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PAPER

CRIMINALISTICS

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Development and Validation of a Virtual Examination Tool for Firearm Forensics*,†,‡

ABSTRACT: The transition from 2D imaging to 3D scanning in the discipline of firearms and toolmark analysis is likely to provide examiners an unprecedented view of microscopic surface topography. The digital examination of measured 3D surface topographies has been referred to as virtual microscopy (VM). The approach offers several potential advantages over traditional comparison microscopy. Like any new analytic method, VM must be validated prior to its use in a crime laboratory. This paper describes one of the first validation studies of virtual microscopy. Fifty-six participants at fifteen laboratories used virtual microscopic tools to complete two proficiency-style tests for cartridge case identification. All participating trained examiners correctly reported 100% of the identifications (known matches) while reporting no false positives. The VM tools also allowed examiners to annotate compared surfaces. These annotations provide insight into the types of marked utilized in comparative analysis. Overall, the results of the study demonstrate that trained examiners can successfully use virtual microscopy to conduct firearms toolmark examination and support the use of the technology in the crime laboratory.

KEYWORDS: forensic science, 3D imaging, surface metrology, cartridge cases, virtual examination, virtual microscopy, firearms identification, software

Several emerging technologies capable of measuring three-dimensional toolmark surface topographies are entering the discipline of firearm and toolmark examination. These instruments utilize a range of different scanning technologies to measure an object's three-dimensional surface. These approaches include focus-variation microscopy, confocal microscopy, point laser profilometry, scanning interferometry, and photometric stereo (1–3). A high-resolution 3D measurement is an indirect representation of the 3D surface topography. If accurately measured, there is a one-to-one geometric mapping between the measured surface and the actual surface. These measurements can be used in place of the direct physical specimen. Several previous works have used 3D measurements to study striated and impressed toolmarks as well as toolmarks produced by firearms on fired ammunition components (4–9).

The use of indirect digital representations is well established in the crime laboratory. For example, digital photographs (10,11), digital 3D laser scanning of a crime scene (12), digital fingerprint scans (13,14), and digital mass spectra are all indirect representations of a source object. When a digital copy is used, it is necessary to verify that the measured digital object is an accurate representation of the source object. In the case of 3D forensic surface topographies, accuracy can be achieved by calibrating the scanner and running quality control checks using a reference specimen. The detailed methodology for obtaining an accurate 3D measurement is beyond the scope of this paper. The examination of measured 3D surface topographies in lieu of physical specimens is referred to as virtual microscopy.

There are several open questions regarding virtual microscopy; for example, can virtual microscopy take the place of physical examination or will virtual microscopy simply complement traditional examination, how can the technology best be used in a laboratory setting, and what quality assurance procedures are required for this integration. It is important to investigate whether virtual microscopic examination is qualitatively any different than traditional examination of the physical objects. That is, can an examiner make the same quality comparison using the 3D visualization of two cartridge cases as they would make with a traditional comparison microscope. This paper introduces some of these concepts and presents a first step toward answering these questions.

The remainder of this paper is structured as follows: We start with a discussion of Virtual Microscopy. We then discuss methods and present subsections detailing scan acquisition, visualization software, test sets, pretest workshop, and study design. After presenting study results, we close with conclusions and future work. Additional experimental details are provided in the Appendix S1.

Virtual Microscopy

One of the earliest descriptions of virtual microscopy (VM) or virtual comparison microscopy is the virtual comparison scope

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of Senin et al. (15). The authors describe a system with two components, one for scan acquisition and one for scan analysis. Scan acquisition can be accomplished using any accurate 3D scanning technology. Scan analysis requires software that replicates many of the same functions as a traditional comparison microscope. For example, the operator should have the ability to adjust the specimen position, the visualized magnification, and the lighting used for rendering. The virtual microscope may also include features not possible on the traditional microscope. These may include remote access, shared collaborative viewing, artificial surface coloring (annotations), and sample cross-sectioning.

In virtual microscopy, the examiner views and manipulates the measured 3D representation of an object using a computer without physical access to the specimen. This means that once the scan has been acquired, only the digital data file is necessary for examination. Therefore, the scan acquisition subsystem and the scan analysis subsystem may be physically different machines at geographically different locations. It is possible for an examiner at a location with only scan analysis software to obtain data from a second laboratory which has a 3D scan acquisition system.

Uses of Virtual Microscopy

The use of digital data files removes the constraint of requiring physical access to evidence and allows a number of potential uses for virtual microscopy that are not possible with traditional comparison technology. For example, within the medical field, virtual microscopy of high-resolution pathology slides provides advantages in the areas of remote viewing, data sharing, annotation, and data analysis (16). Similar advantages can be achieved within forensic science.

Comparing and Archiving Evidence—With the development and validation of 3D measurement instrumentation, laboratories will gain the ability to create virtual archives of toolmark evidence. The ease with which digital data can be accessed and electronically transported provides several advantages over the traditional evidence handling workflow. This is illustrated in the following hypothetical but realistic scenario: A laboratory is asked to examine evidence from a homicide shooting scene from a local police department. Several months later, a different police agency asks that evidence from a second homicide be examined. A database hit occurs between the two homicides, and the evidence from the two cases needs to be compared. Using traditional comparison microscopy, the evidence from the original homicide would have to be transported back to the laboratory. Virtual microscopy allows for the comparison to occur almost instantaneously, cutting out the need for additional transportation and chain of custody.

The use of virtual microscopy can also be advantageous for laboratories that have large geographic service areas. Through the use of trained staff and strategically located 3D measurement instruments, routine evidence can be scanned off-site and then the virtual images examined and compared at the main laboratory. Again, this saves significant time and resources by eliminating transportation, chain of custody, and other documentation (e.g., marking individual packaging and evidence items) that is currently required.

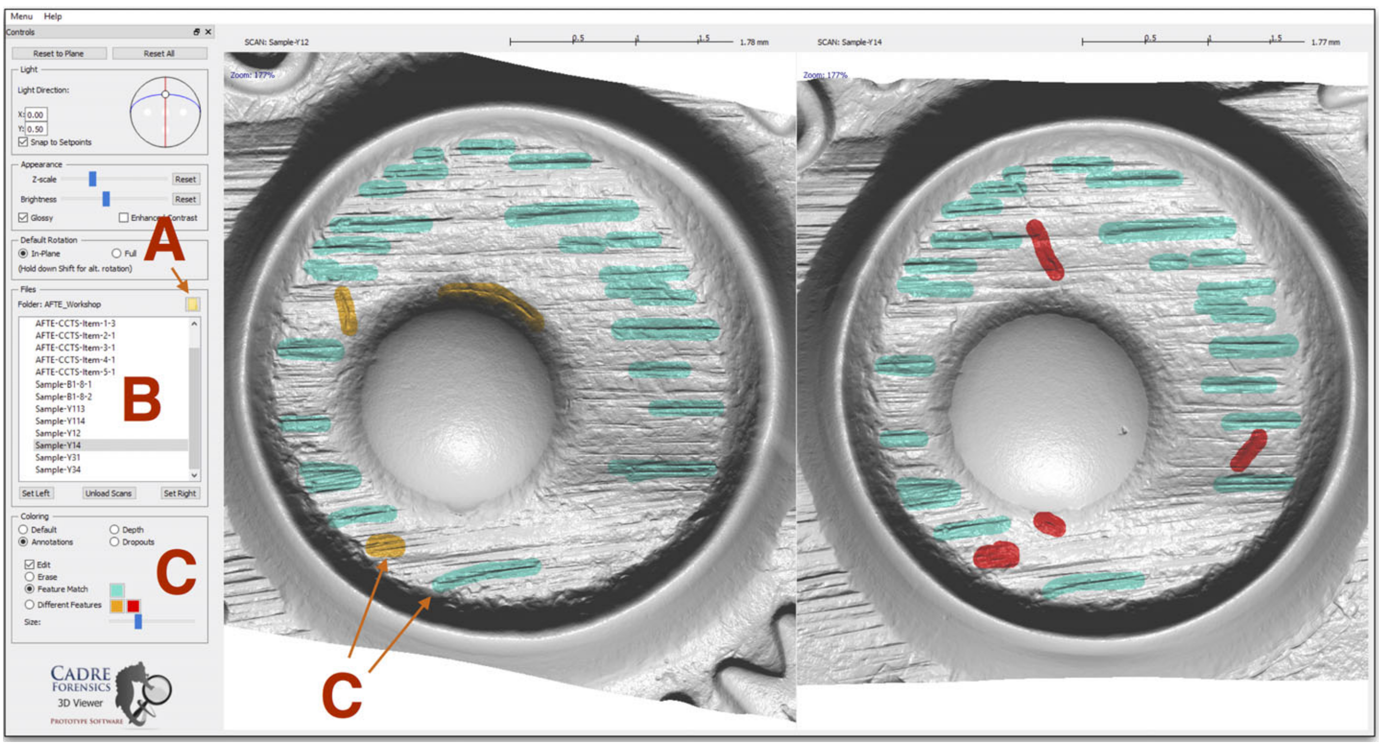

FIG. 1—*Virtual Microscopy Viewer (VMV) software. The VMV software provides a virtual comparison microscope. Examiners can adjust the virtual light position, manipulate the cartridge case orientation, position, and zoom (locked or unlocked). In a typical workflow, the user first selects a folder of scans (A) and then sends individual scans to the left or right view panel (B). Pairs of cartridge cases 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. The color annotations shown here are simplified and do not represent a complete marking of the similar and dissimilar regions of the shown surfaces. [Color figure can be viewed at wileyonlinelibrary.com]*

The ease with which digital data files can be exchanged also supports the seeking of outside consult or expertise on specific cases. For example, an examiner in California could seek a second opinion from an examiner in Virginia by simply sharing the 3D scan data. Once again, digital data files will simplify the chain of custody process.

