a comparison between Items 2 and 4, 43 of the participants compared Items 2 and 4 and all 43 (100%) correctly identified them to each other.

**CCTS Test Set AFTE**: The AFTE test set was not part of the formal study. It was used during the AFTE workshop. We received 11 completed data sheets. Of the 11, 100% made the correct identifications and eliminations with the exception of two labs that do not allow elimination on individual marks. These two labs marked the actual elimination as an inconclusive.

The goal of the VM study was to demonstrate proof-of-concept that VM could be used by examiners as a substitute for traditional comparison microscopy. The study successfully demonstrated that similarity in both striated and impressed marks could be identified. We demonstrated that the visualization tools were generally easy to learn and that the annotation mode provides valuable insights into the decision process. The studies also provided insight towards ways of improving VM. The only comment received regarding the visualization software related to the 'locked rotation' mode. A clearer locked vs unlocked toggle button was requested; this is an easy change that we will implement. We also learned that annotations should be requested for specific pairs of casings and we should ask that examiners mark *all regions* used in making their conclusion. Overall these are small tweaks to the VM workflow.

# 5 Scholarly Products Produced

The primary product of the proposed research is the presentation of our results and progress. At the May 2016 AFTE national meeting we gave a technical presentation entitled “Best Practices and Performance Measure for a 3D Imaging and Analysis System”. This presentation was well received; we received many great questions after the talk. At the same meeting we ran a virtual microscopy workshop titled “3D Virtual Microscopy of Cartridge Casings: Technology Intro and Hands-On”. Presentations were given by Weller, Smith, Stoker, and Lilien. During the hands-on session participants worked through a training tutorial and a virtual CTS test. Over the summer, Lilien gave a technical presentation and training session to examiners at the Atlanta ATF office. In October 2016 Lilien presented at the 2016 Eastern Regional AFTE Meeting (FBI Organized, Fredericksburg, VA). In December 2016 Lilien presented at the Centre of Forensic Sciences’s Firearms Symposium in Toronto, Ontario and at the York University Department of Computer Science in York, Ontario. We prepared a research paper titled “Establishing Best Practices and Performance Measures for a 3D Imaging and Analysis System” [5]. A paper describing the Virtual Microscopy studies listed above is in preparation and will be submitted to a peer-reviewed journal in Winter 2017 [6]. The above publications and presentations continue our tradition of disseminating our research results. Over the four years from 2013 through 2016 we presented at twelve forensic conferences and ran training sessions at eight local, state, and federal crime labs.

# 6 Summary

We successfully completed the proposed aims during the project period. We developed a protocol for scanning and analyzing firing pin impressions (Aim 1). We deployed the latest scanning system to crime labs to investigate the role of such a system in verification (Aim 2). We developed software for Virtual Microscopy, ran an AFTE workshop on Virtual Microscopy with several invited speakers, and we successfully recruited 15 labs and 56 individuals to participate in our VM examiner study (Aim 3). Through the year we continued collaboration with academic, industry, and government colleagues. We gave four presentations at academic conferences and workshops, a training session at a federal crime lab, and had a full-length research paper submitted for publication.

# Appendix

### Implications for Criminal Justice Policy and Practice

Our primary impact has been the development of a novel 3D imaging and analysis system with reduced cost and improved accuracy compared to existing solutions. Our work directly addresses several aims of the NIJ's Applied Research and Development in Forensic Science for Criminal Justice Purposes program.

Through direct collaboration, networking, talks, seminars, and publications we have made many forensic labs (local, state, and federal), practitioners, and policy makers within the criminal justice system aware of this work. We are developing measurement and analytic techniques, grounded in mathematical science that are able to provide accurate quantitative sample comparison and database search. We're expanding the types of toolmarks that can be analyzed by our scan acquisition hardware and tailoring analysis and report generation tools towards practitioner needs. We developed Virtual Microscopy software that supports the new open X3P file format for free exchange of surface topography data. We validated the use of this software in the largest VM study conducted to date. For most of the 56 participants this was their first exposure to 3D visualization tools and Virtual Microscopy.

This work benefits the criminal justice system and their ability to present firearm identification and toolmark evidence in the courtroom. Additional impact will be made as more crime labs become aware of the work and as we continue to disseminate results (*e.g.*, presenting the VM study results at the upcoming Denver AFTE meeting). In 2016, two team members, Lilien and Weller continued their involvement with the Firearms subcommittee of NIST's new OSAC initiative. Through their work on the OSAC, Weller and Lilien are creating guidelines and standards for emerging forensic technologies.

At least seven crime laboratories have had access to our technology. This would not have been possible prior to receiving recent NIJ awards. For labs that currently have 2D imaging systems, our 3D system provides a significant improvement in imaging and match accuracy. For labs that currently have alternative 3D imaging systems, we feel our system offers more flexibility and transparency with respect to how the scanner works, increased resolution, improved visualization, and interpretable match score.

# Figures and Tables

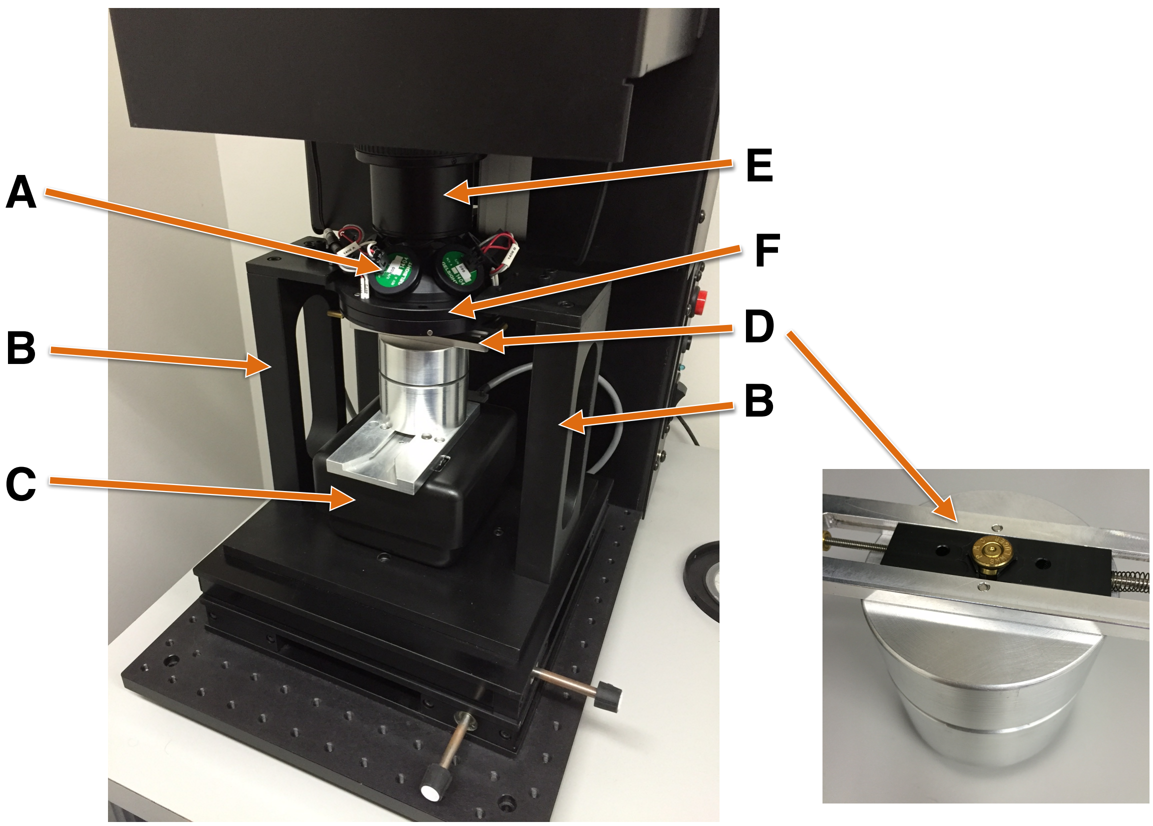



Figure 1: **Scanning System and Holder.** The updated 3D scanner. The new design includes dome lights (A), bilaterial lightplate supports (B), and a lift mechanism with integrated force sensor (C). The casing holder secures the casing using the extractor groove (D). The camera and lens descend from above (E). In-plane lightplate lights are embedded around the lightplate glass (F).

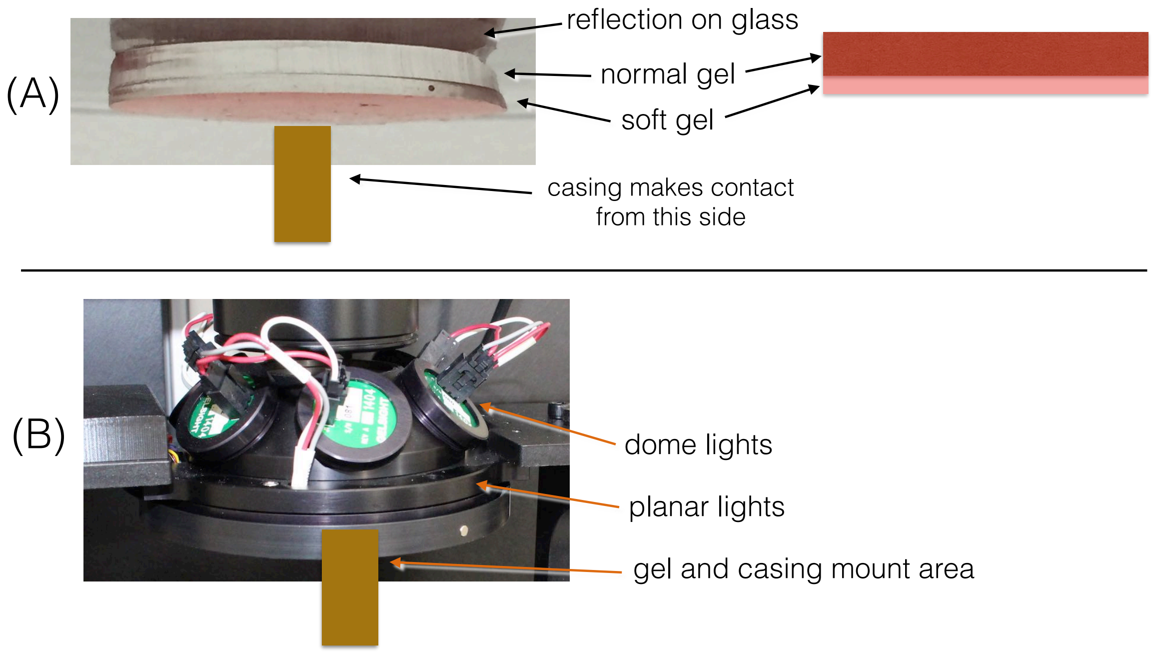
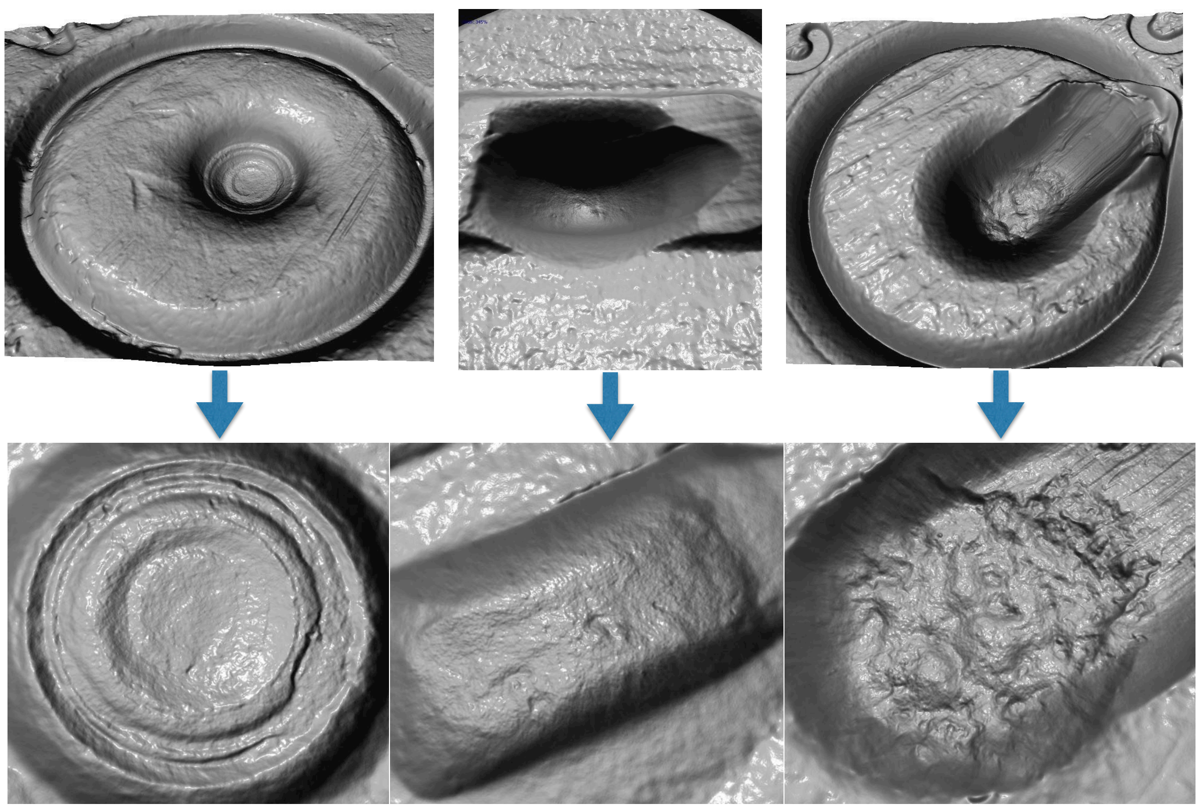



