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Iranian Journal of Social Sciences and Humanities Research

UCT . J. Soc. Scien. Human. Resear. (UJSSHR)

Volume 5,Issue3

83-89 (2017)

ISSN 2382-9753

A Review of Forensic Analysis in Criminal Cases

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Original Article:

Received 25 July. 2017 Accepted 20 Aug. 2017 Published 17 Nov. 2017

ABSTRACT

The historical development, contributions and limitations of the two traditional approaches to trace evidence analysis are reviewed. The first approach was as generalist practitioner, looking broadly at an assemblage of many different particle types. The second was that of specialist practitioner, with attention focused on one specific particle type. Four factors have significantly impacted the effectiveness of these approaches: (1) increasing technological capabilities, (2) increasing complexity in the character of manufactured materials, (3) changes in forensic laboratory management, and (4) changing scientific and legal expectations. More recently, new technologies have been applied to some trace evidence problems, intended to address one or more limitations. This has led to a third approach founded on discrete, highly technical methods addressing specific analytical problems. Clearly new technologies have the potential to revolutionize forensic trace evidence, but just as clearly some of the traditional capabilities have been rendered ineffective, or lost entirely, by the way we have come to approach the problem. Having critically defined the current limitations of and the desired outcomes, the next focus should be consideration of alternative approaches that might achieve such a result.

Keywords

Trace evidence, Historical Development, Established Methods Specialization, New technologies

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Peer review under responsibility of **Iranian Journal of Social Sciences and Humanities Research**

Introduction

It is undisputable that forensic trace evidence analysis has undergone major changes since the times when analysis was confined to broadly trained general practitioners analyzing a wide range of traces using a light microscope. Some of these changes parallel those that have occurred generally within the forensic sciences, others reflect the impact of changing priorities, and others reflect the impact of new technologies.

A complex problem has emerged that is reflected in the diminishing use of trace evidence, reductions in funding and open debate regarding the viability of the discipline. This paper is offered as a critical review of the nature and causes of the problem, helping to define and understand objectives, but stopping short of considering possible alternative solutions. This is intentional. It is both confounding and confusing to hold the debate about a problem together with a debate about the solution; disagreements about one become interwoven with disagreements about the other. Solutions can be offered and debated based not on how they address a well-defined problem, but rather because those offering the solutions view the problem differently. It is our strongly held view that to compare different solutions we must start with a common problem and, as such, this work is intended to provide the foundation for constructive consideration of alternative solutions (or indeed, a more focused debate on the problem).

Forensic trace evidence analysis has traditionally been approached in one of two fundamentally different ways: as a generalist practitioner, looking broadly at an assemblage of many different particle types, or as a specialist practitioner, with attention focused on one specific particle type.

This paper begins with descriptions of these two traditional approaches, their historical development and an analysis of their respective contributions and limitations. Over time, the significance and impact of the limitations has evolved in response to increasing technological capabilities in the laboratory, increasing complexity in the character of manufactured materials, changes in laboratory management and changing expectations in the scientific and legal communities. The effectiveness of each approach is assessed as it currently exists within the context of these changes.

The more recent changes in technology have the potential to revolutionize trace evidence analysis. At the same time there has been an increased emphasis on scientific practices and standardization within forensic laboratories. These have had an impact on the traditional approaches and have led to a third approach, founded on component processes that employ new technologies. After evaluating the contributions and limitations of this third approach, we consider the different ways that technologies could be developed to address unmet needs in forensic trace evidence analysis. The route toward effective use of these new technologies is contrasted with the ways that forensic science laboratories are currently choosing and employing them. The conclusion is that although new technologies are contributing, we are not on a path that will result in their most effective and appropriate use. A new approach is required.

The paper concludes with a summary of the hallmarks of an effective trace evidence capability and delineation of some key elements that we expect to be included in new approaches that attempt to address current limitations.

Traditional approaches to forensic trace evidence analysis

Forensic scientists have long recognized the tremendous variety of particles that are ubiquitous in our environment. Hans Gross proclaimed that particle dusts are our ‘‘environment or surroundings in miniature’’ [1,2]. Edmond Locard echoed that they ‘‘may be formed of all the debris of all kinds of bodies. . . all the substances, organic or inorganic, existing on the earth’’ [3,4]. Heavily represented particle types on this list are minerals, plant and animal debris, microbes, industrial dusts, and fragments of manmade materials, but, as noted by De Forest [5] essentially anything can be encountered as crucial trace evidence in casework.