Finally, it will be possible to assemble virtual archives of the evidence captured through 3D instrumentation. Laboratories will be able to create open case files consisting of 3D images of all evidence and then instantaneously access or share this information.

Training—Virtual microscopy has significant advantages when used in training. Supervisory staff can scan and develop standardized comparison sets to train new examiners. Examples of training sets include class characteristics, subclass examples, and best known nonmatches. Additionally, through the use of virtual microscopy, the profession can share interesting examples. This will allow the profession to address a frequent critique, that firearm and toolmark examiners train using different examples and thus each may have different criteria for an identification. Through the use and sharing of 3D samples, the discipline will have a more shared experience to draw from. For example, imagine that an examiner has presented a study of a new firearm model at a national conference and that they have also collected 3D surface topographies of relevant test fires. The presenter can make these scan files available to all conference attendees. Participants can then download and compare the exemplars for themselves. This type of knowledge sharing is possible with virtual microscopy yet impractical with traditional physical methods.

Validation Studies and Proficiency Testing—There is significant interest in validation studies and establishing examiner error rates. An excellent review has recently been published by Murdock et al. (17). One criticism of many validation studies is that within a study, each examiner receives a different set of test fires. While they are generally similar (all having been fired through the same set of firearms), there is some variability in the markings on each set of test fires. A virtual microscopy proficiency examination where examiners are asked to complete their entire examination using 3D visualization would provide several advantages. First, all examiners can be provided the exact same data files, meaning that they all see the exact same cartridge cases. This eliminates test to test variability. Second, a digital interface allows for a richer type of examiner interaction. An examiner can identify, via digital visual annotation, all areas of geometric similarity or difference. This means that an examiner's proficiency can be measured not only by the correctness of the identification or elimination conclusion but also in the number of correctly annotated regions of geometric similarity or difference.

Documentation and Verification—Virtual microscopy software may allow the annotation of individual or pairs of specimens to highlight the surface features. For example, all regions of topographic similarity used in reaching an identification conclusion can be marked in one color, potential differences can be marked

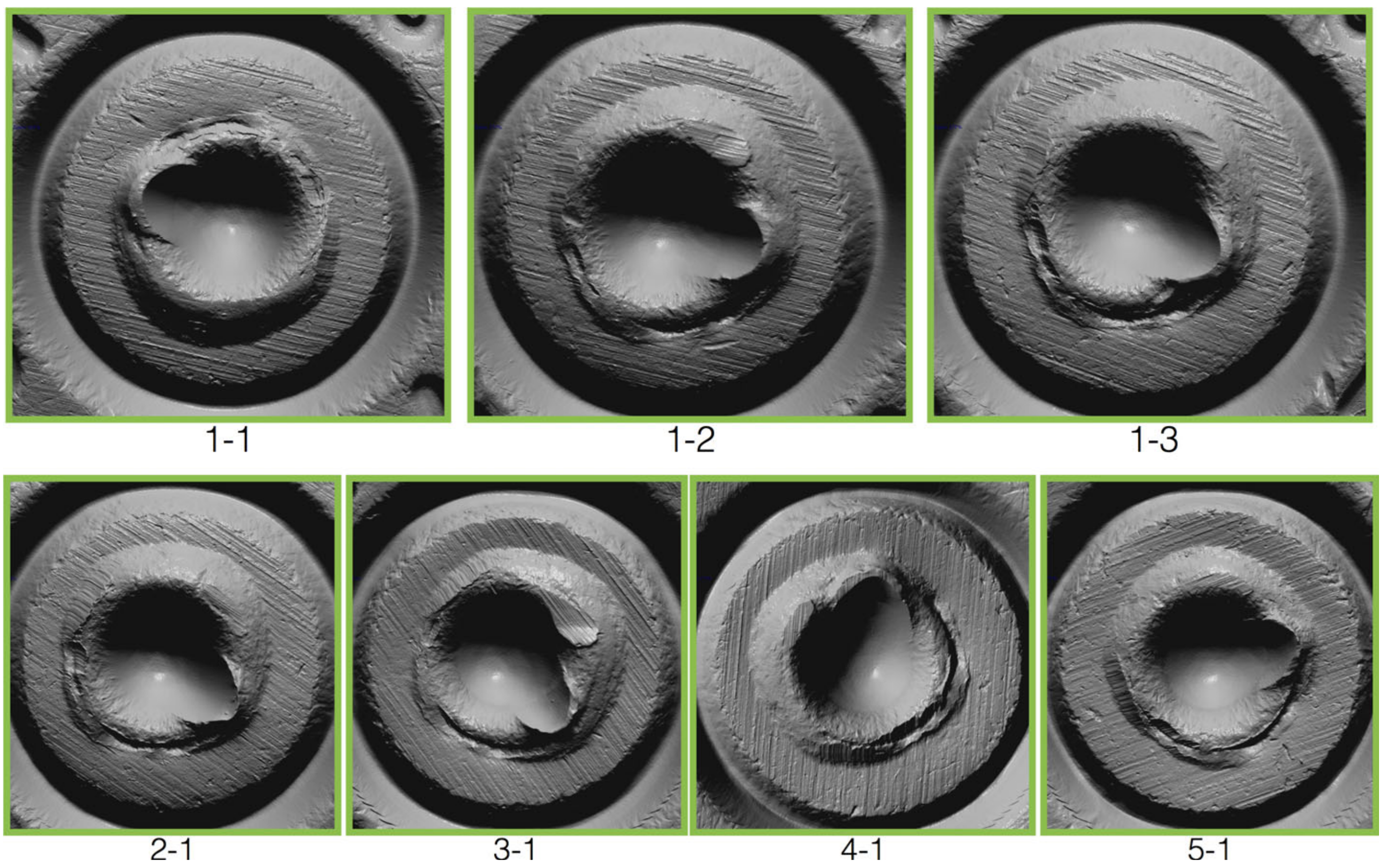

FIG. 2—*Virtual microscopy cartridge cases: CCTS1. Test set CCTS1. All cartridge cases are displayed oriented as scanned. All cartridge cases in CCTS1 come from the same firearm (green border). [Color figure can be viewed at wileyonlinelibrary.com]*

in a second color, and potential subclass marks annotated in a third color. Virtual microscopy data exchange supports verification. During verification, a second examiner evaluates the digital scans and verifies the work of the first examiner. In blind verification, both the surface annotations and the conclusion of the first examiner are hidden from the second examiner. The second examiner is therefore "blind" to the work of the first examiner. Similar and dissimilar regions identified by the second examiner may be compared to the regions identified by the first examiner. A verification result is obtained if both examiners mark the same regions and reach the same conclusion. If different regions are marked or different conclusions are reached then a third examiner or arbiter can be brought in to resolve the potential conflict. Verification and blind verification are important parts of a laboratory's quality control process.

X3P Common File Format

The data collaboration and sharing benefits described above are facilitated if different manufacturers are capable of exchanging surface topographies in a common file format. The OpenFMC (Open Forensic Metrology Consortium) (http://www.openfmc.org) has recently adopted the X3P file format for the storage of three-dimensional surface topography data. The OpenFMC group includes academic, industry, and government forensic researchers and practitioners dedicated to the development and adoption of novel technology. Free software for reading and viewing X3P data is available at www.openfmc.org.

Validation of Virtual Microscopy

Prior to its routine use in a crime laboratory, it is important to validate the use of any new technology. Validation seeks to ensure that a new process or procedure is reliable and that it meets the operational needs of the user. With respect to virtual microscopy, several aspects need to be demonstrated. First, the technology must rely upon accurate 3D measurements. Success is dependent upon the ability of these systems to acquire high-resolution, accurate, and reproducible scans under a range of normal operating conditions. If the 3D surface topographies are not accurate, then the results of virtual microscopy may be unreliable. Best practices may dictate that measurements be traceable in that they are collected on hardware whose accuracy can be linked back to a known specimen through an unbroken chain of calibrations. Therefore, it is important that quality control checks be in place and that 3D measurement hardware complies with all relevant standards and guidelines for use in firearm and toolmark examination. In addition, it will be necessary to demonstrate that virtual microscopy can reliably achieve comparison results at least as good as that obtained using conventional methods. The study presented in this paper is one such result.