Figure 2: **Firing Pin Impression Scanning.** (A) Closeup and diagram of the soft-top gel. The softer gel layer makes contact with the casing and more easily conforms to the surface. The normal firmness base layer serves as a solid structural support for the gel piece. (B) Dome lights complement the planar lights. The raised position of the dome lights allows them to better illuminate the depth of the FPI while minimizing shadowing effects.

(A)



(B)

Figure 3: **Baseline Corrected Firing Pin Impression.** (A)(left) The natural depth of the firing pin impression means that to obtain grazing light, the light source would need to be positioned below the surface of the breech-face impression (inside the casing) as shown. This is impossible. (A)(right) Removing the FPI baseline changes the light-source position required for grazing light. (B) Three example firing pin impressions are shown. (top) The FPI as it appears in the natural scan, (bottom) the scan as it appears after baseline correction. (left) Hi-Point (center) Glock (right) Radom.

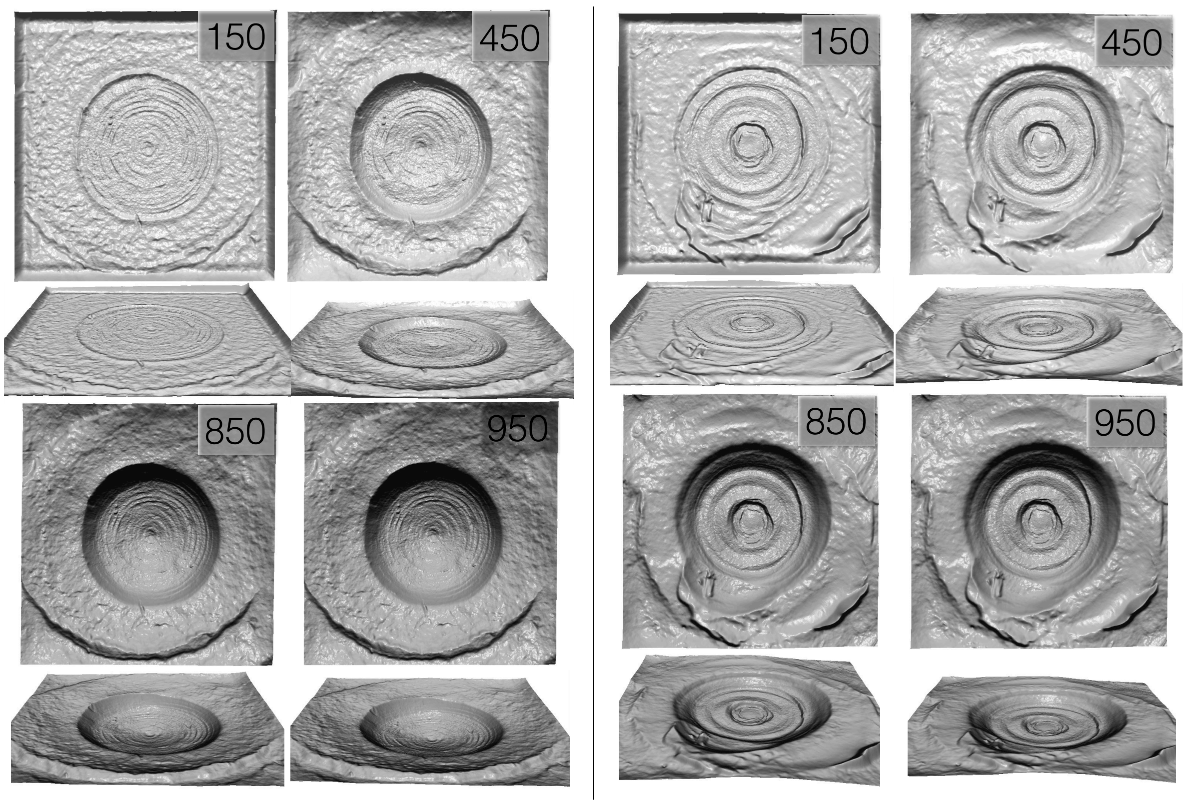



Figure 4: **Baseline Correction Thresholds.** The baseline correction procedure uses a high-pass threshold. Spatial frequencies below the threshold are attenuated resulting in the removal of the FPI baseline. Several threshold values were considered. Baseline corrected topographies for four threshold values (150, 450, 850, and 950 microns) are shown for firearms 303-87013 (left) and B94009 (right). Top-down and partial side views are shown. Smaller threshold values result in a flatter representation; while additional baseline is removed there's a risk that some informative surface features may be attenuated.

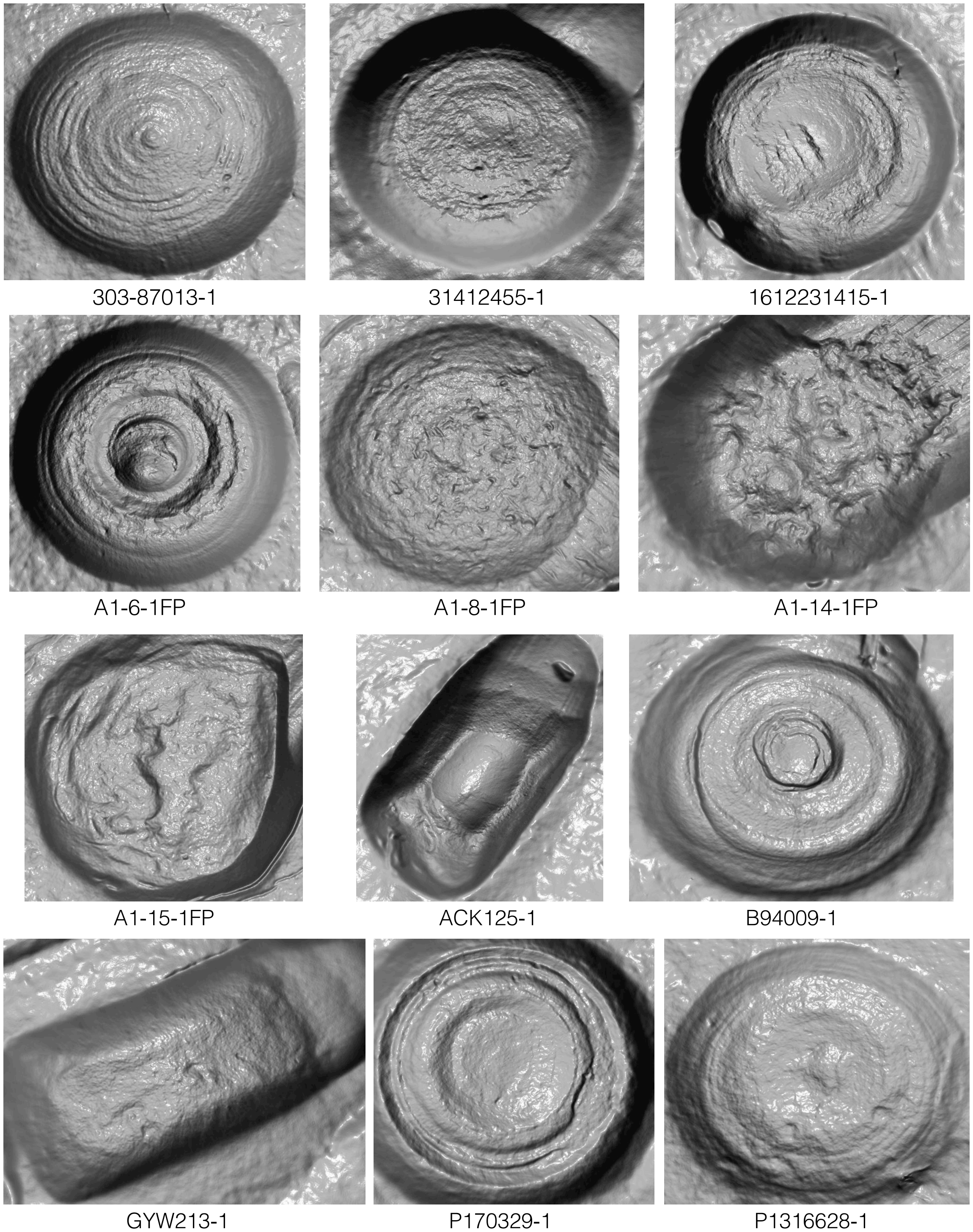



Figure 5: **Firing Pin Impression Firearm Set.** Representative casings from each of the 12 firearms used in the FPI study. Shown here are the baseline corrected FPIs. The FPIs have a range of toolmark types (granular, concentric rings, and asymmetric defects). Ammunition: Winchester (303-87013, 1612231415, P170329), PMC (31412455, A1-6, A1-8, A1-14, A1-15, GYW213), GFL (ACK125), RP (B94009, P1316628). Firearm makes are listed in Table 2.

