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Virtual Comparison Microscopy Revolutionizing Firearms Identification: A Review of Methods, Validity, and Admissibility

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ABSTRACT: Virtual comparison microscopy (VCM) affords firearms identification beneficial techniques and tools that the more traditional method of light comparison microscopy (LCM) does not offer. This new imaging method allows for the fast generation of 3-dimensional images that can be used for the examination of surface topography with a resolution unprecedented in firearms identification. Whether through coherence scanning interferometry or photometric stereomicroscopy, VCM is hitting its stride in a new age of firearms examination. While several validation studies indicate that VCM has a lower inconclusive rate and a lower error rate than LCM, a precedent has been set for the admissibility of VCM at trial. Having cleared all validity, admissibility, and standards hurdles, VCM is now poised to revolutionize the process of firearms identification.

KEYWORDS: 3D, acceptance, firearms identification, reliability, VCM, virtual comparison microscopy.

INTRODUCTION: FIREARMS IDENTIFICATION AS A SCIENCE

Firearms identification is an empirical science concerned with the examination and comparison of bullets and cartridge cases [27,38]. The main purpose of this discipline is to determine if a link is present between a suspect firearm and evidence items from the scene of a crime or from an autopsy. This is possible due to microscopic burrs and imperfections in the firearm created randomly during manufacturing. When a firearm is made, the various cutting and shaping processes leave behind imperfections in the metal that mark the bullet and cartridge case when they come into contact with the firearm surfaces [6,27]. Because the firearm is a fixed tool, subsequent firings involve contact with these imperfections, resulting in striations, or scratch marks, in the same relative location. The firearms examiner thus compares these striations using a comparison microscope in search of agreement of said striations, or the lack thereof. If there is such agreement between known samples and evidence samples, then a result of identification is founded. Likewise, if there is sufficient disagreement of these striations, then elimination is warranted. The third valid result possible is that of inconclusive. Similar to other disciplines, this simply means that the information available was insufficient to reach a determination.

The foundation of firearms identification is the principle of the built-up edge (BUE) [6,27]. The BUE refers to the microscopic layer of metal that builds up on the cutting surface of a tool as it machines certain firearms components, whether the barrel or slide (**Figure 1**). This BUE of metal will build until it reaches its carrying capacity and breaks off at random intervals, leaving the burrs and imperfections discussed previously. The BUE is to firearms identification what the short tandem repeat (STR) is to DNA.

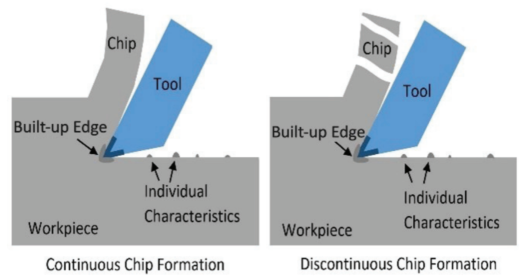

Figure 1. How BUE creates individual characteristics during machining, with continuous chip formation (left) and discontinuous chip formation (right). (Reproduced with permission from *AFTE J* 56:197; 2024 [6].)

The cutting tool itself also contributes to the individuality of the marks left on a firearm. As the cutting tool wears from use, its surface will change, altering the marks that it leaves on the firearm surfaces. Damage to the cutting tool may become apparent. Any imperfections in the cutting surface will correspond to a mark on the firearm (**Figure 2**). For instance, the reaming blade used to form the barrel will leave marks on the surface of the lands, or raised portions, of the rifling in the barrel, which comes into direct contact with the bullets as they travel down the barrel. Any damage or wear to the reaming tool will leave concentric rings in the barrel that will in turn scratch the surface of a bullet (**Figure 3**).

History of Firearms Identification

The earliest known example of the use of firearms identification in a case dates back to 1835. Henry Goddard, an early detective in London, observed an imperfection in a bullet, which he was able to identify back to the bullet mold in which it was made. Much later, in 1912, Professor V. Balthazard of France was the first to photograph the sur-

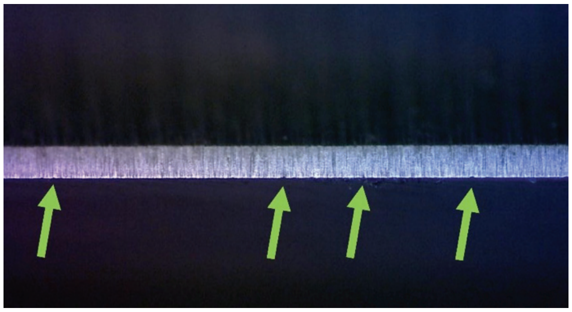

Figure 2. Cutting surface of a reaming blade with imperfections and wear damage (indicated by green arrows) at 200× total magnification. (Reproduced with permission from *AFTE J* 56:197; 2024 [6].)