Once validated, a laboratory should establish standard operating procedures (SOPs) for the use of 3D virtual microscopy. These SOPs should include scan acquisition (if data are being collected in the laboratory) and the use of visualization software. Laboratories should demonstrate and document examiner proficiency with the software prior to their being allowed to use the technology in casework. These are not insurmountable

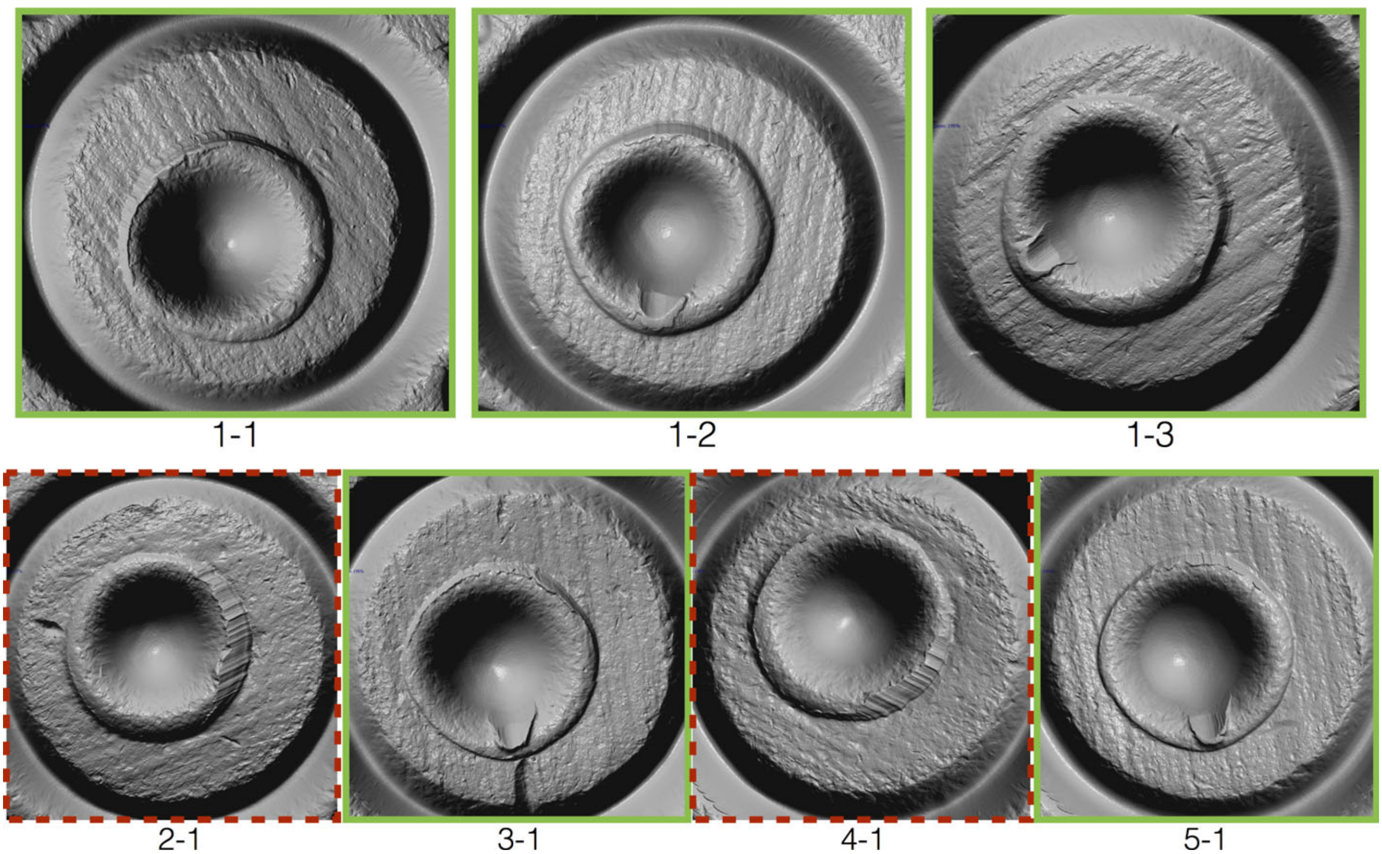

FIG. 3—*Virtual microscopy cartridge cases: CCTS2. Test set CCTS2. All cartridge cases are displayed oriented as scanned. Items 1-1, 1-2, 1-3, 3-1, and 5-1 are from the same firearm (green border). Items 2-1 and 4-1 are both from a second different firearm (red dashed border). [Color figure can be viewed at wileyonlinelibrary.com]*

challenges, and recent results suggest that validation will be successful.

Materials and Methods

Virtual microscopy was evaluated through a conference workshop and two proficiency tests. Specialized virtual microscopy software was written and utilized in both the workshop and study. Scans were acquired on the Cadre TopMatch-GS 3D scanner.

3D Scan Acquisition

The 3D surface topographies used in this study were collected using the TopMatch-GS 3D version 1 hardware (Cadre Research, Chicago, Illinois USA). Details of the version 1 system are available in previous publications (3,18,19). The version 1 hardware was the latest system available at the time data was collected; however, a new version of the hardware is now available which automates several steps of the scanning process. The version 1 scanner measures an object's three-dimensional surface topography using three-dimensional imaging algorithms and the retrographic sensor of Johnson and Adelson. In contrast to other direct imaging methods (e.g., confocal microscopy and focus-variation microscopy), the use of a painted elastomeric gel removes the influence of surface reflectivity on the measured topography. The primers of each cartridge case were scanned at approximately 1.4 micron/pixel lateral resolution with submicron depth resolution. Scan acquisition required approximately 2 min per cartridge case. Because the TopMatch system supports the common X3P file format, scan files could easily be exported for use on other compatible systems.

Software

Virtual Microscopy Viewer (VMV) software was written which provides an easy interface for side-by-side comparison of 3D surface topographies (e.g., cartridge cases). The user first identifies the folder containing the desired 3D data files (Fig. 1*A*) and then clicks on individual filenames to pull up individual cartridge cases for comparison (Fig. 1*B*). From the side-by-side view, the user can interact with the visualization to adjust the virtual light position, manipulate (rotate, translate, and zoom) the cartridge cases, and save high-resolution image files of the current view. The software provides both locked and unlocked viewing modes. An enhanced contrast mode can be enabled to bring out additional surface detail. Finally, as part of their documentation, users can virtually mark cartridge case surfaces

to indicate regions of geometric similarity and dissimilarity (Fig. 1*C*). Annotations are created using the mouse as a paintbrush or marker. The user selects a marker size and indicates if they are annotating a region of similarity or difference. Users can erase spurious marks or errors. These color annotations can be saved for future review. A training tutorial booklet was created to accompany the software. The booklet walks the user

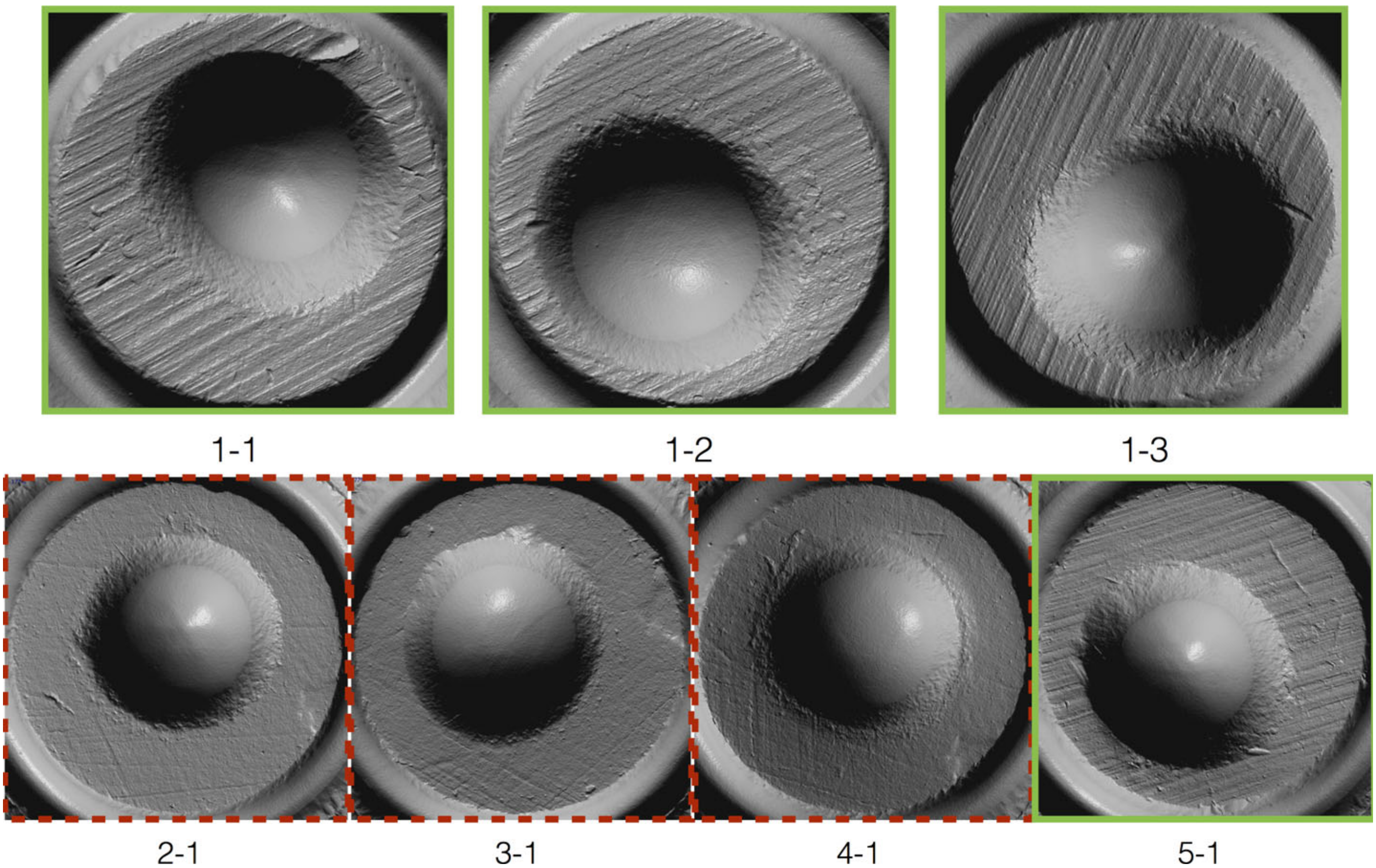

FIG. 4—*Virtual microscopy cartridge cases: workshop set. All cartridge cases are displayed oriented as scanned. Items 1-1, 1-2, 1-3, and 5-1 are from the same firearm (green border). Items 2-1, 3-1, and 4-1 are from a second different firearm (red dashed border). Note that these cartridge cases have no flow-back or aperture shear. [Color figure can be viewed at wileyonlinelibrary.com]*