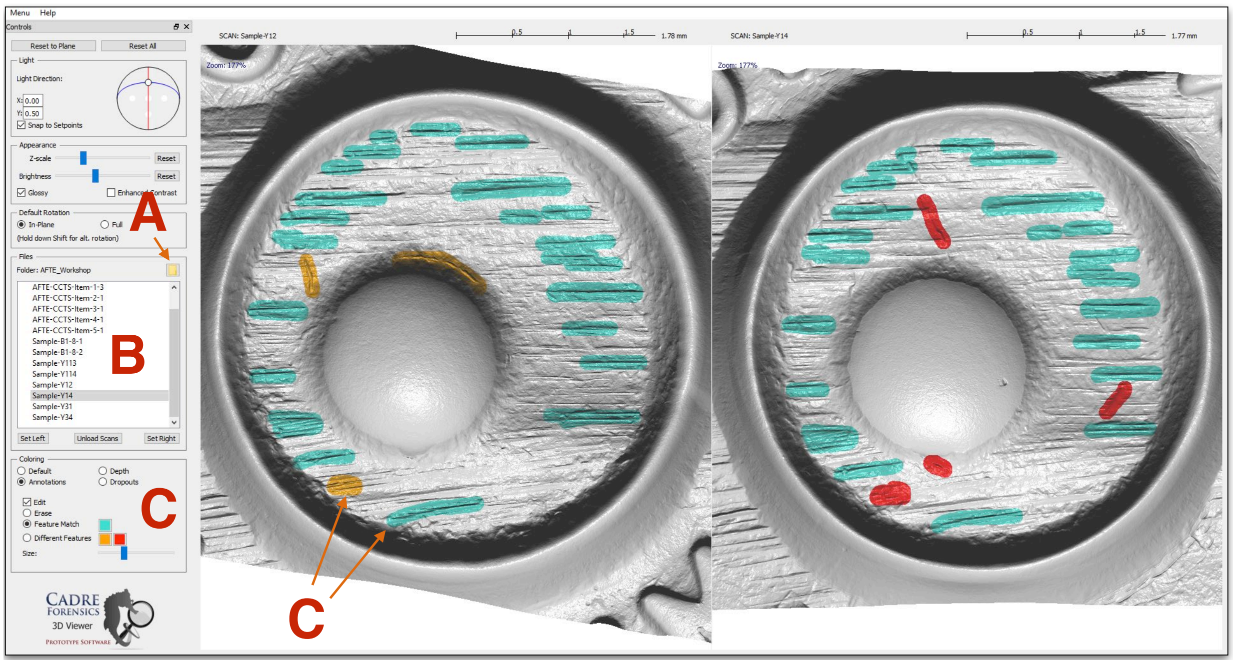



Figure 6: **Virtual Microscopy Viewer (VMV) Software.** The VMV software provides a virtual comparison scope. Examiners can adjust the virtual light position, manipulate the casing orientation, position, and zoom (locked or unlocked). In a typical workflow, the user first selects a folder of scans (A) then sends individual scans to the left or right view panel (B). Pairs of casings can be annotated (C) to indicate regions of similarity or difference. Annotations and high-resolution screenshots can be saved for use in presentations. A toggleable enhanced contrast mode was added to bring out additional surface detail.

| **Site Name** | **Location** |
|---|---|
| Dept of Forensic Science Virginia | Manassas, VA |
| Dept of Forensic Science Virginia | Norfolk, VA |
| Dept of Forensic Science Virginia | Richmond, VA |
| Dept of Forensic Science Virginia | Roanoke, VA |
| FBI Firearms and Toolmark Unit | Quantico, VA |
| Hamilton County Coroner's Office | Cincinnati, OH |
| Harris County Institute of Forensic Sciences | Houston, TX |
| Kansas Bureau of Investigation | Topeka, KS |
| Miami-Dade Police Department Crime Laboratory | Doral, FL |
| National Inst of Standards and Technology | Gaithersburg, MD |
| New Hampshire State Police Forensic Laboratory | Concord, NH |
| San Francisco Police Department Forensic Lab | San Francisco, CA |

Table 1: **Participating Labs.** Fifty six participants (46 trained examiners, 10 trainees) across fifteen sites participated in our Virtual Microscopy study. Three sites elected to remain anonymous and are not listed here. The listing of a lab does not constitute endorsement. We are grateful to all participants for their involvement.

The AFTE Range of Conclusions has been implemented as a reference for participants to report their findings. If the wording below differs from the normal wording of your conclusions, adapt these conclusions as best you can and use your preferred wording for question 2.

AFTE Range of Conclusions:

Identification
Agreement of a combination of individual characteristics and all discernible class characteristics where the extent of agreement exceeds that which can occur in the comparison of toolmarks made by different tools and is consistent with the agreement demonstrated by toolmarks known to have been produced by the same tool.

Inconclusive

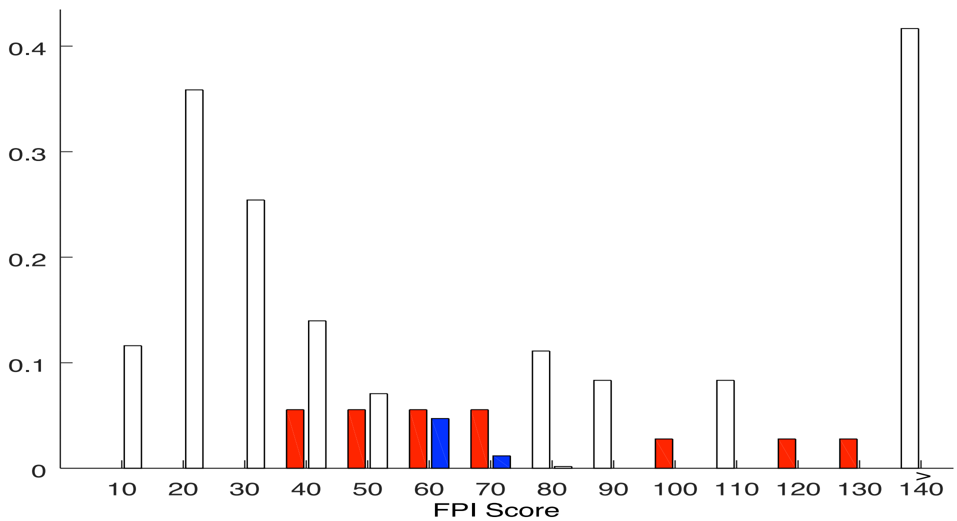
A. Some agreement of individual characteristics and all discernible class characteristics, but insufficient for an identification.

B. Agreement of all discernible class characteristics without agreement or disagreement of individual characteristics due to an absence, insufficiency, or lack of reproducibility.

C. Agreement of all discernible class characteristics and disagreement of individual characteristics, but insufficient for an elimination.

Elimination $
Significant disagreement of discernible class characteristics and/or individual characteristics. $

Figure 7: **AFTE Range of Conclusions.** The AFTE range of conclusions as they appear on the VM study worksheet. We interpret any inconclusive result (A, B, or C) as simply ‘inconclusive’.




| Firearm | KM Range | KNM Range | Top Correct | KM > 80 | KNM > 80 | Ex. Rating |
|---|---|---|---|---|---|---|
| 303-87013 | 168-208 | 12-74 | 3/3 | 3/3 | 0/99 | 3 |
| 31412455 | 81-96 | 9-65 | 3/3 | 3/3 | 0/99 | 2 |
| 1612231415 | 196-222 | 6-55 | 3/3 | 3/3 | 0/99 | 4 |
| A1-6 | 156-196 | 4-70 | 3/3 | 3/3 | 0/99 | 2 |
| A1-8 | 391-472 | 23-78 | 3/3 | 3/3 | 0/99 | 3 |
| A1-14 | 132-153 | 9-45 | 3/3 | 3/3 | 0/99 | 4 |
| A1-15 | 83-155 | 0-46 | 3/3 | 3/3 | 0/99 | 3 |
| ACK125 | 38-53 | 0-44 | 3/3 | 0/3 | 0/99 | 4 |
| B94009 | 73-109 | 7-62 | 3/3 | 2/3 | 0/99 | 1 |
| GYW213 | 57-80 | 9-61 | 3/3 | 1/3 | 0/99 | 2 |
| P170329 | 50-71 | 10-78 | 3/3 | 0/3 | 0/99 | 1 |
| P1316628 | 108-117 | 11-71 | 3/3 | 3/3 | 0/99 | 3 |
| | | Total: | 36/36 | 27/36 | 0/1188 | |

Table 2: **Firing Pin Impression Matching Results.** Match scores for the Known Matches (KM) and Known NonMatches (KNM) are shown for each of the twelve firearms in the test set. (top) Histogram of all scores, KM (red), KNM (blue). The top bin includes all scores above 140. Y-axis indicates fraction of pairs with respective scores. (bottom) Firearm by firearm analysis. Shown are the range of scores for the Known Matches, Known NonMatches, the number of times the top ranked casing is correct, the number of KM with score >80, the number of KNM with score >80 and the Examiner Rating. The Examiner Rating is an assessment by Todd Weller of the quality and quantity of toolmarks present as they relate to an examiner's ability to make an identification. The Examiner Rating is on a 5 point scale: 4: well marked for ID, 3: decently marked for ID, 2: some agreement of marks but insufficient for conclusive ID, 1: inconclusive (no agreement of marks), 0: sample insufficient for comparison. The ratings in this column were assigned by Mr. Weller before the algorithm analysis was performed. Based on the histogram, a score threshold of 80 was selected for this small study. The top ranking result is correct for all casings; however, for some casings that match has a score below 80. No KNM have a score above 80. The most difficult firearms for the algorithm to match are ACK125, B94009, GYW213, and P170329. Three of these firearms were rated 1 or 2 by Mr. Weller indicating that they may be more difficult to identify. (Ruger: 3142455,303-87013), (Hi-Point: P1316628,P170329), (FEG: B94009), (AA Arms: 161223145), (Glock: ACK125,GYW213), (FEG: 1-6), (Radom: 1-14,1-15), (FN: 1-8)

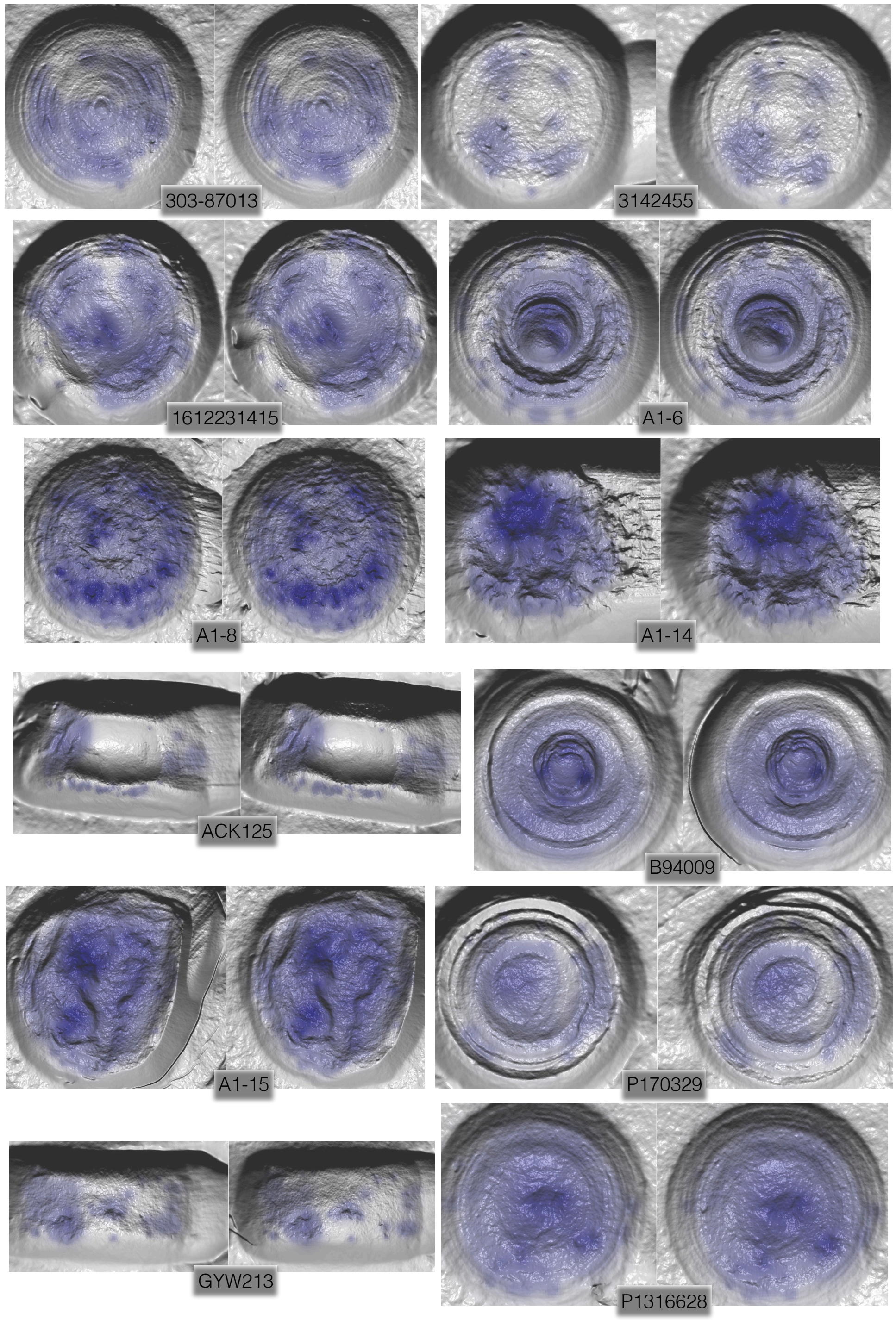
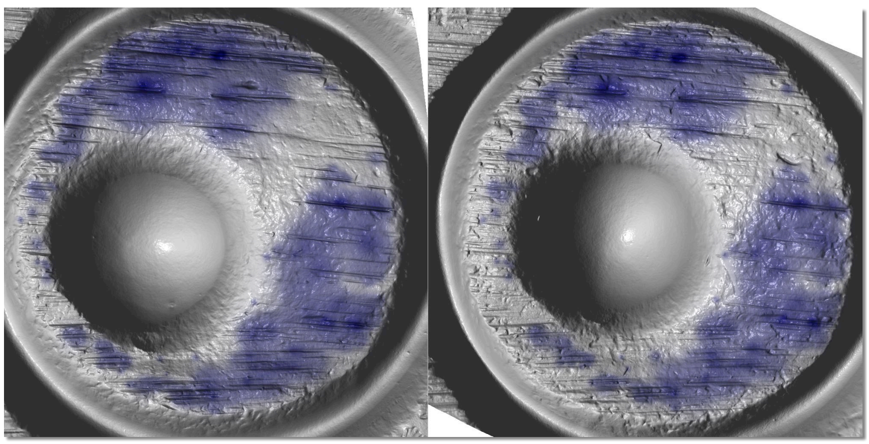
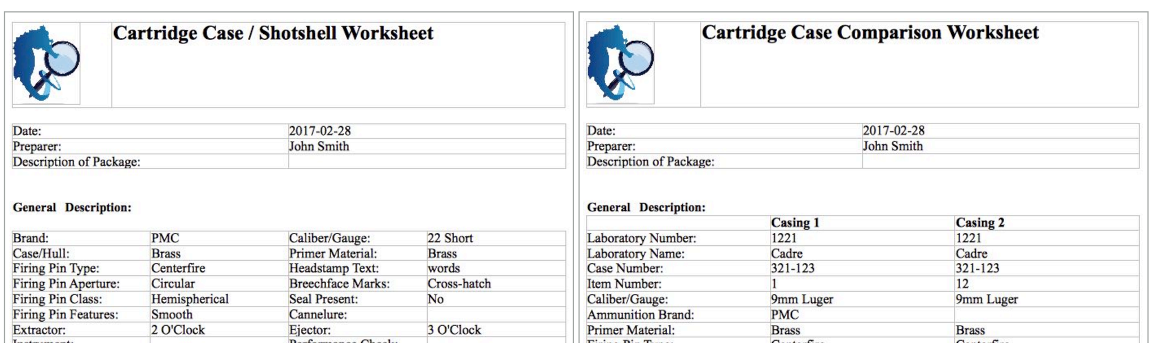