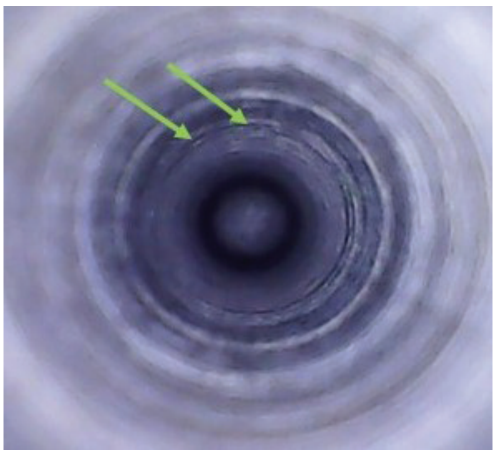

Figure 3. Bore scope image of the barrel blank after the reaming operation but before rifling. Concentric rings can be seen along the inside of the barrel (indicated by green arrows), created as the reaming tool with surface imperfections (seen in Figure 2) removed metal. (Reproduced with permission from *AFTE J* 56:197; 2024 [6].)

faces of bullets and cartridge cases for comparison [27,38]. Balthazard would enlarge the photographs and compare the surface contours of two bullets or two cartridge cases to determine the firearm from which they originated. This first crude comparison in the absence of instrumentation was the starting point of modern firearms identification. By 1925, Calvin Goddard and Philip Gravelle had refined a microscope first used in the fabric industry into the first comparison microscope for firearms comparisons [27,38]. With the advent of the comparison microscope, modern firearms identification as we know it today was born. The comparison microscope consists essentially of two light microscopes, each with its own stage and objectives, connected by an optical bridge so that two objects can be compared side by side under one eye piece. The technology used would remain largely unchanged for almost a century until the development of 3-dimensional surface topography technology, which has recently begun to play ~~the~~ central role in firearms identification.

I. EARLY COMPARISON METHODS

A. Photograph Comparison

Before the advent of the comparison microscope in 1925, the only way to compare two fired bullets or cartridge cases was to photograph the surface of the aforementioned evidence under rudimentary magnification. The firearms examiner would then hold photographs of test-fired bullets or cartridge cases up to the photographs of evidence bullets and cartridge cases for comparison. This indirect comparison method fell into disfavor in the firearms identification community with the advent of the comparison microscope. This sentiment would last for almost a century, until the emergence of virtual comparison microscopy [27,38].

B. Helixometer

The helixometer, invented by Calvin Goddard and John Fisher in 1925, was the first instrument of many to be developed to assist firearms examiners. The helixometer is similar to a bore scope in that it shines a light source through a prism and lens to allow for the examination of the rifling of a firearm barrel, specifically the rate and direction of twist and the number of lands and grooves. This device also allows the examiner to evaluate how the barrel was manufactured. Goddard used the helixometer in his landmark reexamination of the Sacco and Vanzetti case in 1925 [38].

C. Striagraph

The striagraph, invented by John Davis in 1958, was the first 3D instrument for firearms examination use [37]. It operated by mapping the surface topography of the rifling of a firearm and identifying the microscopic characteristics that constitute evidence of the firearms that fired them. Davis described the striagraph as “a measuring, tracing, and recording device suited to the analysis of micro surface-contours, that is, to the detection of microscopic irregularities in surface smoothness” [18]. It can thus be considered the forerunner of 3-dimensional comparison technology.