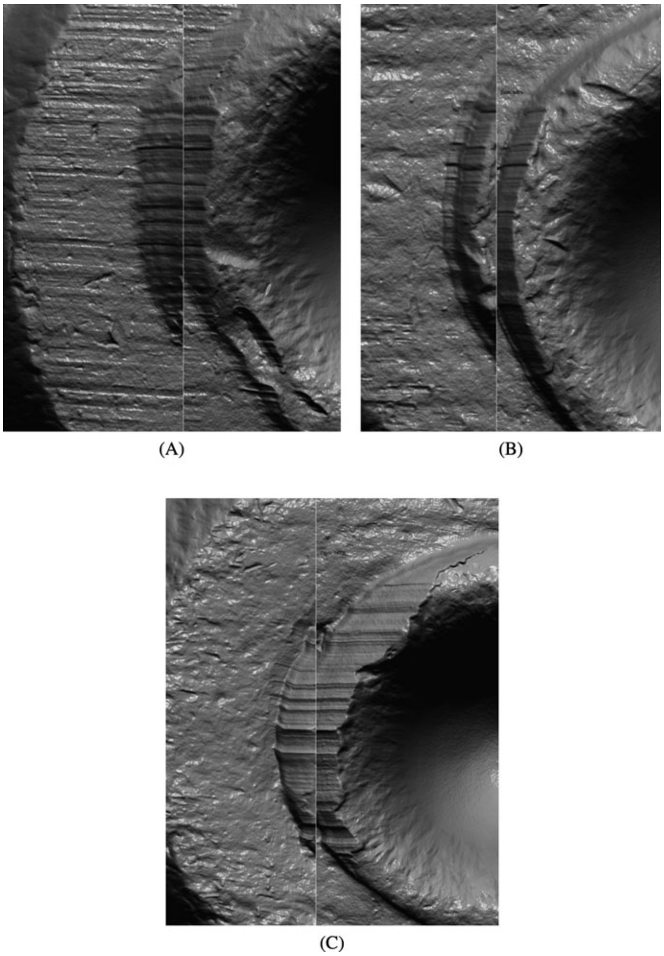

FIG. 5—*Virtual microscopy cartridge case aperture shears. A number of the cartridge cases in the virtual microscopy study have strong aperture shears. Each panel (A, B, C) shows a side-by-side split view of two cartridge cases. Virtual lighting was set to come from the 12 o'clock position to provide a glancing light source. (A) CCTS1 two cartridge cases of Item 1 (match), (B) CCTS2 two cartridge cases of Item 1 (match), (C) CCTS2 cartridge cases from Items 2 and 4 (match).*

through all aspects of the software's functionality. It demonstrates visualization of several cartridge cases with different classes of breech-face impression and aperture shear. Upon completion of the activities in the booklet, participants should be proficient with the general operation of the software.

Test Sets

Three proficiency-style test sets were created: one for the AFTE workshop and two for the virtual microscopy study. The study sets were named Workshop, CCTS1, and CCTS2. Screenshots of the cartridge cases in these three sets are shown in Figures 2–4 (the colored borders in these figures were not shown to the participants and have been added to this manuscript for the reader). Each study set consisted of a total of seven cartridge cases. Participants were told the first three cases (Item 1) were test fires from the same firearm. The remaining four cartridges (Items 2–5) were cartridges obtained at a hypothetical crime scene. The participants therefore were tasked with comparing the four "unknowns" to the three "knowns" for each set.

Different cartridge cases contain different types of toolmarks. For example, some cartridge cases have strong aperture shears. The aperture shear (or primer shear) is a striated toolmark formed by the firing pin aperture and is typically found on the cartridge case primer near the firing pin impression. The analysis of these striated marks requires alignment of the cartridge case aperture shears under the split screen dividing line (Fig. 5). The cartridge cases of the Workshop test set have no aperture shear and their analysis requires examination of impressed surface features. Therefore, successful analysis of the three different test sets required proficiency with the virtual microscopy software and expertise in firearms examination (e.g., ability to correctly align, compare, and interpret the matching and nonmatching surface geometry).

We designed a data collection worksheet containing a typical crime scene scenario, instructions, list of items submitted, detailed description of AFTE range of conclusions, and conclusion checkboxes (Figs 6–8). All cartridge case scans were loaded onto participating computers. The measured surfaces included only the cartridge case's breech-face impression, aperture shear, and a small region of the head just beyond the primer. Participants were instructed to base their conclusions only on the breech-face impression and aperture shear marks of the provided 3D surface topographies.

- Workshop Cartridge Cases (38 special): A single firearm (Colt Model Trooper MK III 357 Magnum CTG pistol; Federal American Eagle ammunition) was used to test fire the three cartridge cases 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 cartridge cases of Items 2, 3, and 4.
- CCTS1 Cartridge Cases (9 mm Luger): One firearm (Taurus PT 24/7; PMC ammunition) was used to test fire the three cartridge cases of Item 1 and the individual test fires of Items 2–5.
- CCTS2 Cartridge Cases (9 mm Luger): One firearm (Ruger P95DC; PMC ammunition) was used to create the three test fires of Item 1 and the individual test fires of Items 3 and 5. A second different firearm (Ruger P85 MK II; PMC ammunition) was used to fire the cartridge cases of Items 2 and 4.

Training Workshop

Prior to undertaking the main study, the training booklet and software were evaluated by approximately thirty participants at a virtual microscopy workshop. The workshop was conducted at the May 2016 national AFTE meeting. During a hands-on portion of the workshop, small groups of two to three attendees worked through the training tutorial and then informally completed the Workshop virtual proficiency test. While most participants found the software intuitive and easy to use a few individuals had initial awkwardness manipulating the 3D scans. This is understandable given the limited time individuals had with the software and the limited experience most participants had with manipulating digital 3D objects. It often takes time to become fluent with the manipulation of digital 3D objects (just as it takes time to learn to operate a comparison microscope). The workshop confirmed that the software and data collection worksheets were ready for use in the main virtual microscopy study.

Virtual Microscopy Study

We conducted a study to evaluate the feasibility of using virtual microscopy for cartridge case examination. A training booklet was created which contains figures and step-by-step

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.

Instructions:

The 3D surface topographies of each casing have been collected and loaded onto the viewer software. Each scan is labeled with the item number. The scans include only the breech-face impression and aperture shear marks. Please based your conclusions only on the breech-face impression and aperture shear marks. Do not consider firing pin impression or ejector marks (even if you can see some of these marks). Your conclusions should be based solely on the virtual microscopy. Please be sure to complete the training tutorial before beginning the CTS test.

FIG. 6—*Worksheet scenario and instructions.*

Question:

Were any of the questioned expended cartridge cases (Items 2-5) discharged from the same firearm as the known expended cartridge cases (Item 1)?

Item	Identification	Inconclusive A.	Inconclusive B.	Inconclusive C.	Elimination
2	☐	☐	☐	☐	☐
3	☐	☐	☐	☐	☐
4	☐	☐	☐	☐	☐
5	☐	☐	☐	☐	☐

FIG. 7—*Worksheet question. Examiners indicated their results using this series of clickable checkboxes.*

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.

FIG. 8—*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."*

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 materials prior to participating in the proficiency-style tests. We solicited volunteer participation from all US crime laboratories via announcements at conference presentations and the online AFTE forums. Fifteen laboratories received internal approval to participate. We did not turn away any US crime laboratory that received permission to participate. The study had 56 participants (46 trained examiners and 10 trainees). Three laboratories wished to keep their participation anonymous, the other twelve laboratories are listed in Table 1. It is important to stress that the listing of these laboratories does not imply their endorsement. We are grateful to all participants and participating laboratories.

To eliminate the computer hardware and display as experimental variables, three identical laptops (Dell Inspiron 15-7559 Laptops with 15″ high-resolution (4K) display and external USB mouse) were rotated among thirteen of the participating laboratories. Two laboratories used their own hardware and we verified that these computers met our display requirements. The performance of participants from these two laboratories was at least as good as the laboratories that used our laptops (i.e., there were no identification errors reported by these two laboratories). When a laboratory using our loaner laptops completed the study, it was provided a shipping label so that the computer could be sent to the next participating laboratory. Each computer was loaded with the virtual microscopy software, the training scan data, and the CCTS1 and CCTS2 test scan data. Each laboratory was provided a unique login, and each individual was given a unique participant code.

Each participant worked through the printed training booklet and the Workshop test set. Self-reported times for this step were between 20 and 40 min. When a participant felt ready, they began the CCTS1 and CCTS2 proficiency tests. Participants recorded their conclusions on a data collection worksheet and saved these annotations to disk. These annotations included regions of similarity and dissimilarity. When all participants from a laboratory had completed the study, the laboratory's point-of-contact ran a special program to package the results and upload this packaged file to our server. Each laboratory was given a few weeks to complete the training tutorial and proficiency tests. Participants were asked to complete the study on their own; however, this was not proctored or enforced.

TABLE 1—*Fifty-six participants (46 trained examiners, 10 trainees) across fifteen sites participated in the virtual microscopy study.*

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 Institute of Standards and Technology	Gaithersburg, MD
New Hampshire State Police Forensic Laboratory	Concord, NH
San Francisco Police Department Forensic Laboratory	San Francisco, CA

Three sites elected to remain anonymous and are not listed here. The listing of a laboratory does not constitute endorsement. We are grateful to all participants for their involvement.