Figure 8: **FPI Matching Heatmaps.** KM for each firearms are shown as aligned by the matching algorithm. Surfaces appear with heatmap coloring to indicate the identified regions of geometric similarity. Areas shaded in darker blue indicate more local geometric similarity, non-blue parts of the surface do not possess algorithm identified similarity. Light shading over a large region indicates general agreement of contour.





**Cartridge Case / Shotshell Worksheet**

| | |
|---|---|
| Date: | 2017-02-28 |
| Preparer: | John Smith |
| Description of Package: | |

**General Description:**

| | | | |
|---|---|---|---|
| Brand: | PMC | Caliber/Gauge: | 22 Short |
| Case/Hull: | Brass | Primer Material: | Brass |
| Firing Pin Type: | Centerfire | Headstamp Text: | words |
| Firing Pin Aperture: | Circular | Breechface Marks: | Cross-hatch |
| Firing Pin Class: | Hemispherical | Seal Present: | No |
| Firing Pin Features: | Smooth | Cannelure: | |
| Extractor: | 2 O'Clock | Ejector: | 3 O'Clock |

**Cartridge Case Comparison Worksheet**

| | |
|---|---|
| Date: | 2017-02-28 |
| Preparer: | John Smith |
| Description of Package: | |

**General Description:**

| | Casing 1 | Casing 2 |
|---|---|---|
| Laboratory Number: | 1221 | 1221 |
| Laboratory Name: | Cadre | Cadre |
| Case Number: | 321-123 | 321-123 |
| Item Number: | 1 | 12 |
| Caliber/Gauge: | 9mm Luger | 9mm Luger |
| Ammunition Brand: | PMC | |
| Primer Material: | Brass | Brass |

Figure 9: **Analysis and Report Functionality.** (top) Our previously developed heatmap highlights regions of geometric similarity identified by the matching algorithm and was found to be useful to examiners in interpreting search results. (bottom) Sample report document for a single casing (left) and casing-to-casing comparison (right). These reports are generated by the software and can be read and edited in Word.

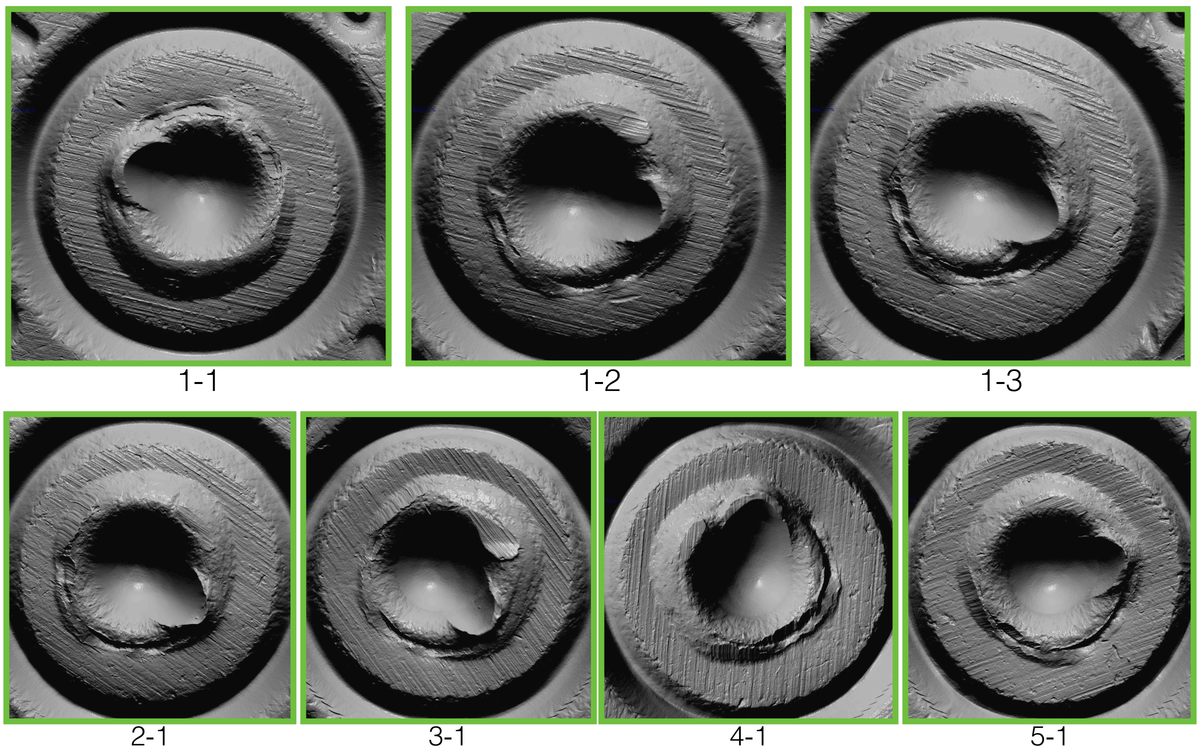



Figure 10: **Virtual Microscopy Casings: CCTS1.** Test set CCTS1. All casings are displayed oriented as scanned. All casings come from the same firearm (green border).

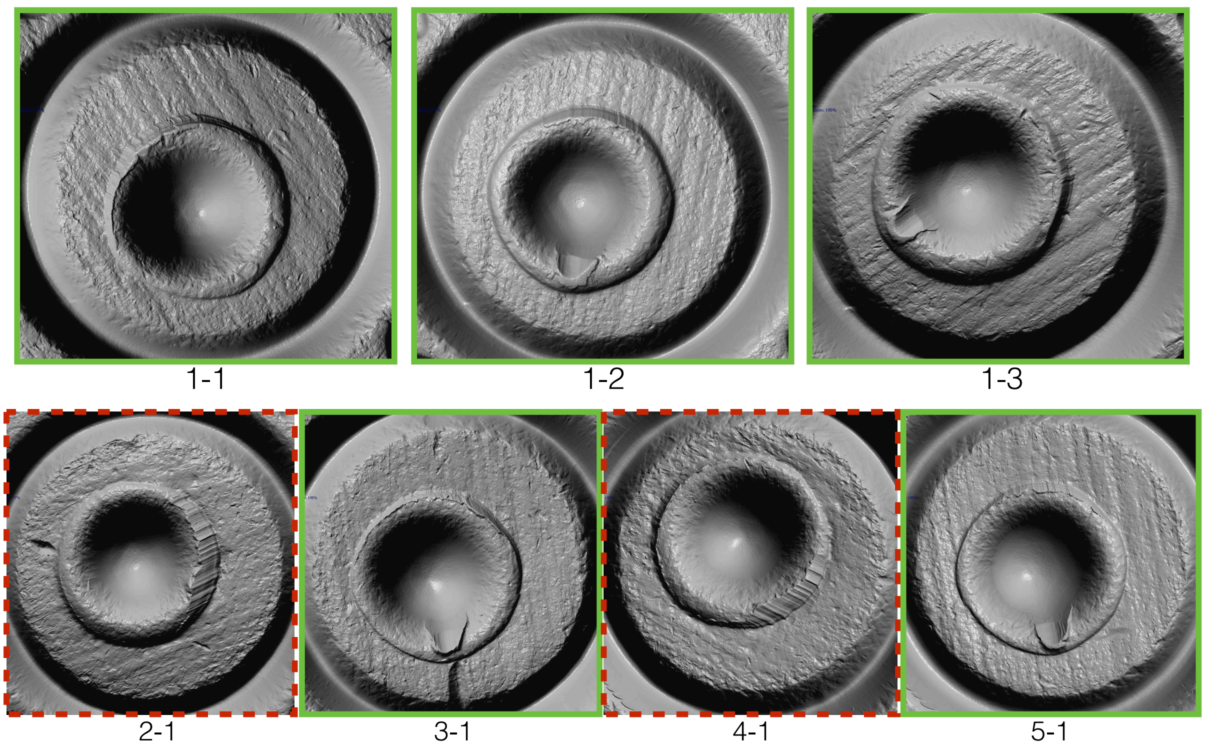



Figure 11: **Virtual Microscopy Casings: CCTS2.** Test set CCTS2. All casings are displayed oriented as scanned. Items 1-1, 1-2, 1-3, 3-1, and 5-1 are from the same firearm (green border). Items 2-1 and 4-1 are both from a second different firearm (red dashed border).