This instrument used a diamond point tracer needle that was placed in contact with the surface of the rifling, similar to the stylus of a record player. This needle was attached to a “wiggler mirror,” which focused a light source through a slit onto a piece of photosensitive paper on a cylindrical drum. As the barrel rotated around the tracing needle, the stylus would move in response to variations in the microscopic surface contours, causing the wiggler mirror to move with it, changing the position of the focal point of the light on the photosensitive paper. As the drum holding the photosensitive paper also rotated, the surface topography of the barrel would be recorded on the paper. Davis was thereby able to achieve surface contour "scans" of bullets using the striagraph [18,38]. The striagraph was based on the profilograph, which was invented in 1936 for the examination of machined surfaces in industrial settings. The profilograph never took off, with the existence of only four recorded. Similarly, the striagraph never took hold in the firearms identification community.

II. MODERN COMPARISON METHODS

A. Light Comparison Microscopy (LCM)

Before entering upon a discussion of the steps followed in studying our fatal and test bullets together upon the comparison microscope, some remarks upon the construction of that instrument and principles on which it operates, are in order. – Col. Calvin H. Goddard [25]

As noted above, a comparison microscope consists of two independent light microscopes, each with an independent stage, objective(s), and light source, connected by an optical bridge. This design allows the examiner to view two independent sample images at the same time through a common ocular (**Figure 4**), a method known as light comparison microscopy (2D LCM).

In general, the comparison microscope has both a coarse and a fine focus (Z-axis), as well as means of adjusting the stages along both the X- and Y-axes for individual sample positioning, allowing the examiner to orient both samples in the field of view so that they are aligned for direct visual comparison of the similar (in-phase) regions of the two samples.

Magnification in the modern comparison microscope is typically achieved through the use of a zoom-based optical system or a compound objective optical system, with the number of magnification setpoints and range of magnification dependent upon the manufacturer's design and configuration; the primary magnification for most examinations falls in the 10×–80× magnification range. While magnifications of greater than 200× are possible, they are generally not useful for direct two-dimensional comparisons.

Modern comparison microscopes generally include a digital instrumentation camera to acquire images of the samples being compared, normally mounted either on the top of an ocular or on a camera port associated with the optical bridge. These cameras are used to capture 2D

Figure 4. Comparison microscope from Leeds Forensic Systems. (Reproduced with permission of Leeds Forensic Systems: Minneapolis, MN.)

images that are representative of sample regions being viewed by the examiner for documentation purposes.

Since Goddard's introduction of his version of the comparison microscope in 1925, the comparison microscope has been the workhorse for the firearms laboratory for nearly a century. Yet despite being a key tool in the process of examination, the major drawback of the comparison microscope is the time required to analyze a case. Modern enhancements of the comparison microscope have improved the image quality, speed, and accuracy of examinations; however, sample processing has not been able to keep up with backlogs and delays. After all, a highly trained examiner must compare each item of evidence individually, which is a time-consuming process.

B. 2D Imaging

The need for faster results led to the creation of the National Integrated Ballistic Information Network (NIBIN) in 1997 by the ATF, which employs the Ultra Forensic Technology BrassTrax and BulletTrax imaging systems to collect 2D images of cartridge cases and bullets, respectively. BulletTrax has difficulties scanning damaged or fragmented bullets, with damage being very common to fired bullets. Although still in use today, the BulletTrax system has been largely superseded by the BrassTrax system, as it is a better database with faster scanning throughput. These systems were created to speed up comparisons and to generate a database with which to tie shooting scenes together. BrassTrax takes monochrome images of the surface of a fired cartridge case and compares the 256 shades of grey cell by cell throughout the surface of the primer area of the cartridge case. If enough cells have the same shade of grey in the same relative orientation, a potential association will result, subject to each agency's official threshold. As the NIBIN database is searched everyday between new and older entries, it is much quicker than the comparison microscope; however, it is not without its disadvantages, for the potential associations still require confirmation by a firearms examiner, typically via comparison microscopy. To resolve this presumptive testing issue, the ATF created the National Correlation Center located in Huntsville, Alabama, USA, to confirm potential associations. However, these comparisons are indirect and consist of going back to comparison via photograph but in a remote manner.

Another example of 2D imaging is the Ballistics IQ system by Evidence IQ, which is marketed as a triage system to streamline entry into NIBIN. This system is similar to that of BrassTrax in that it provides a rank order of the similarity of surface contours in 2D images, and it has the same drawbacks as NIBIN. Its results are not accepted in trial and must be confirmed by a firearms examiner through direct comparison of the evidence items.