Results and Discussion

Fifteen sites and 56 participants took part in the study with each individual completing two separate proficiency tests as described above. To our knowledge, this is the largest virtual microscopy study performed to date. The inclusion of both trained examiners and trainees allowed us to measure the performance of both groups. The study was blind in that examiners did not know the true source of the cartridge cases. Each examiner completed study worksheets and saved their individual cartridge case annotations. Examiners were asked to utilize the AFTE range of conclusions (Fig. 8). Any conclusion of "inconclusive" A, B, or C was counted as simply "inconclusive" in the results table. We decided that it was unreasonable to ask every participant to annotate all 21 cartridge case pairs for each test (seven cartridge cases results in 21 unique pairs). We therefore asked participants to annotate at least one elimination and one identification. The instructions stated, "If you make any identifications between Item 1 and another item, please select at least one identification and color the surface with annotations. If you make any Eliminations please select at least one elimination and color the surface with annotations to indicate the basis for the elimination." This resulted in different participants annotating different pairs. Fortunately, most individuals annotated Item 1 and we were therefore able to obtain summary information in the form of annotation maps (described below). In hindsight, it may have been better to specify specific pairs of cartridge cases to annotate. For example, the first cartridge case of Item 1 should be compared to each of Items 2, 3, 4, and 5. We may also ask examiners to mark only those regions used in reaching their conclusion rather than any regions of similarity or difference. These slight wording changes will improve the information that can be obtained from surface annotations in future studies.

We produced a series of color annotation maps to illustrate the regions of similarity and dissimilarity identified by the participants. Two styles of maps were created. The "Combined" maps show a density of annotations for a single cartridge case by combining the annotations from multiple individuals (e.g., Fig. 9). In these images, regions of the surface that were annotated appear in color and regions that were not annotated are uncolored. The colors range from red to blue and indicate the fraction of annotations for the specified surface topography that had the area marked. For example, if 40 participants annotated cartridge case X and if only three of the 40 participants marked a specific section of the cartridge case surface than that region would appear blue. If 38 of the 40 participants had marked the region, it would appear red. The color scale is shown on the top of some of the image maps. The second type of map is an "Individual" map which shows the regions of a single cartridge case surface annotated by a single individual (e.g., Fig. 11). All marked sections of an individual map appear light blue. Because participants could annotate the surface as being either "similar" or "different," we can generate both similarity maps that indicate the percentage of participants that marked a region as similar and Difference maps that indicate the percentage of participants that marked a region as different. Annotations are made when a participant is viewing a pair of scans (e.g., X and Y). In most of the figures below, we only show the annotations on the first cartridge case (e.g., X). Note that scans are shown in a common orientation in the annotation maps; however, the scans were presented to participants in a random orientation (oriented as scanned).

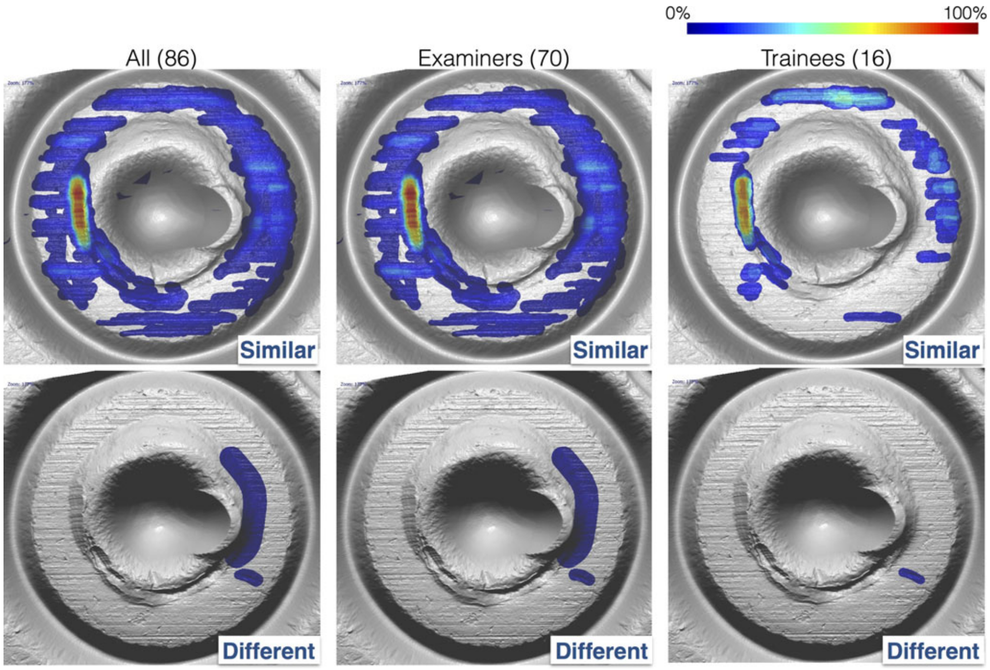

FIG. 9—*Annotation image map (CCTS1: Item 1-1): combined. Cartridge case Item 1-1 is shown in all six panels. Surface is colored by the percentage of participants annotating this item that marked the corresponding surface area. All comparisons involving Item 1-1 are combined into this image. (left column) all participants, (center column) trained examiners, (right column) trainees. Number in parentheses is the number of annotations from the specified participant type. (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 cartridge case 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. [Color figure can be viewed at wileyonlinelibrary.com]*

- CCTS Test Set 1: Fifty-six participants completed CCTS1 as part of the virtual microscopy study. One firearm (Taurus PT 24/7 9 mm; PMC ammunition) was used to test fire the three cartridge cases of Item 1 and the individual test fires of Items 2–5. The results for all participants are shown in Tables 2 and 3. 100% of examiners and 100% of trainees made all

TABLE 2—*CCTS1 individual responses.*

PCode	Item 2	Item 3	Item 4	Item 5	PCode	Item 2	Item 3	Item 4	Item 5
2A692	Yes	Yes	Yes	Yes	**K4QFH**	Yes	Yes	Yes	Yes
2NCV4	Yes	Yes	Yes	Yes	***KLV8F**	Yes	Yes	Yes	Yes
38JLN	Yes	Yes	Yes	Yes	**KVDEG**	Yes	Yes	Yes	Yes
3R5RK	Yes	Yes	Yes	Yes	**L27CR**	Yes	Yes	Yes	Yes
***4X99B**	Yes	Yes	Yes	Yes	***L8K3R**	Yes	Yes	Yes	Yes
5CY6N	Yes	Yes	Yes	Yes	***M3S8F**	Yes	Yes	Yes	Yes
***5RSCS**	Yes	Yes	Yes	Yes	**N4VH2**	Yes	Yes	Yes	Yes
***6YNZV**	Yes	Yes	Yes	Yes	**P3CK6**	Yes	Yes	Yes	Yes
7LP7H	Yes	Yes	Yes	Yes	**QDG65**	Yes	Yes	Yes	Yes
7UVY4	Yes	Yes	Yes	Yes	**QETKB**	Yes	Yes	Yes	Yes
7VKHK	Yes	Yes	Yes	Yes	**RCRE7**	Yes	Yes	Yes	Yes
9AGVK	Yes	Yes	Yes	Yes	**REX7C**	Yes	Yes	Yes	Yes
9ZJHW	Yes	Yes	Yes	Yes	**REXBV**	Yes	Yes	Yes	Yes
AGMWE	Yes	Yes	Yes	Yes	**RGMRM**	Yes	Yes	Yes	Yes
APJTM	Yes	Yes	Yes	Yes	**SCSD8**	Yes	Yes	Yes	Yes
BUTM9	Yes	Yes	Yes	Yes	**SFFDU**	Yes	Yes	Yes	Yes
BWCFS	Yes	Yes	Yes	Yes	**SPZES**	Yes	Yes	Yes	Yes
***BZKDL**	Yes	Yes	Yes	Yes	**TTJ8U**	Yes	Yes	Yes	Yes
C7N89	Yes	Yes	Yes	Yes	***UA62Y**	Yes	Yes	Yes	Yes
CLHT6	Yes	Yes	Yes	Yes	**UCNA6**	Yes	Yes	Yes	Yes
D4RPD	Yes	Yes	Yes	Yes	**UKWHL**	Yes	Yes	Yes	Yes
DAB22	Yes	Yes	Yes	Yes	**UZJYL**	Yes	Yes	Yes	Yes
DPC33	Yes	Yes	Yes	Yes	***VBU8D**	Yes	Yes	Yes	Yes
DR53Q	Yes	Yes	Yes	Yes	***VGQ3T**	Yes	Yes	Yes	Yes
E5C74	Yes	Yes	Yes	Yes	**WA5FB**	Yes	Yes	Yes	Yes
F9FFQ	Yes	Yes	Yes	Yes	**WPSC4**	Yes	Yes	Yes	Yes
FZ9HM	Yes	Yes	Yes	Yes	**XLV73**	Yes	Yes	Yes	Yes
HVQDZ	Yes	Yes	Yes	Yes	**XMR27**	Yes	Yes	Yes	Yes

"Were any of the questioned expended cartridge cases (Items 2–5) discharged from the same firearm as the known expended cartridge cases (Item 1)?").
Starred participants indicate trainees.
PCode: participant code. Inc: inconclusive. Overall, no mistakes were made by trained examiners or trainees (see Table 3 and annotation details in Figs 9–11).