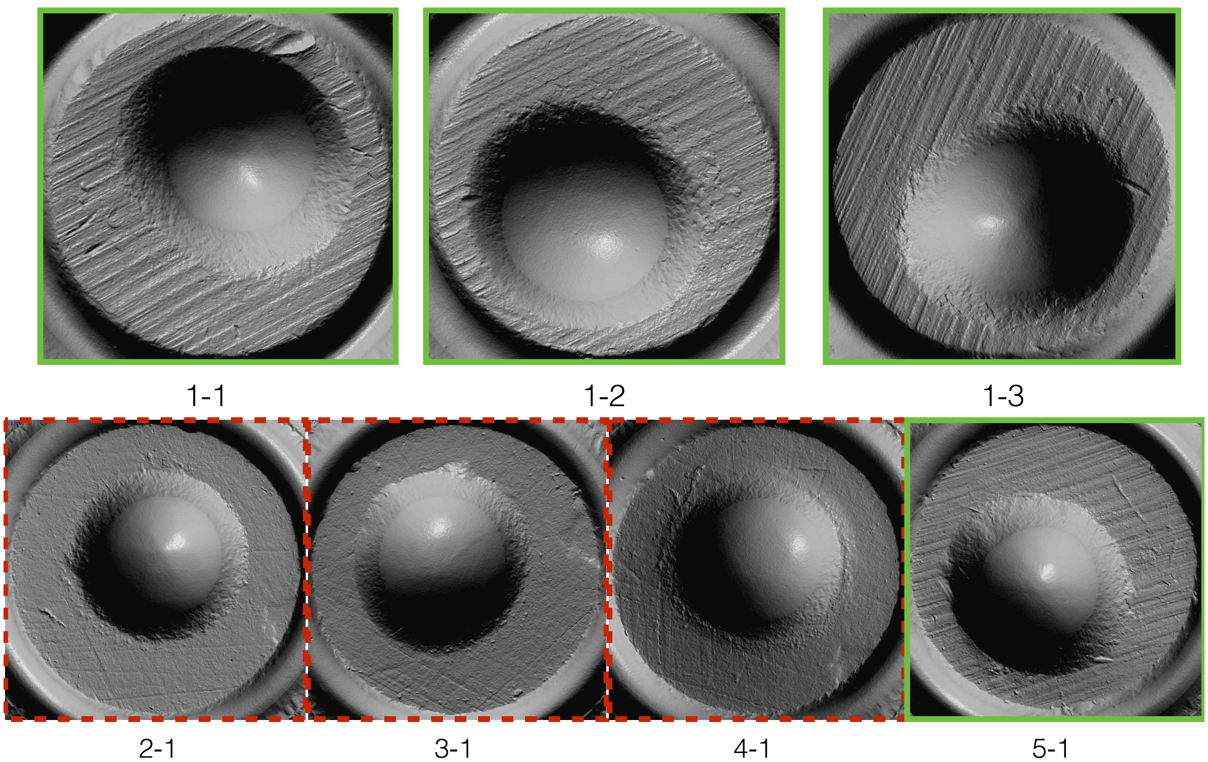
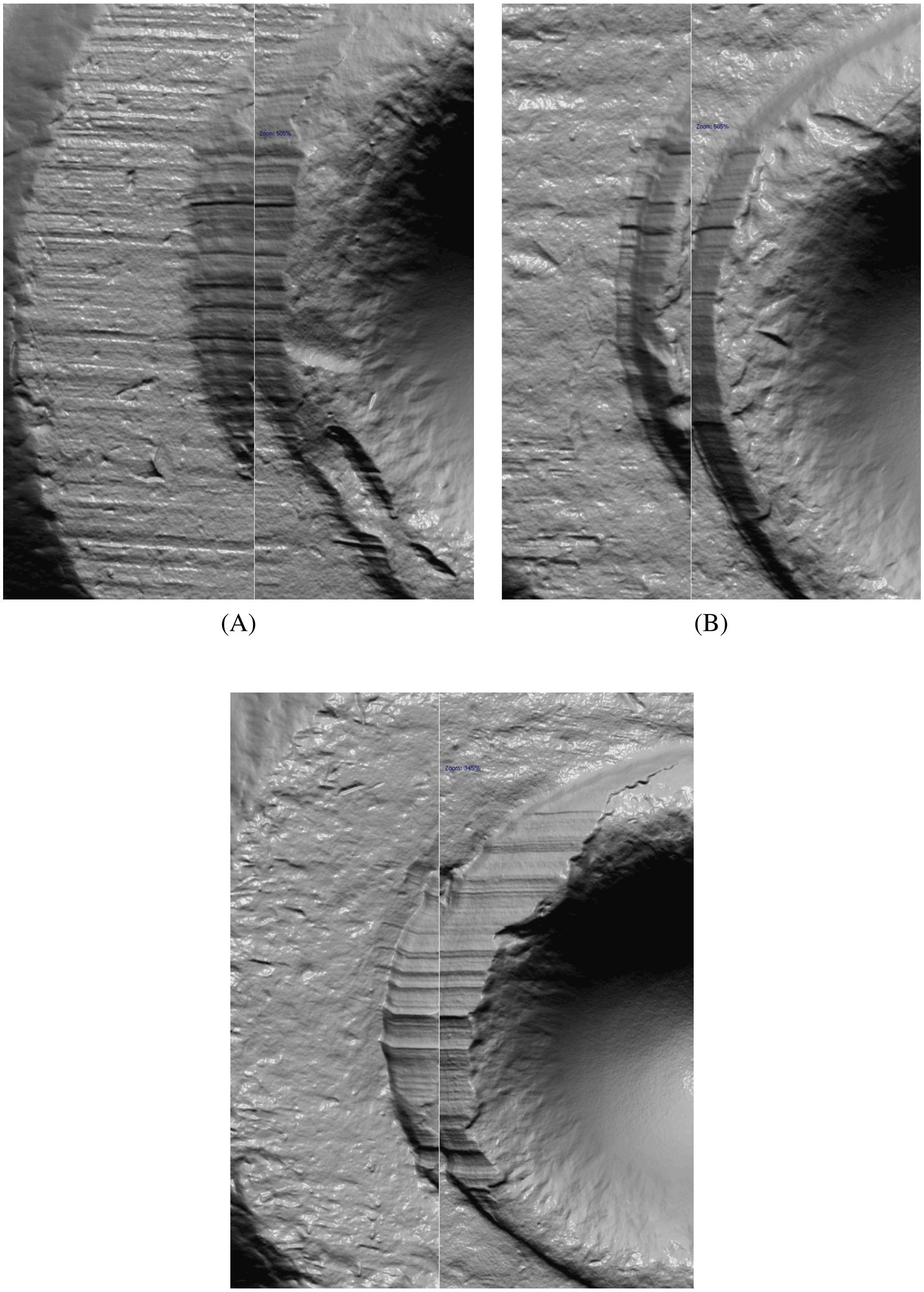



Figure 12: **Virtual Microscopy Casings: AFTE Set.** All casings are displayed oriented as scanned. Items 1-1, 1-2, 1-3, and 5-1 are from the same firearm (green border). Items 2-1, 3-1, and 4-1 are from a second different firearm (red dashed border). Note that these casings have no flow-back or aperture shear.



(A) (B)

(C)

Figure 13: **Virtual Microscopy Casing Shear.** A number of the casings in the Virtual Microscopy study have strong aperture shears. Each panel (A,B,C) shows a side-by-side split view of two casings. Virtual lighting was set to come from the 12 o'clock position to provide a glancing light source. (A) CCTS1 two casings of Item 1 (match), (B) CCTS2 two casings of Item 1 (match), (C) CCTS2 casings from Items 2 and 4 (match).

| PCode | Item 2 | Item 3 | Item 4 | Item 5 |
|---|---|---|---|---|
| 2A692 | Yes | Yes | Yes | Yes |
| 2NCV4 | Yes | Yes | Yes | Yes |
| 38JLN | Yes | Yes | Yes | Yes |
| 3R5RK | Yes | Yes | Yes | Yes |
| ● 4X99B | Yes | Yes | Yes | Yes |
| 5CY6N | Yes | Yes | Yes | Yes |
| ● 5RSCS | Yes | Yes | Yes | Yes |
| ● 6YNZV | Yes | Yes | Yes | Yes |
| 7LP7H | Yes | Yes | Yes | Yes |
| 7UVY4 | Yes | Yes | Yes | Yes |
| 7VKHK | Yes | Yes | Yes | Yes |
| 9AGVK | Yes | Yes | Yes | Yes |
| 9ZJHW | Yes | Yes | Yes | Yes |
| AGMWE | Yes | Yes | Yes | Yes |
| APJTM | Yes | Yes | Yes | Yes |
| BUTM9 | Yes | Yes | Yes | Yes |
| BWCFS | Yes | Yes | Yes | Yes |
| ● BZKDL | Yes | Yes | Yes | Yes |
| C7N89 | Yes | Yes | Yes | Yes |
| CLHT6 | Yes | Yes | Yes | Yes |
| D4RPD | Yes | Yes | Yes | Yes |
| DAB22 | Yes | Yes | Yes | Yes |
| DPC33 | Yes | Yes | Yes | Yes |
| DR53Q | Yes | Yes | Yes | Yes |
| E5C74 | Yes | Yes | Yes | Yes |
| F9FFQ | Yes | Yes | Yes | Yes |
| FZ9HM | Yes | Yes | Yes | Yes |
| HVQDZ | Yes | Yes | Yes | Yes |

| PCode | Item 2 | Item 3 | Item 4 | Item 5 |
|---|---|---|---|---|
| K4QFH | Yes | Yes | Yes | Yes |
| ● KLV8F | Yes | Yes | Yes | Yes |
| KVDEG | Yes | Yes | Yes | Yes |
| L27CR | Yes | Yes | Yes | Yes |
| ● L8K3R | Yes | Yes | Yes | Yes |
| ● M3S8F | Yes | Yes | Yes | Yes |
| N4VH2 | Yes | Yes | Yes | Yes |
| P3CK6 | Yes | Yes | Yes | Yes |
| QDG65 | Yes | Yes | Yes | Yes |
| QETKB | Yes | Yes | Yes | Yes |
| RCRE7 | Yes | Yes | Yes | Yes |
| REX7C | Yes | Yes | Yes | Yes |
| REXBV | Yes | Yes | Yes | Yes |
| RGMRM | Yes | Yes | Yes | Yes |
| SCSD8 | Yes | Yes | Yes | Yes |
| SFFDU | Yes | Yes | Yes | Yes |
| SPZES | Yes | Yes | Yes | Yes |
| TTJ8U | Yes | Yes | Yes | Yes |
| ● UA62Y | Yes | Yes | Yes | Yes |
| UCNA6 | Yes | Yes | Yes | Yes |
| UKWHL | Yes | Yes | Yes | Yes |
| UZJYL | Yes | Yes | Yes | Yes |
| ● VBU8D | Yes | Yes | Yes | Yes |
| ● VGQ3T | Yes | Yes | Yes | Yes |
| WA5FB | Yes | Yes | Yes | Yes |
| WPSC4 | Yes | Yes | Yes | Yes |
| XLV73 | Yes | Yes | Yes | Yes |
| XMR27 | Yes | Yes | Yes | Yes |

| EXAMINERS | Item 2 | Item 3 | Item 4 | Item 5 |
|---|---|---|---|---|
| Yes (ID) | 46 (100%) | 46 (100%) | 46 (100%) | 46 (100%) |
| No (Elim) | 0 (0%) | 0 (0%) | 0 (0%) | 0 (0%) |
| Inconclusive | 0 (0%) | 0 (0%) | 0 (0%) | 0 (0%) |

| TRAINEES | Item 2 | Item 3 | Item 4 | Item 5 |
|---|---|---|---|---|
| Yes (ID) | 10 (100%) | 10 (100%) | 10 (100%) | 10 (100%) |
| No (Elim) | 0 (0%) | 0 (0%) | 0 (0%) | 0 (0%) |
| Inconclusive | 0 (0%) | 0 (0%) | 0 (0%) | 0 (0%) |

| ALL | Item 2 | Item 3 | Item 4 | Item 5 |
|---|---|---|---|---|
| Yes (ID) | 56 (100%) | 56 (100%) | 56 (100%) | 56 (100%) |
| No (Elim) | 0 (0%) | 0 (0%) | 0 (0%) | 0 (0%) |
| Inconclusive | 0 (0%) | 0 (0%) | 0 (0%) | 0 (0%) |

Figure 14: **CCTS1 Results** (top) Individual responses (*"Were any of the questioned expended cartridge cases (Items 2-5) discharged from the same firearm as the known expended cartridge cases (Item 1)?"*). PCode: Participant Code. Purple dots indicate trainees. (bottom) Match statistics. 100% of examiners and 100% of trainees made all correct identifications **Overall, no mistakes were made by trained examiners or trainees**. See annotation details in Figures 15-17.