III. VIRTUAL COMPARISON MICROSCOPY

Virtual comparison microscopy (3D VCM) is an area of metrology in which 3-dimensional models are generated through various imaging techniques [2,4,5,9,13,19,23,37,45,46,49] discussed below that all incorporate a light source to capture images digitally. These digital images are then processed by software to stitch or generate a 3D image of the surface topography of a sample. This is of particular interest to the firearms identification community because it allows for the remote examination of fired bullets and cartridge cases and offers better resolution and contour discrimination [29,42,43]. With these VCM methods, reflective surfaces like primers no longer present major issues. These virtual methods also allow a sample database to be constructed in which surface contours may be searched and their similarity statistically compared [8,10,12,14,15,16,17,24,41]. This allows examiners to determine a similarity score for two items of evidence for a weight of evidence analysis [20,31,47,51,52]. Several 3D VCM systems calculate a numerical similarity score between two surface characteristics of samples that is a function of the special relationship of the sample's features (striated or impressed marks and spatial orientation of said marks). This is known as the cross-correlation function (CCF_{max}). The closer the CCF value is to 0, the less similar two samples are, while the closer it is to 1, the more similar the two samples are. However, each VCM system manufacturer uses the CCF with differing statistical models to achieve separation of same source and different source samples. For instance, Evofinder uses the Pearson Correlation Coefficient for a Gaussian curve; meaning the CCF calculated by the system is the number reported. This leads to a CCF of 0.100, although close to 0, may in fact be an identification when comparing two Glock polygonal rifled bullets, which do not mark well. Whereas, a Beretta CCF of 0.600 may be an indication of different source samples and a CCF of 0.998 may be more indicative of an identification for that specific firearms system. Simply put, the CCF for the Evofinder is isolated to the firearm make as far as what constitutes same or different source. A good rule of thumb is if two test-fired samples (knowns) have a similarity score of say 0.400 and a questioned sample is 0.398 to one of those knowns then a conclusion of identification may be warranted. Conversely, Cadre's VCM system calculates the CCF and then applies a calculation to bring the value closer to the poles (0 or 1) to establish greater separation of same and different source samples. All that to say, each VCM manufacturer uses different algorithms to calculate and interpret the CCF similarity score. It is important to note that a threshold like that for the NIBIN 2D system, which is determined by the individual laboratories, will need to be established by each laboratory that is implementing their own 3D VCM system. At present, most 3D VCM systems will provide a rank order list of samples by similarity score; however, a trained examiner would have to compare each sample, either by VCM or LCM, in order to report whether they have the same or different origins.

A. Confocal

The confocal microscope scans the surface of an object with a laser and images the surface through the laser light reflected onto a detector. To prevent blurry images, the laser light travels through a pin hole just before the detector **(Figure 5)**, eliminating the light rays outside the focal plane. As the laser scans the surface of an object, the software builds a Z stack of images recording the topography in the Z plane [28,39]. Sensofar, which utilizes aspects of focus variation and interferometry, is the leading confocal system used in the firearms laboratory.

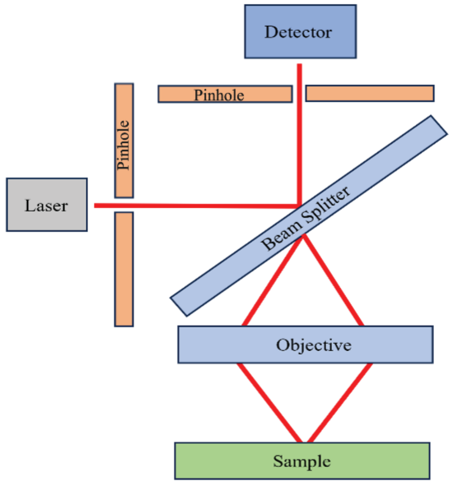

Figure 5. Schematic of confocal microscopy.

B. Focus Variation

Focus variation uses the sharpness of an image to determine a sample's height. An upper plane and lower plane are selected, followed by exposure to a light source and digital imaging. The objective, which has a narrow depth of field, scans the surface of the sample and records areas that are in optimal focus, from which a Z stack of images is generated that brings all depths of field into focus at once. This yields a 3D model of the surface topography of the sample [39]. One system that uses this technology in the firearms identification field is Alicona.