TABLE 3—*CCTS1 match statistics.*

	Item 2	Item 3	Item 4	Item 5
Examiners				
Yes (ID)	46 (100%)	46 (100%)	46 (100%)	46 (100%)
No (Elimination)	0 (0%)	0 (0%)	0 (0%)	0 (0%)
Inconclusive	0 (0%)	0 (0%)	0 (0%)	0 (0%)
Trainees				
Yes (ID)	10 (100%)	10 (100%)	10 (100%)	10 (100%)
No (Elimination)	0 (0%)	0 (0%)	0 (0%)	0 (0%)
Inconclusive	0 (0%)	0 (0%)	0 (0%)	0 (0%)
All				
Yes (ID)	56 (100%)	56 (100%)	56 (100%)	56 (100%)
No (Elimination)	0 (0%)	0 (0%)	0 (0%)	0 (0%)
Inconclusive	0 (0%)	0 (0%)	0 (0%)	0 (0%)

100% of examiners and 100% of trainees made all correct identifications.

correct identifications. No mistakes were made by trained examiners or trainees. Annotation maps are shown in Figures 9–11. Figure 9 and Figure 10 (top) show that most individuals used the aperture shear to make the identification. Close-ups of the marked surface areas appear in Figure 10 (bottom). Examination of each participant's annotations when comparing Items 1-1 and 2-1 (a match) are shown in Figure 11. These images represent the constituent parts of the maps at the top of Figure 10. They show that 25 of 26 participants which annotated this pair of cartridge cases marked the aperture shear as geometrically similar. Approximately half the participants marked regions of the breech-face impression. Because the participants were not asked to indicate all regions of similarity, it is unclear whether examiners did not recognize the similarity on the breech-face impression, whether they considered them similar but subclass, or whether they limited their marks to the aperture shear simply because the shear was sufficient for an identification conclusion. Possible wording changes to address this are proposed below.

- CCTS Test Set 2: Fifty-six participants completed CCTS2 as part of the virtual microscopy study. One firearm (Ruger P95DC 9 mm; PMC ammunition) was used to test fire the three cartridge cases of Item 1 and the individual test fires of

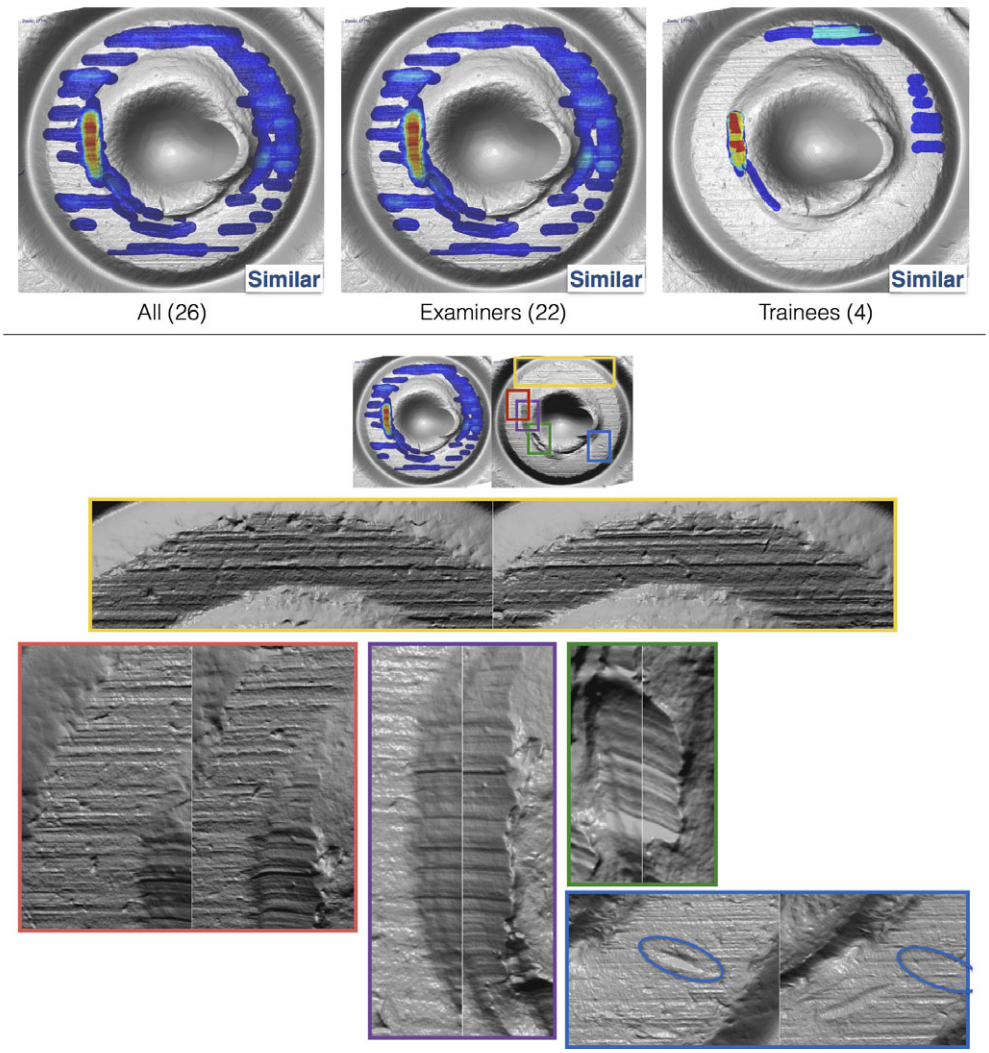

FIG. 10—*Annotation image map (CCTS1: Item 1-1 as compared to Item 2-1) (match): (top) combined similarity maps are shown for Cartridge Case Item 1-1 as compared to Item 2-1. (bottom) Close-ups of the various regions annotated in the comparison. Colored boxes on the cartridge case correspond to similarly 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. Some participants may not have marked the strong horizontal breech-face impression lines out of concern that they may be subclass. 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 cartridge case (blue oval). See caption of Figure 9 for additional detail on these plots. [Color figure can be viewed at wileyonlinelibrary.com]*

FIG. 11—*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 Figure 10 are the combination of the individual maps in this figure. [Color figure can be viewed at wileyonlinelibrary.com]*

Items 3 and 5. A second firearm (Ruger P85 MK II 9 mm; PMC ammunition) was used to fire the cartridge cases of Items 2 and 4. The results for all participants are shown in Tables 4 and 5. 100% of examiners made all correct identifications. 0% of examiners made false identifications. 100% of examiners correctly marked elimination (or inconclusive) for the nonmatch. Note that 13% of participating examiners are not allowed to eliminate on individual characteristics (therefore, for the purpose of this study, their markings of inconclusive are valid). Overall, no errors were made by any trained examiner. Among the trainees, one trainee made false identifications between Item 1 and 2 and Item 1 and 4. One trainee missed making an identification between Items 1 and 3 and marked the comparison inconclusive (an annotation map was not provided).

Annotation maps are shown in Figures 12–15. Figure 12 shows that most individuals used aperture shear to make the identifications. Close-ups of the surfaces appear in Figure 12 (bottom). The regions include two areas of breech-face impression similarity that were marked by most participants. Examination of each participant's annotations when comparing Items 1 and 3 (a match) is shown in Figure 13. These images represent the constituent parts of the maps at the top of Figure 12. They show that nine of fifteen participants which annotated this pair of cartridge cases marked the aperture shear as being similar; twelve individuals marked the 10 o'clock breech-face impression marks as similar (The clock positions refer to the position as oriented in Figures 12–14 where the firing pin drag is positioned to the right.). Approximately half of the participants indicated breech-face impression similarity at the 5 o'clock position.

Items 1 and 2 are from different firearms. The annotation maps for these items are shown in Figure 14. The difference maps show that inconsistencies in aperture shear and breech-face impression detail (located at 5 o'clock and 10 o'clock) were the most frequently annotated differences. The 5 and 10 o'clock breech-face impression patches are the same regions identified as similarities in identifications to Item 1 (Fig. 12 top). Therefore,

TABLE 4—*CCTS2 individual responses.*

PCode	Item 2	Item 3	Item 4	Item 5	PCode	Item 2	Item 3	Item 4	Item 5
2A692	No	Yes	No	Yes	**K4QFH**	No	Yes	No	Yes
2NCV4	No	Yes	No	Yes	***KLV8F**	Inc	Yes	Inc	Yes
38JLN	No	Yes	No	Yes	**KVDEG**	No	Yes	No	Yes
3R5RK	No	Yes	No	Yes	**L27CR**	Inc	Yes	Inc	Yes
***4X99B**	No	Yes	No	Yes	***L8K3R**	Yes	Yes	Yes	Yes
5CY6N	Inc	Yes	Inc	Yes	***M3S8F**	Inc	Yes	Inc	Yes
***5RSCS**	Inc	Yes	Inc	Yes	**N4VH2**	No	Yes	No	Yes
***6YNZV**	Inc	Yes	Inc	Yes	**P3CK6**	No	Yes	No	Yes
7LP7H	No	Yes	No	Yes	**QDG65**	No	Yes	No	Yes
7UVY4	No	Yes	No	Yes	**QETKB**	No	Yes	No	Yes
7VKHK	Inc	Yes	Inc	Yes	**RCRE7**	No	Yes	No	Yes
9AGVK	No	Yes	No	Yes	**REX7C**	No	Yes	No	Yes
9ZJHW	No	Yes	No	Yes	**REXBV**	No	Yes	No	Yes
AGMWE	No	Yes	No	Yes	**RGMRM**	No	Yes	No	Yes
APJTM	No	Yes	No	Yes	**SCSD8**	No	Yes	No	Yes
BUTM9	No	Yes	No	Yes	**SFFDU**	No	Yes	No	Yes
BWCFS	No	Yes	No	Yes	**SPZES**	No	Yes	No	Yes
***BZKDL**	Inc	Yes	Inc	Yes	**TTJ8U**	No	Yes	No	Yes
C7N89	No	Yes	No	Yes	***UA62Y**	Inc	Yes	Inc	Yes
CLHT6	No	Yes	No	Yes	**UCNA6**	No	Yes	No	Yes
D4RPD	Inc	Yes	Inc	Yes	**UKWHL**	No	Yes	No	Yes
DAB22	No	Yes	No	Yes	**UZJYL**	No	Yes	No	Yes
DPC33	No	Yes	No	Yes	***VBU8D**	No	Inc	Inc	Yes
DR53Q	No	Yes	No	Yes	***VGQ3T**	No	Yes	No	Yes
E5C74	No	Yes	No	Yes	**WA5FB**	No	Yes	No	Yes
F9FFQ	No	Yes	No	Yes	**WPSC4**	No	Yes	No	Yes
FZ9HM	Inc	Yes	Inc	Yes	**XLV73**	Inc	Yes	Inc	Yes
HVQDZ	No	Yes	No	Yes	**XMR27**	No	Yes	No	Yes

"Were any of the questioned expended cartridge cases (Items 2–5) discharged from the same firearm as the known expended cartridge cases (Item 1)?"
Starred participants indicate trainees. Inconclusive results are shown in light gray, Incorrect identifications are shown in dark gray.
PCode: participant code. Inc: inconclusive.
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 Items 1 and 3 and listed the comparison as inconclusive.
Overall, two mistakes (of forty conclusions) were made by trainees (see Table 5 and annotation details in Figs 12–15).