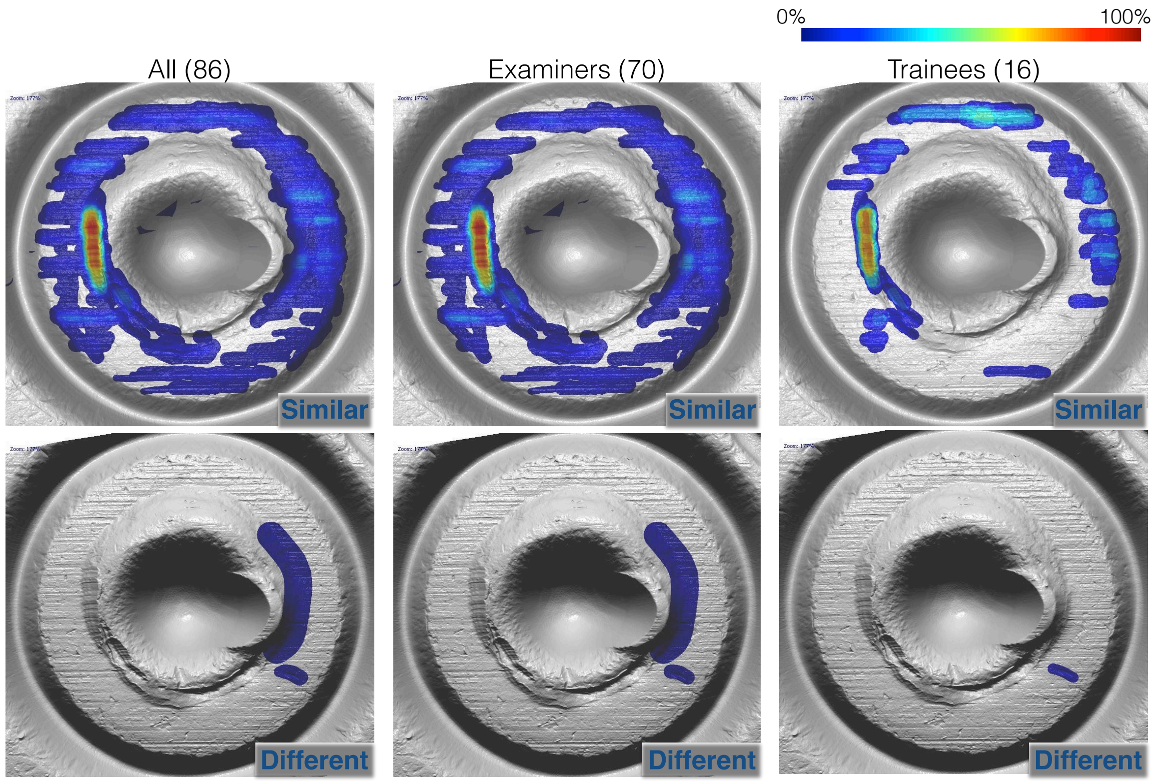
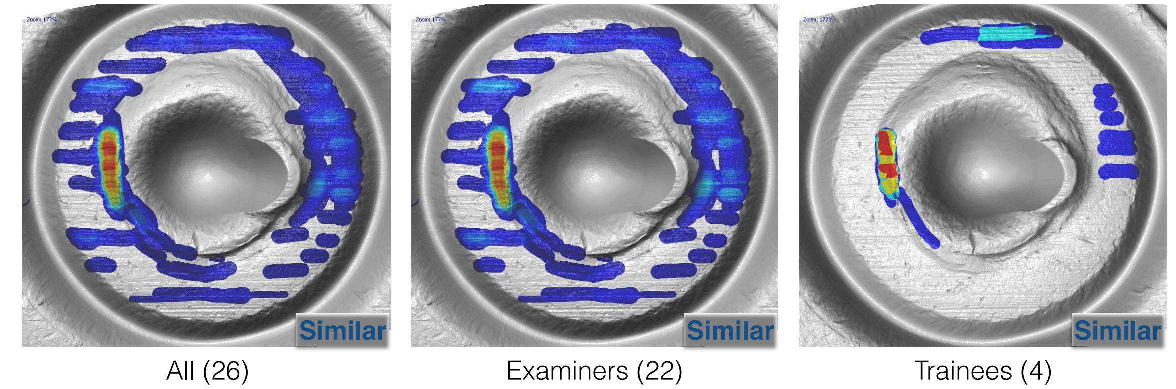



Figure 15: **Annotation Image Map (CCTS1: Item 1-1): Combined.** Casing Item 1-1 is shown in all six panels. Surface is colored by the percentage of participants annotating this item that marked the corresponding surface area. All comparisons involving Item 1-1 are combined into this view. (left column) all participants, (center column) trained examiners, (right column) trainees. Number in parentheses is the number of annotations from the specified participants. (top row) Similarity maps: regions marked as similar between Item 1-1 and Item X for all X, (bottom row) Difference maps: regions marked as dissimilar between Item 1-1 and Item X for all X. The image maps in this figure show the regions of the casing used in all comparisons. Note that the similarity image maps show that the aperture shear (red shaded region) was the most frequently used toolmark for identification.



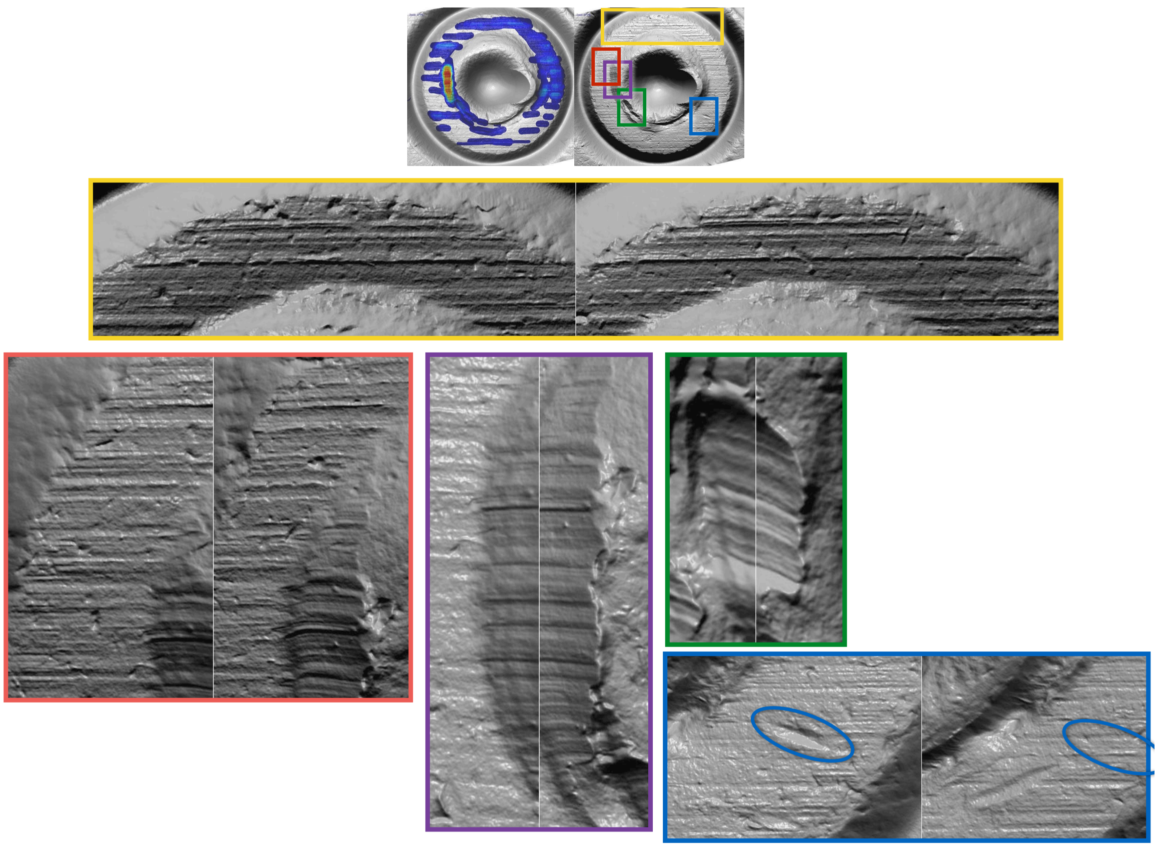



Figure 16: **Annotation Image Map (CCTS1: Item 1-1 as compared to Item 2-1) (Match):** (top) Combined similarity maps are shown for Casing Item 1-1 as compared to Item 2-1. (bottom) Closeups of the various regions annotated in the comparison. Colored boxes on the casing correspond to similarly colored zoom boxes. Most boxes indicate similarity, the blue box (bottom right) is a region marked as different. The main aperture shear appears in the purple box. A secondary shear (used by some examiners) appears in green. Patches of the breech-face impression used by some examiners are shown in the red and yellow boxes. Finally, a few examiners marked a region of breech-face impression difference as indicated in the blue box. This likely reflects surface damage on one casing (blue oval). See caption of Fig 15 for additional detail on these plots.

Figure 17: **Annotation Image Map (CCTS1: Item 1-1 as compared to Item 2-1):** Individual similarity maps for trained examiners (above line) and trainees (below line). Because only one participant is shown in each map a single color is used. The images on the top row of Fig 16 are the combination of the individual maps in this figure.

| PCode | Item 2 | Item 3 | Item 4 | Item 5 |
|---|---|---|---|---|
| 2A692 | No | Yes | No | Yes |
| 2NCV4 | No | Yes | No | Yes |
| 38JLN | No | Yes | No | Yes |
| 3R5RK | No | Yes | No | Yes |
| ● 4X99B | No | Yes | No | Yes |
| 5CY6N | Inc | Yes | Inc | Yes |
| ● 5RSCS | Inc | Yes | Inc | Yes |
| ● 6YNZV | Inc | Yes | Inc | Yes |
| 7LP7H | No | Yes | No | Yes |
| 7UVY4 | No | Yes | No | Yes |
| 7VKHK | Inc | Yes | Inc | Yes |
| 9AGVK | No | Yes | No | Yes |
| 9ZJHW | No | Yes | No | Yes |
| AGMWE | No | Yes | No | Yes |
| APJTM | No | Yes | No | Yes |
| BUTM9 | No | Yes | No | Yes |
| BWCFS | No | Yes | No | Yes |
| ● BZKDL | Inc | Yes | Inc | Yes |
| C7N89 | No | Yes | No | Yes |
| CLHT6 | No | Yes | No | Yes |
| D4RPD | Inc | Yes | Inc | Yes |
| DAB22 | No | Yes | No | Yes |
| DPC33 | No | Yes | No | Yes |
| DR53Q | No | Yes | No | Yes |
| E5C74 | No | Yes | No | Yes |
| F9FFQ | No | Yes | No | Yes |
| FZ9HM | Inc | Yes | Inc | Yes |
| HVQDZ | No | Yes | No | Yes |

| PCode | Item 2 | Item 3 | Item 4 | Item 5 |
|---|---|---|---|---|
| K4QFH | No | Yes | No | Yes |
| ● KLV8F | Inc | Yes | Inc | Yes |
| KVDEG | No | Yes | No | Yes |
| L27CR | Inc | Yes | Inc | Yes |
| ● L8K3R | Yes | Yes | Yes | Yes |
| ● M3S8F | Inc | Yes | Inc | Yes |
| N4VH2 | No | Yes | No | Yes |
| P3CK6 | No | Yes | No | Yes |
| QDG65 | No | Yes | No | Yes |
| QETKB | No | Yes | No | Yes |
| RCRE7 | No | Yes | No | Yes |
| REX7C | No | Yes | No | Yes |
| REXBV | No | Yes | No | Yes |
| RGMRM | No | Yes | No | Yes |
| SCSD8 | No | Yes | No | Yes |
| SFFDU | No | Yes | No | Yes |
| SPZES | No | Yes | No | Yes |
| TTJ8U | No | Yes | No | Yes |
| ● UA62Y | Inc | Yes | Inc | Yes |
| UCNA6 | No | Yes | No | Yes |
| UKWHL | No | Yes | No | Yes |
| UZJYL | No | Yes | No | Yes |
| ● VBU8D | No | Inc | Inc | Yes |
| ● VGQ3T | No | Yes | No | Yes |
| WA5FB | No | Yes | No | Yes |
| WPSC4 | No | Yes | No | Yes |
| XLV73 | Inc | Yes | Inc | Yes |
| XMR27 | No | Yes | No | Yes |

| EXAMINERS | Item 2 | Item 3 | Item 4 | Item 5 |
|---|---|---|---|---|
| Yes (ID) | 0 (0%) | 46 (100%) | 0 (0%) | 46 (100%) |
| No (Elim) | 40 (87%) | 0 (0%) | 40 (87%) | 0 (0%) |
| Inconclusive | 6 (13%) | 0 (0%) | 6 (13%) | 0 (0%) |

| TRAINEES | Item 2 | Item 3 | Item 4 | Item 5 |
|---|---|---|---|---|
| Yes (ID) | 1 (10%) | 9 (90%) | 1 (10%) | 10 (100%) |
| No (Elim) | 3 (30%) | 0 (0%) | 2 (20%) | 0 (0%) |
| Inconclusive | 6 (60%) | 1 (10%) | 7 (70%) | 0 (0%) |

| ALL | Item 2 | Item 3 | Item 4 | Item 5 |
|---|---|---|---|---|
| Yes (ID) | 1 (1.8%) | 55 (98%) | 1 (1.8%) | 56 (100%) |
| No (Elim) | 43 (77%) | 0 (0%) | 42 (75%) | 0 (0%) |
| Inconclusive | 12 (21%) | 1 (1.8%) | 13 (23%) | 0 (0%) |