C. Interferometry

Much like confocal microscopy, interferometry involves measuring a sample's reflectivity from spatially coherent light bounced off its surface. The light reflected from the sample is compared to that of a reference mirror in monochrome to build a map of the sample's surface topography. What this method measures are the difference in light intensity as a function of distance (Δd) and the relative height (Δh) between the sample and the reference mirror. These wavelength scans can be mapped on a contour map to show surface topography with the X- and Y-axes being intensity and distance, respectively, and the Z axis relative height. This is also known as Michelson interferometry or coherence scanning interferometry (CSI) [39].

Alternatively, as the light wave interference moves across the peaks and valleys of a surface, shifts in the interference indicate measurable differences in height. This is similar to the shift in the image of an object placed in a glass of water relative to the open air, which is a special case of what is called fringe displacement. This method is known as phase-shifting interferometric microscopy (PSI microscopy) [39].

Michelson interferometry is limited by the objective magnification, specifically the aperture size. This can be overcome with a Mirau objective, which gives greater resolution in the X-Y plane [39]. This is akin to the attenuated total reflectance (ATR) used in Fourier transform infrared spectroscopy (FTIR).

D. Photometric Stereomicroscopy

Photometric stereomicroscopy is a measurement method by which light sources, generally red LED, around the sample illuminate the sample surface from different incident angles. As the light source moves around the sample, images are taken and stitched together by software to build the 3D surface geometry by a method known as photogrammetry (**Figure 6**) [20,33,34,39,44]. Examples of technology employing this method are the Evofinder system by Leeds Forensic Systems Scannbi Technologies, the Top-Match system by Cadre Forensics using Gelsight technology, and the Ultra Forensics Quantum 3D Microscope (Q3M). Photometric stereomicroscopy is currently the method of choice in crime laboratories across the United States.

IV. VALIDATION STUDIES

A. Error Rates

A tremendous amount of research has been conducted in the field of firearms identification on both the LCM and VCM methods. A vitally important factor for evaluating a new method is its potential error rate, which is typically expressed as the numbers of false positives (FP) and false negatives (FN). The spotlight is generally placed on the number of false positives because of the severity of this type I error. In particular, a type I error in the forensic

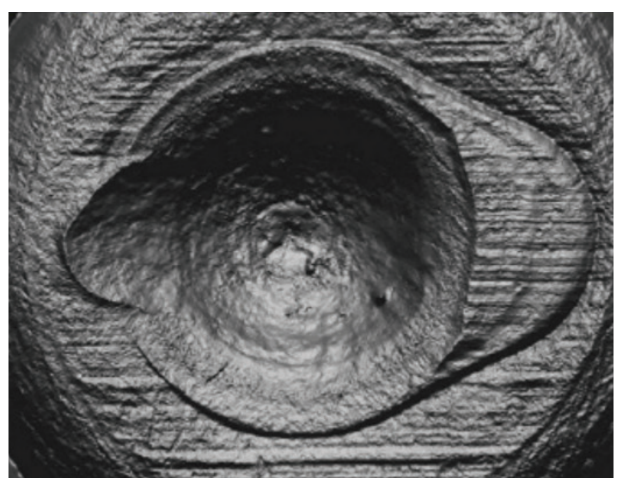

Figure 6. Firing pin 3D image generated using photometric stereomicroscopy with photogrammetry on the Leeds Forensic Systems Evofinder instrument. (Reproduced with permission of Leeds Forensic Systems: Minneapolis, MN.)

disciplines means that an innocent person will go to prison. The number of false positives in traditional LCM validation studies is generally below 1% [3,6,22,32,36]. In comparison, VCM has a false positive rate less than 0.3% (**Table 1**). Similarly, the average inconclusive rate for LCM is roughly 40%, versus less than 0.5% for VCM (**Table 1**) [11,21,26,30,34,35,40,48,50]. This figure is for a variety of study designs conducting head-to-head comparisons of traditional comparison microscopy and VCM, where the ground truth included known non-match as well as known match samples; VCM exhibited less inconclusive results and ~~less~~ error [30]. Additionally, 3D microscope manufacturers have begun adding built-in error rate likelihood ratios. For example, the Ultra Forensics Q3M calculates the false match rate (FMR) of each comparison.