TABLE 5—*CCTS2 match statistics.*

	Item 2	Item 3	Item 4	Item 5
Examiners				
Yes (ID)	0 (0%)	46 (100%)	0 (0%)	46 (100%)
No (Elimination)	40 (87%)	0 (0%)	40 (87%)	0 (0%)
Inconclusive	6 (13%)	0 (0%)	6 (13%)	0 (0%)
Trainees				
Yes (ID)	1 (10%)	9 (90%)	1 (10%)	10 (100%)
No (Elimination)	3 (30%)	0 (0%)	2 (20%)	0 (0%)
Inconclusive	6 (60%)	1 (10%)	7 (70%)	0 (0%)
All				
Yes (ID)	1 (1.8%)	55 (98%)	1 (1.8%)	56 (100%)
No (Elimination)	43 (77%)	0 (0%)	42 (75%)	0 (0%)
Inconclusive	12 (21%)	1 (1.8%)	13 (23%)	0 (0%)

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).

one can conclude that these regions were used to make correct identifications and eliminations to Item 1. While one examiner marked a small similar region at 8 o'clock, they still correctly marked the pair as an elimination.

The availability of the annotation maps allows investigation into the false identifications made by trainee L8K3R (Fig. 15). Unfortunately, very little similarity is indicated in these maps and it is difficult to infer the reason that a false identification was made. A "best" alignment between the aperture shears of Items 1 and 2 is shown in Figure 15 (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 their examination process and where the student's reasoning went awry.

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.

- Workshop Test Set: The Workshop test set was used during the AFTE workshop and was not part of the formal study. Eleven completed data sheets were returned. Of these, 100% made the correct conclusions with the exception of two laboratories that do not allow elimination on individual marks. These two laboratories marked the actual elimination as an inconclusive.

Conclusions and Future Work

To our knowledge, this work represents the largest study on the feasibility of virtual microscopy for firearm forensics conducted to date. Utilizing the technique of virtual microscopy, more than fifty participants successfully completed two proficiency-style tests. Trained examiners achieved performance similar to what would be expected using traditional light microscopy. That is, there were no errors, all identifications were made, and, where laboratory policy allowed, participants eliminated all known nonmatches. Inconclusive results were only obtained from trained examiners when their laboratory policy disallowed exclusion based on individual marks.

Annotation maps which indicated the regions of similarity and difference recognized by participants can provide valuable insights into the examiner's decision-making process. Future studies will clarify the annotation instructions and specify which

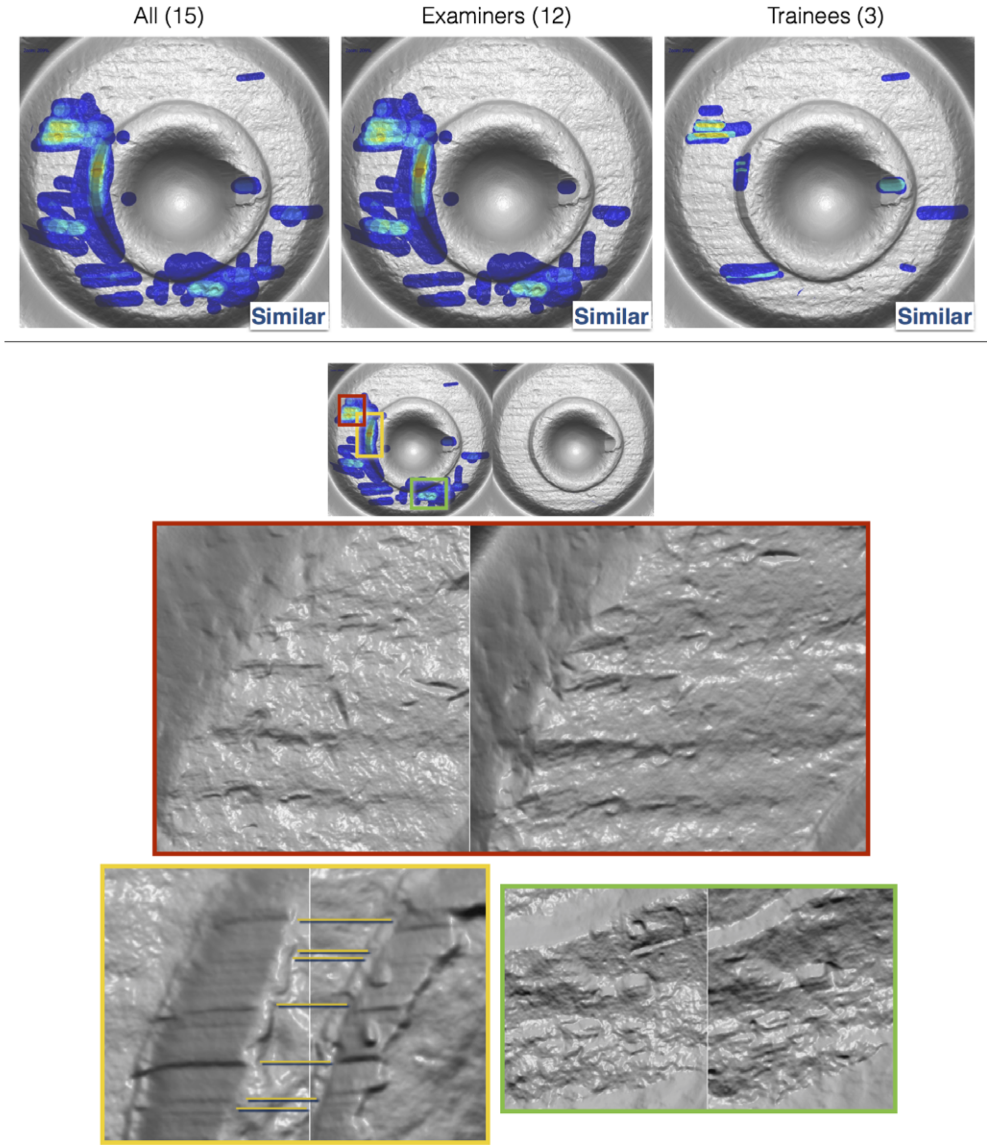

FIG. 12—*Annotation image map (CCTS2: Item 1-2 as compared to item 3-1) (match): (top) combined similarity maps are shown for Cartridge Case Item 1-2 as compared to Item 3-1. Items 1-2 and 3-1 were fired through the same firearm. Therefore, we expect regions of similarity in the image map. No areas of dissimilarity were reported by any participant (not shown). (bottom) Close-ups of the three most frequently marked regions of similarity. Colored boxes on the cartridge case correspond to similarly colored zoom boxes. Although the aperture shear does not reproduce well in the printed images, the similarity is clearly visible within the software. [Color figure can be viewed at wileyonlinelibrary.com]*

pairs of topographies should be annotated. Care must be taken as to not lead the participant. For example, it would not be a good idea to ask the participants to annotate only the comparison of Item 2–4 and Item 1–3 as it might indicate that these pairs identify or eliminate. The next time we run a standard proficiency-style examination, we will ask all participants to annotate the comparisons of Item 1-1 to each questioned item (e.g., Items 2, 3, 4, and 5) and to indicate all individual marks used to reach their conclusion.

The developed virtual microscopy platform can be extended to different study designs. For example, we are now designing independent sample tests in a manner similar to (20–22). Each independent sample set contains only 2–4 test fires. Each participant will be asked to compare all samples within a set. This independent sample test set design appears to be favored by landscape reports such as PCAST (23).

Almost all participants in the described study utilized identical 15″ laptop computers. We are optimistic that this restriction is not necessary. Requiring that a single laptop type be used complicates administration of the study and restricts participants to visualization on a display smaller than a typical desktop monitor. Our experience with 3D topographic analysis tells us that visualization is typically better on a larger format display. Therefore, future studies will simply specify minimum graphics requirements (e.g., resolution) and screen size.

Although virtual microscopy provides several advantages over traditional light microscopy, it also has some limitations. The largest limitation is that comparison is restricted to the surfaces that were captured during scan acquisition. For example, it is uncommon to topographically measure chamber marks. Should an examiner desire to examine chamber marks they will likely need to go back to the original specimen. Therefore, it goes without saying that laboratories should not discard cartridge cases once a scan has been acquired.