Figure 18: **CCTS2 Results** (top) Individual responses ("*Were any of the questioned expended cartridge cases (Items 2-5) discharged from the same firearm as the known expended cartridge cases (Item 1)?*"). Purple dots indicate trainees. (bottom) Match statistics. 100% of examiners made all correct identifications. 0% of examiners made false identifications. 13% of examiners are not permitted to eliminate on individual characteristics (therefore their conclusions of inconclusive are perfectly acceptable). **Overall, no mistakes were made by trained examiners**. One trainee (L8K3R) made false identifications between Item 1 and 2 and Item 1 and 4. One trainee (VBU8D) was not able to make an identification between Item 1 and 3 and listed the comparison as inconclusive. **Overall, two mistakes (of forty conclusions) were made by trainees**. See annotation details in Figures 19-22.

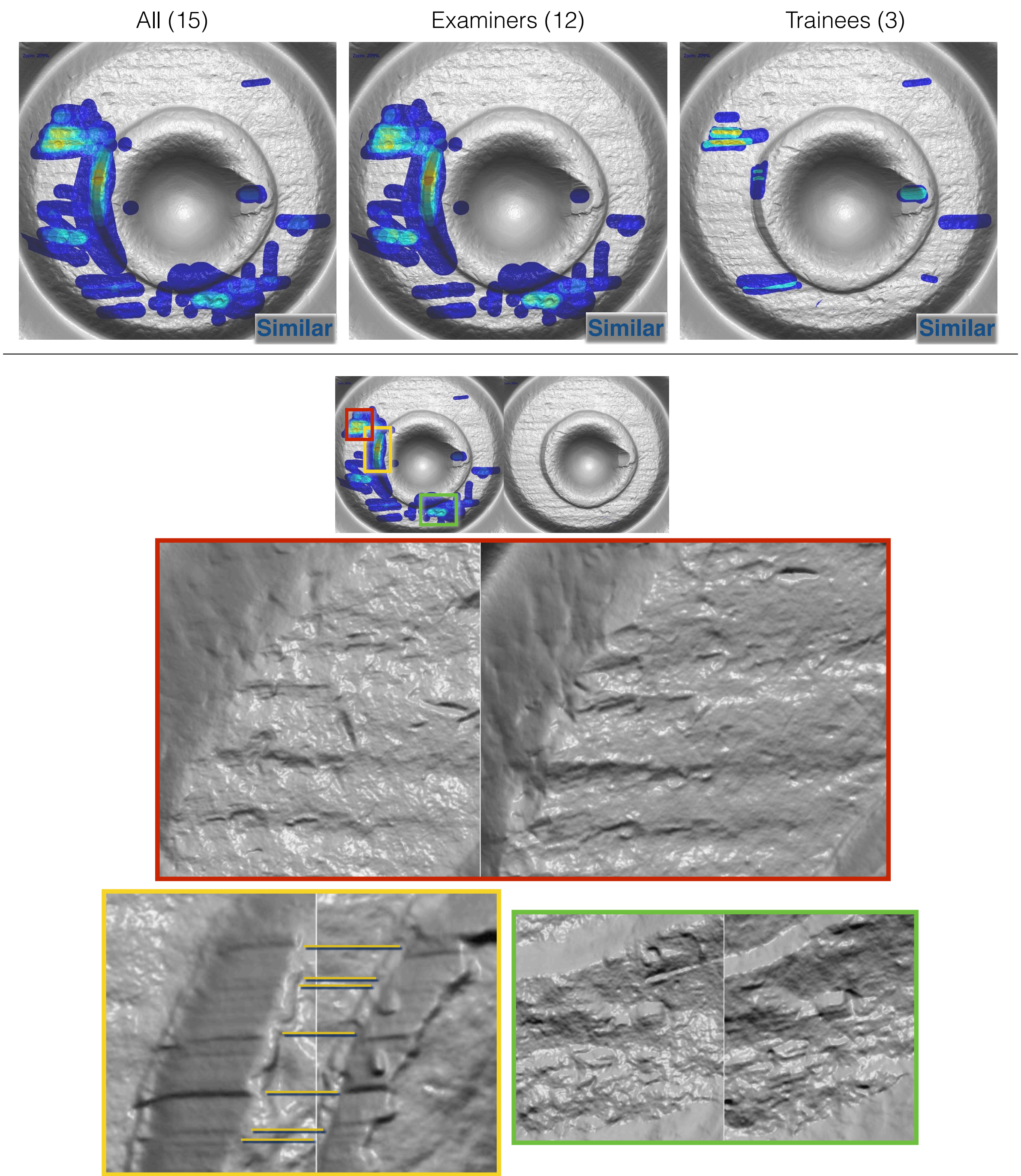



Figure 19: **Annotation Image Map (CCTS2: Item 1-2 as compared to item 3-1) (Match):** (top) Combined similarity maps are shown for Casing Item 1-2 as compared to Item 3-1. Items 1-2 and 3-1 were fired through the same firearm. Therefore we expect regions of similarity in the image map. No areas of dissimilarity were reported by any participant (not shown). (bottom) Closeups of the three most frequently marked regions of similarity. Colored boxes on the casing correspond to similarly colored zoom boxes.

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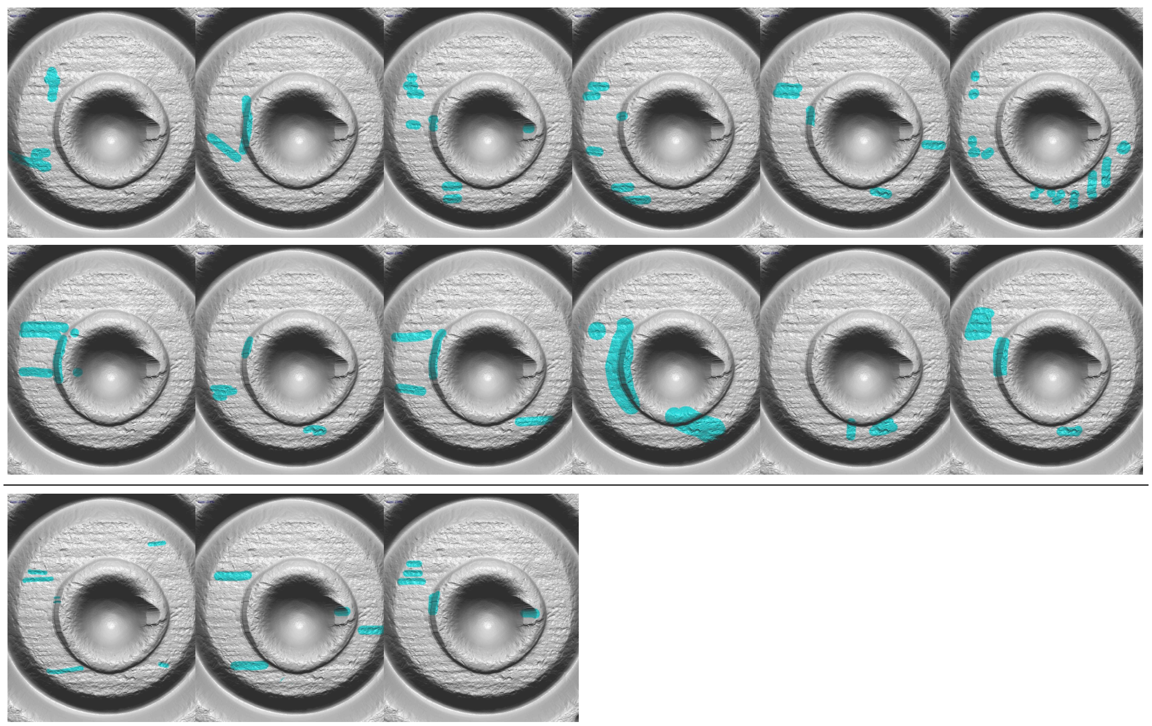

Figure 20: **Annotation Image Map (CCTS2: Item 1-2 as compared to Item 3-1):** (Match) Individual similarity maps for trained examiners (above line) and trainees (below line). Because only one participant is shown in each map a single color is used. The images on the top row of Fig 19 are the combination of the individual maps in this figure.

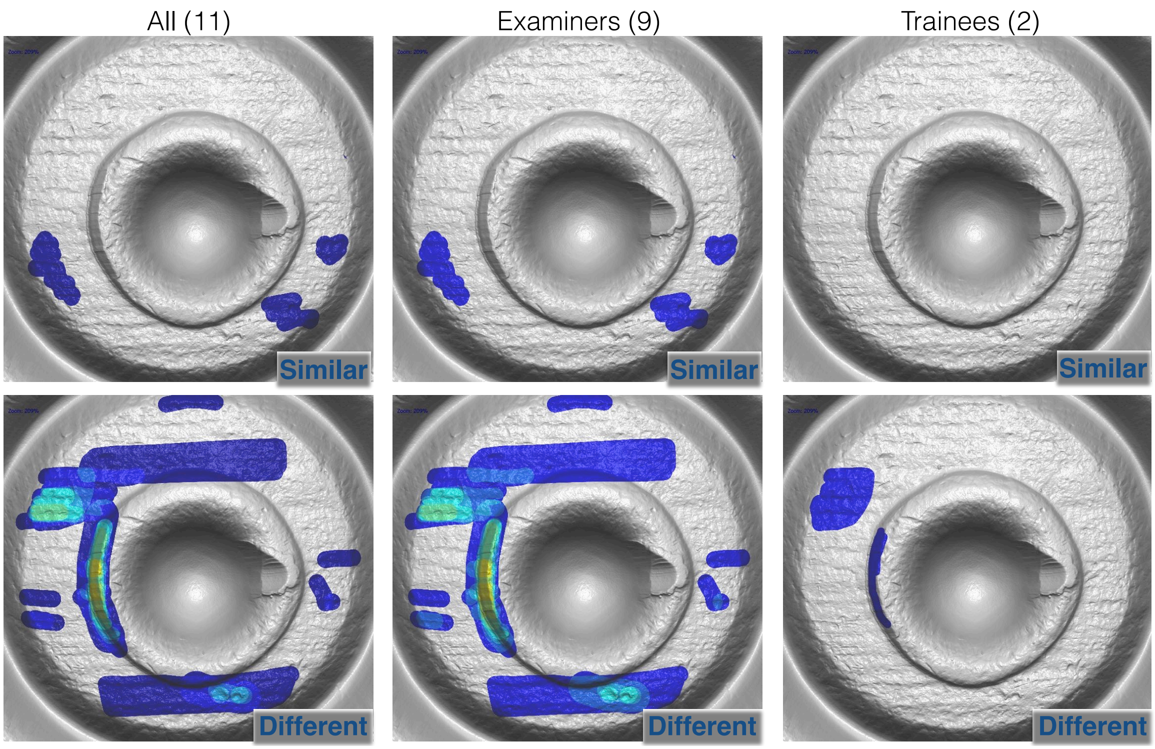


Figure 21: **Annotation Image Map (CCTS2: Item 1-2 as compared to item 2-1): Combined.** (NonMatch) Items 1-2 and 2-1 were fired through **different** firearms. Therefore we expect regions of difference in the image map. The maps show that the aperture shear was used to identify the differences between the two casings. One participant indicated some breech-face impression similarity (near 8 o'clock).