Table 1. V CM validation study results

		False positive		**False negative**		**Inconclusive**		**Error**	
Author	**Year**	**Population**	***n***	**%**	***n***	**%**	***n***	**%**	**(%)**
Duez [21]	2018	535	2	0.370	0	0	26	4.860	0.374
Ott [39]	2017	2,701	0	0	12	0.440	0	0	0.444
Song [47]	2018	5,245	9	0.170	2	0.038	0	0	0.210
Chapnick [11]	2020	1,184	3	0.430	0	0	354	29.899	0.253
Knowles [29]	2021	520	0	0	2	0.390	129	24.808	0.385
Weller [49]	2015	121,840	3	0.002	0	0	0	0	0.002
Lilien [33]	2020	1,232	3	0.250	0	0	507	41.153	0.244
Mattijssen [34]	2020	79,800	1,012	1.270	2	0.002	0	0	1.271
Hare [25]	2017	3,773	2	0.053	20	0.530	0	0	0.583
Total		**216,830**	**1034**	**0.283**	**38**	**0.156**	**1016**	**0.469**	**0.494**

V. STANDARDS

A. Consensus Bodies

There are several standards consensus bodies attempting to creating published standards on best practices in firearms identification. The main consensus bodies are the American Academy of Forensic Sciences Academy Standards Board (AAFS-ASB) and the Organization of Scientific Area Committees (OSAC) at the National Institute of Standards and Technology (NIST). The Association of Firearm and Tool Mark Examiners (AFTE) has been instrumental in the creation and implementation of standards but is not itself a standards consensus body [39].

B. VCM Standards

As virtual methods are relatively new, published standards trail the state of the field. Standards currently published for VCM primarily concern its validation and implementation (**Table 2**) [39]. Key requirements for the implementation of 3D include a developmental validation, deployment validation, and ongoing performance checks, which are intended to demonstrate that the method is fit for purpose and reproducible. Individuals using the instrument must be trained, competency-tested, and proficiency-tested annually. Data collection and exchange must be conducted in XML 3D Profile (X3P), the standard file format for 3D imaging [39].

Table 2. Published ASB standards governing 3D

Standard	**Description**	**Key requirements**
ANSI/ASB 061	3D measurement systems and quality control	• Developmental validation • Deployment validation • Ongoing performance checks • Quality control failure protocol • Measurement traceability • Data exchange format
ANSI/ASB 062	Topography comparison software	• Data and format • Software • Software validation • User training • Statistical comparison models • Criteria for implementation
ANSI/ASB 063	Implementation of 3D	• Developmental validation • Deployment validation • Ongoing performance checks • Competency/proficiency testing

VI. ACCEPTANCE OF VCM METHODS AT TRIAL

With VCM just beginning to become prevalent in casework, examples of its admissibility at trial are as yet scant. However, in the first Daubert challenge to VCM's admissibility in United States v. Ronald Clayton Rhodes

& Lorenzo Laron Jones, Judge Michael McShane of the District of Oregon ruled that it was in fact admissible, having met the Federal Rules of Evidence 702 and the five prongs of Daubert [1]. This first challenge of VCM took place in January 2023 regarding work conducted at the FBI Laboratory. In August 2023, a second ruling granted post-conviction relief in State of Arizona v. Bryan Peter Foshay. In this case, VCM was used in the first analysis of the firearms evidence along with LCM [1].

SUMMARY

The impact of virtual comparison microscopy on the field of firearms identification is as great as that of the comparison microscope in 1925 [27]. This new metrology technique allows for the fast exchange of data between sites, can streamline examination to reduce backlogs, and through the use of similarity scores is starting to remove some of the subjectivity in firearms identification [20]. However, even with similarity scores, the final conclusion still requires a scientist's interpretation and opinion. Virtual comparison microscopy meets the five prongs of Daubert because: (a) it is generally accepted in the scientific community; (b) it has a potential error rate; (c) there are standards and controls; (d) it is testable and has proven to be reproducible; and (e) it has been subject to peer review both in scientific articles and by the validation of a second scientist. The general acceptance of VCM is evident in its current use in casework by the FBI and several state crime laboratories. The error rate of VCM has been tested and reproduced, showing false positive rates below 0.30% on average [11,21,26,30,34,35,40,48,50]. The ASB and OSAC have published standards for the validation, software, quality control, and implementation of VCM in casework [39]. Finally, there have been several studies of VCM published in peer-reviewed journals. VCM is thus well on its way to being the gold standard of firearms identification.

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