The study described in this document demonstrates that virtual microscopy can be used by examiners as a substitute for

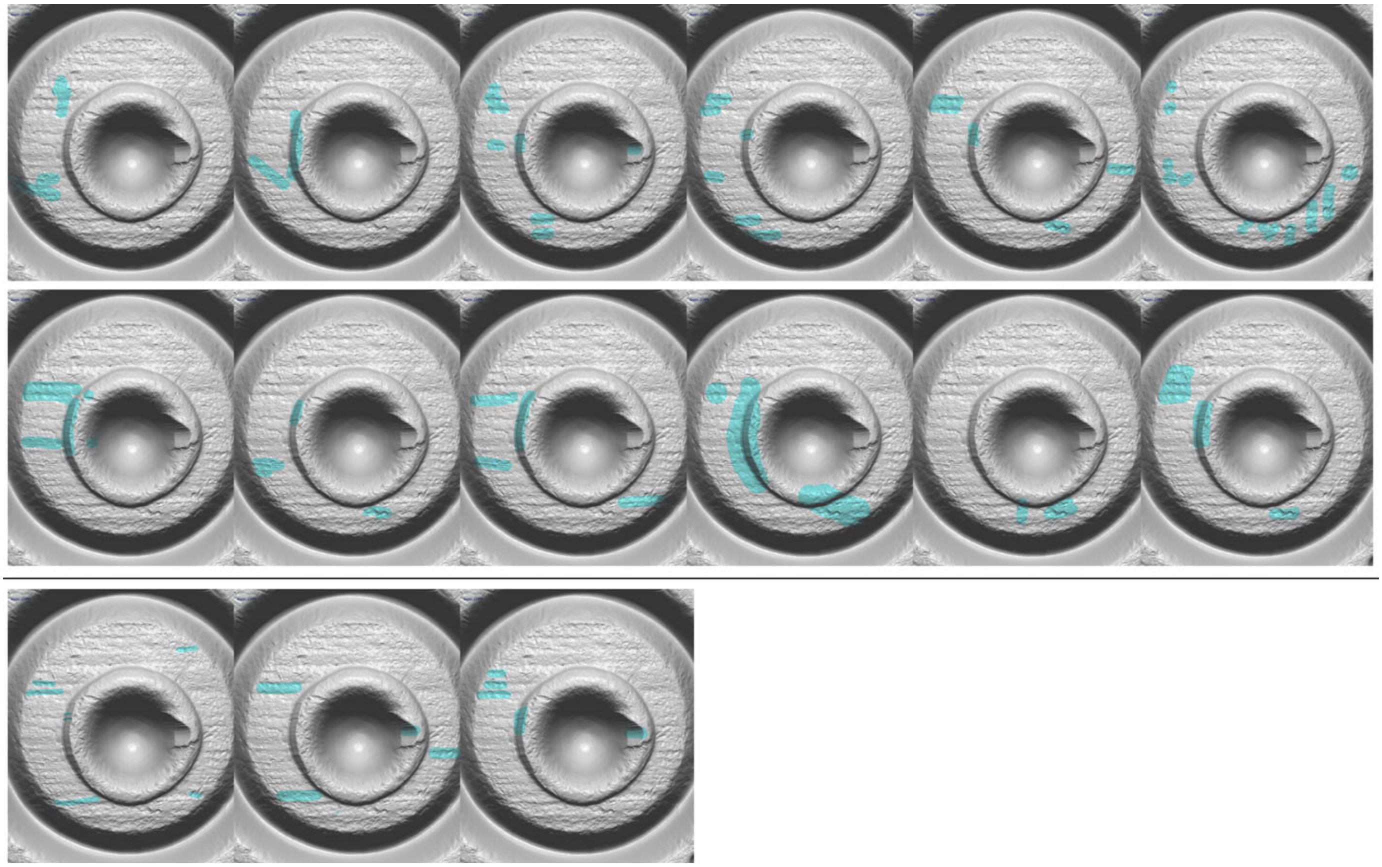

FIG. 13—*Annotation image map (CCTS2: Item 1-2 as compared to Item 3-1): (match) individual similarity maps for trained examiners (above line) and trainees (below line). Because only one participant is shown in each map, a single color is used. The images on the top row of Figure 12 are the combination of the individual maps in this figure. [Color figure can be viewed at wileyonlinelibrary.com]*

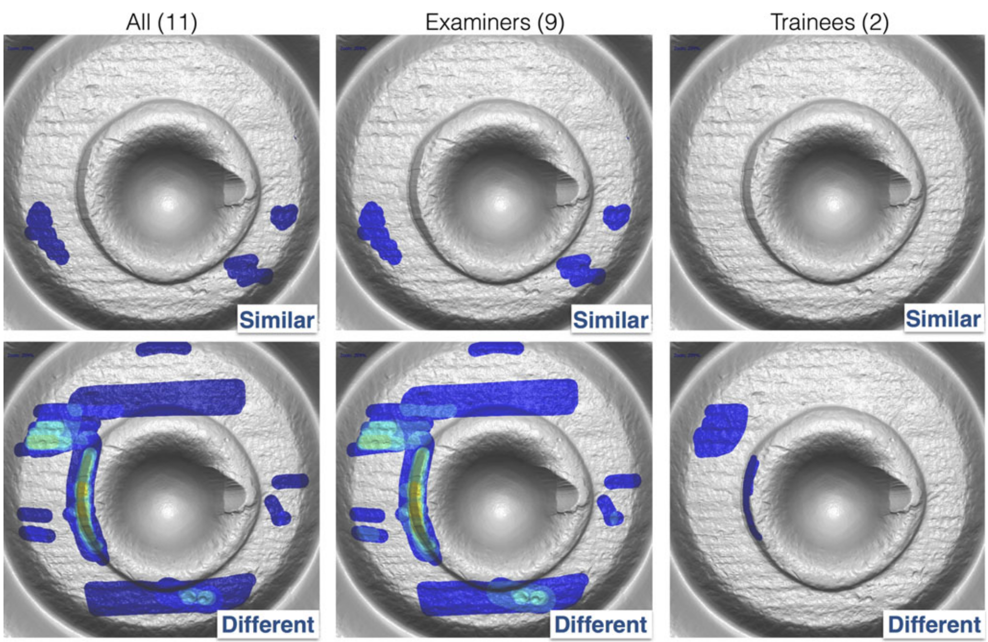

FIG. 14—*Annotation image map (CCTS2: Item 1-2 as compared to item 2-1): combined. (NonMatch) Items 1-2 and 2-1 were fired through different firearms. Therefore, we expect regions of difference in the image map. The maps show that the aperture shear was used to identify the differences between the two cartridge cases. One participant indicated three small patches of breech-face impression similarity. [Color figure can be viewed at wileyonlinelibrary.com]*

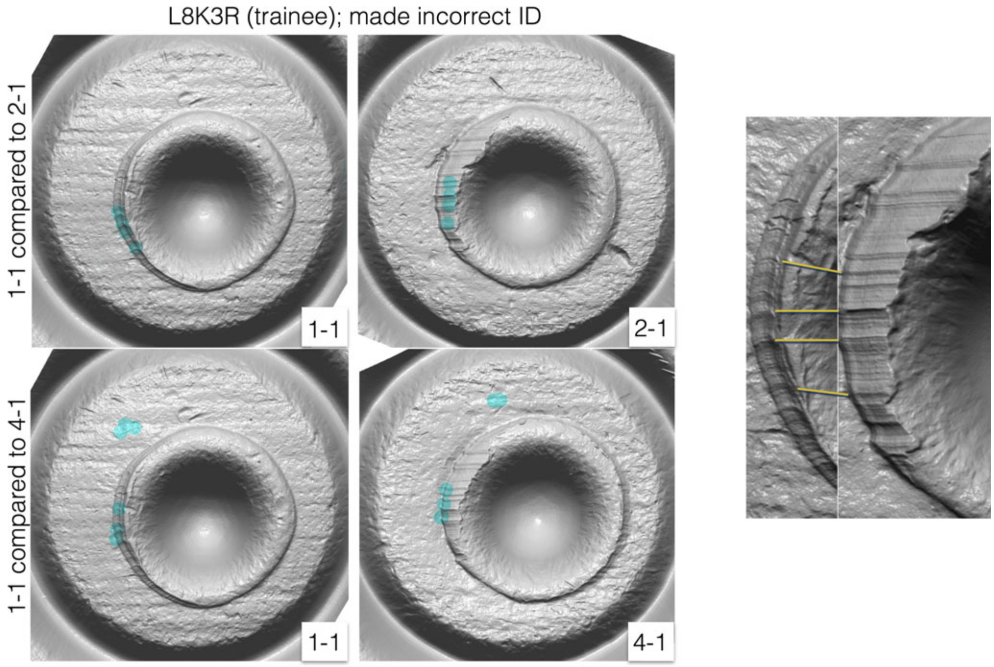

FIG. 15—*False identification by trainee L8K3R (CCTS2): similarity annotation image maps are shown for the pairs Items 1-1 and 2-1 (top) and Items 1-1 and 4-1 (bottom). Unfortunately, very little annotated similarity is indicated in these maps and thus it is difficult to infer the reason a false identification was made. A "best" alignment between the aperture shears of Items 1 and 2 is shown on the right (yellow lines added). The shears are quite different. [Color figure can be viewed at wileyonlinelibrary.com]*

traditional comparison microscopy. The results show that similarity in both striated and impressed marks on the breech-face impression and aperture shear could be identified. Participants noted that the visualization tools are easy to learn and that the annotation mode provides valuable insights into the decision process. The results support the idea that virtual microscopy can be a viable substitute for traditional comparison light microscopy.

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Conflict of Interest Statement

The TopMatch system and Virtual Microscopy Viewer software described in this manuscript are projects of Cadre Research Labs. Authors Brubaker, Duez, Lilien, and Weller are supported in part by Cadre Research Labs.

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Supporting Information

Additional Supporting Information may be found in the online version of this article:

Appendix S1. Virtual microscopy test set details.