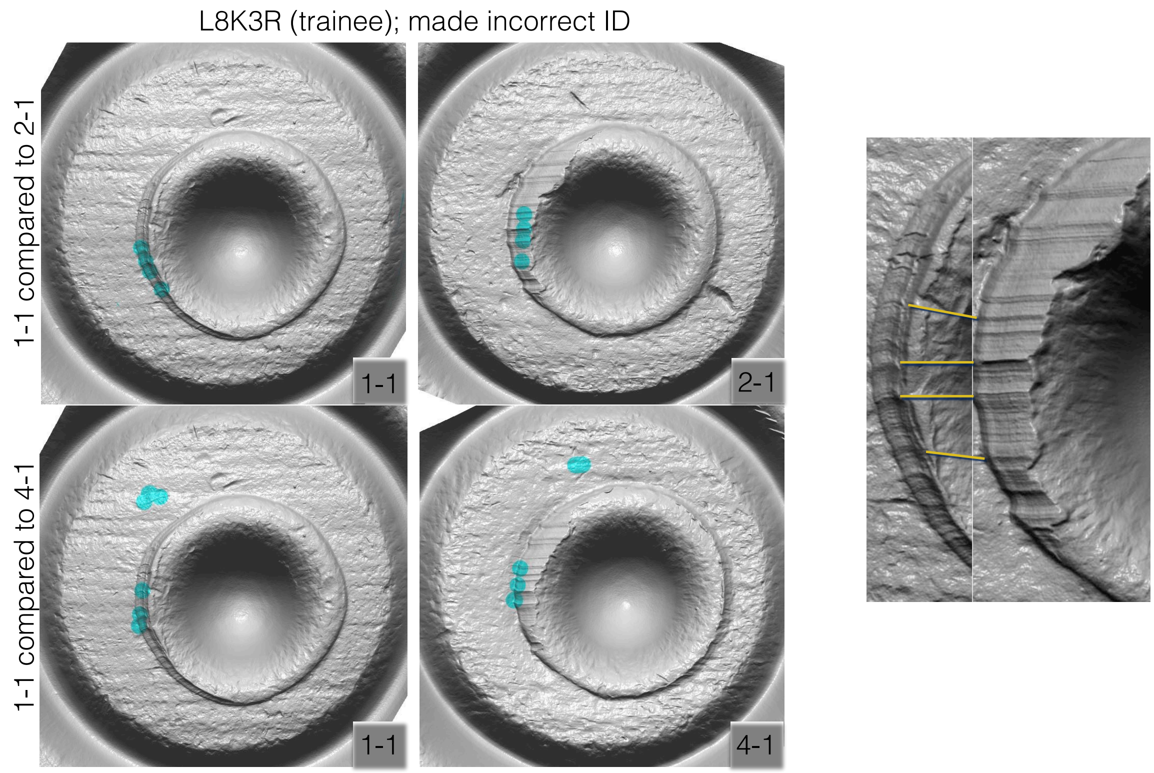


Figure 22: **False Identification by Trainee L8K3R (CCTS2):** Similarity annotation image maps are shown for the pairs Item 1-1 and 2-1 (top) and Item 1-1 and 4-1 (bottom). Unfortunately very little similarity is indicated in these maps and thus it is difficult to infer the reason an identification was made. A 'best' alignment between the aperture shears of Item 1 and 2 is shown on the right (yellow lines added). The shears are quite different.

# Supplementary Material

This supplementary material section contains additional detail on each of the completed experiments and protocols.

## Virtual Microscopy Test Set Details

**Virtual Microscopy Test Set (AFTE)**:

- **Scenario:** Police are investigating a shooting in a retail store. Investigators recovered four expended cartridge cases at the scene - two from the main entrance, one from the floor near the dressing room and one from the floor near the cash register. A suspect was apprehended later that day and police seized a Colt Model Trooper MK III 357 Magnum CTG pistol from his possession. Three rounds of Federal American Eagle .38 caliber 130 grain Full Metal Jacket (which were consistent with the cartridge cases found at the scene) were fired with the suspect firearm and the cartridge cases collected. Investigators are asking you to compare the recovered cartridge cases from the scene with those test fired from the suspect's weapon and report your findings.
- **Casings:** A single firearm (Colt Model Trooper MK III 357 Magnum CTG pistol; Federal American Eagle ammunition) was used to test fire the three casings of Item 1 and the individual test fire of Item 5. A second different firearm (same make and model) (Colt Model Trooper MK III 357 Magnum CTG pistol; Federal American Eagle ammunition) was used to fire the casings of Items 2, 3 and 4.

**Virtual Microscopy Test Set 1 (CCTS1)**:

- **Scenario:** Police are investigating a homicide at a residence. Investigators recovered four expended cartridge cases at the scene - two from the living room and two from the victim's bedroom. A suspect was apprehended later that day and police seized a Taurus PT 24/7 9mm pistol from his possession. Three rounds of PMC 9mm (which were consistent with the cartridge cases found at the scene) were fired with the suspect firearm and the cartridge cases collected. Investigators are asking you to compare the recovered cartridge cases from the scene with those test fired from the suspect's weapon and report your findings.
- **Casings:** A single firearm (Taurus PT 24/7 9mm; PMC ammunition) was used to test fire the three casings of Item 1 and the individual test fires of Items 2-5.

**Virtual Microscopy Test Set 2 (CCTS2)**:

- **Scenario:** Police are investigating a shooting at a gas station. Investigators recovered four expended cartridge cases at the scene - two from the parking lot, one from the floor near the entrance and one from the floor near a snack display. A suspect was apprehended later that day and police seized a Ruger P95DC 9mm handgun from his possession. Three rounds of PMC 9mm (which were consistent with the cartridge cases found at the scene) were fired with the suspect firearm and the cartridge cases collected. Investigators are asking you to compare the recovered cartridge cases from the scene with those test fired from the suspect's weapon and report your findings.
- **Casings:** A single firearm (Ruger P95DC 9mm; PMC ammunition) was used to test fire the three casings of Item 1 and the individual test fires of Items 3 and 5. A second different firearm (Ruger P85 MK II 9mm; PMC ammunition) was used to fire the casings of Items 2 and 4.

## AFTE Workshop Feedback

At the conclusion of the AFTE Virtual Microcopy workshop we pointed participants to a webform to provide feedback on the workshop and virtual microscopy tools. Below are **all** comments received for the indicated questions. The responses were not cherry-picked, all responses are below. Note that although there were only seven responses (out of the 25 workshop participants) we believe the feedback is still quite informative.

**"What did you find to be the most useful features of the viewer software?"**

- The notes on the procedure were easy to follow
- Ability to move the light source
- Light manipulation
- Being able to control the lighting. It was nice that there was consistent lighting between the two surfaces.
- Lighting angles could be easily varied.
- The amount of detail on the breechface was pretty amazing.
- the ability to control the lighting angle

**"Did any features seem unimportant or awkward? Should they be changed (how) or removed?"**

- Took a little to work the left/right moving of just the right image or both images; but over all easy to move

- I found myself, and the people I was working with, using left click to pan and we just ended up messing with our rotation. In this application rotation is secondary to translation alignment. It seemed more intuitive to have pan on the left mouse button and rotate on the right.
- Locking an area of agreement to stay locked regardless of magnification.
- I didn't love that moving the left side also moved the right. For me, separate adjustments would be easier.
- The most awkward movement was the vertical movement (or lack of windshield wiper). Although with practice, I believe the movements will come more naturally.

**"Did any features seem unimportant or awkward? Should they be changed (how) or removed?"**

- Not sure; would need to apply more samples/time
- As far as functionality? I thought it was very user friendly
- It would be nice to have at least one other relational point such as the ejector which could be done by capturing the entire headstamp area.

**"What are your thoughts on the use of Virtual Microscopy in the crime lab? Potential Uses? Potential Advantages?"**

- It's coming. Provides greater visualization of marks / topography.
- The detail is very good. It should make presentation of comparisons much easier.
- Paired with a quantitative algorithm, it would be great. Until then, seems like double work.
- Our lab was interested prior to my attending the workshop. once I show the software and what I learned, I think they will be even more so. I think maybe for CTS tests as well as blind proficiencies or casework
- The biggest disadvantage is lack of other relational points or ability to look at other areas than the breechface. This is done to overcome subclass concerns as well as provide more information. With additional improvements, I can see development or changes to the verification process that may streamline the process of our workflow. I do like the fact that if used as a CTS, then everyone would be looking at the same samples/images instead of the variation that comes from having your own sample set.

**"New technology always faces potential barriers to adoption. What do you see as potential pitfalls or sticking points for Virtual Microscopy?"**

- Currently start up costs and possibly, system dependent, the application of different 'methods' to comparisons (e.g. can use GelSoft on BF images but not chamber etc or bullets)
- I'm uncertain about the enhanced contrast feature. Features like that may be helpful for certain comparisons but if there isn't a solid explanation behind it, it could be misconstrued as cheating the data. Using that feature felt akin to messing with the lighting on a traditional microscope and seeing features appear or disappear. Certain comparisons looked better and certain ones looked worse but it wasn't obvious how that effect was being applied, so I'm wary of it
- See previous answer. Also, damaged or less than pristine evidence items.
- I think the FP Impression needs to be added. I understand that this is not the end-all and that an examiner may need to look at chamber marks on the actual specimen. I also think that some people, don't get that fact. It's all or nothing.
- Each departments IT regulations and upgrades. Some agencies do not have an IT budget that allows them to stay up to date with the latest OS or software upgrades. Some IT departments are very strict as to what software can be used. Although the FBI does not connect any of the tested computers/software to their WAN, our computers are all connected and therefore admin rights and ability to upgrade or trouble shoot are limited.

**"Any other comments"**

- Nice work! I think being able to manipulate these 3d renderings in a manner similar to a comparison microscope will certainly help the adoption of this technology.
- I thought it was a well organized and well put together class
- I will be in touch with some additional suggestions in the coming weeks
- Thanks for your continued work. I look forward to your future developments and advancements to the algorithms.

In addition, we asked a few questions on a scale of 1-10:

- "Did you get a chance to see the casings on the comparison scope?" (7 responses)
  - All participants completed the virtual microscopy tutorial and exercises; 72% of responses indicated that they also took the time to examine the CTS-like casings under the comparison microscope.

- "How comfortable did you feel with the visualization software by the end of the workshop? (1:least comfortable, 10: most comfortable)" (7 responses)
  - All respondents indicated 8 or above. 57% marked 8. 14% marked 9. 28% marked 10.
- "Compared to your use of a comparison microscopy, how confident are you in your ability to complete a CTS-like exam using software like that used today? (1:not very comfortable, 10:very comfortable)" (7 responses)
  - 6 (86%) of responses indicated 7 or above
- "Do you have any prior experience with 3D scanners or 3D visualization software?" (6 responses)
  - 4 (66%) of responses did not have prior experience. 2 (33%) did have prior experience.

## References

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[5] T. Weller, M. Brubaker, P. Duez, and R. Lilien. Establishing best practices and performance measures for a 3D imaging and analysis system. *submitted for review*, 2017.

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