This tremendous variety of particles occurs on items collected as evidence: clothing, bodies, and weapons – on virtually any object and within virtually any product. The particular combination of particles in or on an item is the result of a history of exposures and contacts, modified by the dynamics of adhesion and loss. As Locard noted, the particles are ‘‘the mute witnesses, sure and faithful, of all our movements and all our encounters’’ [3]. Particles are present and ready for analysis, in almost all casework [6].

The large numbers of adhering particles, as well as their variety, provide an extremely rich source of potential information, but they pose a correspondingly complex analytical problem. What is a reasonably efficient approach to the analysis and interpretation of many thousands of particles, occurring in many hundreds to thousands of different types? Two traditional approaches have been developed to address this complexity. The first approach is that of a generalist, founded upon broad expertise and examination of many particle types. The second approach is one of data reduction, specializing in the detection and analysis of a very few particle types that occur prominently and frequently on evident- teary items.

First generation approach: generalist practitioners

Microscopes began to be commonly used in legal cases in the second half of the19th century, leading to extensive application in forensic toxicology [7] and the detection of food adulteration [8]. The first applications of trace evidence analysis began in the same period and were closely associated with forensic medicine [9], focusing on the analysis of body fluids [10], feces [11], stomach contents [2] and hair [12]. More generalized applications developed in the casework of individual practitioners who used the microscope to identify and compare transferred particles [13]. Microscopic particle analysis was extremely effective, providing a broad range of information that contributed to the solution of a broad range of problems.

Popular fiction romanticized these cases in the form of the boutique scientist, a renaissance man with broad expertise in the recognition and exploitation of minute traces [14–16]. The regular application to criminal investigation was conceptualized and encouraged by Gross [1,2], who strongly advocated engaging experts in microscopy. In the early 1900s case reports appeared frequently in the popular literature and in works on legal medicine. Summaries can be found in Locard [3,4,17,18] and elsewhere [19,20]. Notable case reports during the early 1900s included the work of Popp [20], Heinrich [21], Schneider [22–24], and Bertillon [25]. During the same period, an academic focus on criminalistics emerged in Europe [26–29].

Trace evidence was brought into the mainstream of criminal investigation through the development of dedicated police laboratories [28,30,31] and the publications and practices of Locard [3,4,17,18,27].

The early applications of microscopy to the analysis of trace evidence are striking in their multidisciplinary nature, yet they depended almost entirely on the application of the knowledge and skills of individual boutique practitioners. Three factors encourage aged and enabled this capability. Firstly, expertise in analytical microscopy was much more common. Microscopes were a primary analytical tool used in chemistry, industry, pharmacy, geology, food analysis and botany. Secondly, a broad expertise in the microscopy of materials was reasonably achievable. Compared to later times, there was a much more restricted range and complexity of man- made materials to be encountered (textile fibers and paints are directly relevant examples). Thirdly, analysis with the microscope was state-of-the-art. Microscopically analysis, together with directly associated micro chemical or microbiological methods, revealed all of the then-attainable character of the trace evidence.

With this foundation of microscopy, and within the emerging crime laboratory structure, the 1930s and 1940s saw the development of trace evidence methods focusing on specific materials, notably glass fragments, paint, other building materials , hairs [35] and fibers [76– 79]. Microscopy, supplemented by increasingly sophisticated microchemistry [32] and a generalist approach [32] remained dominant into the 1950s and 1960s. This approach ensured efficient, responsive application to individual cases. Any particle types encountered by an expert micro analyst were addressed by the methodology and their findings could be put immediately into the context of the individual case by the expert generalist practitioner. In this way the relevance of the examination to the case resolution was ensured. Questions of, ‘‘What is detected, why might it be present, and why should it be analyzed?’’ were inherent parts of the examination.

During the second half of the 20th century the factors that had encouraged multidisciplinary analysis of trace evidence by individual boutique scientists were rapidly diminishing. Expertise in analytical microscopy became less common as college curricula changed and chemical analysis in industry and pharmacy came more to rely on chromatography, spectroscopy and chemical instrumentation [40]. The range of materials encountered as trace evidence had also increased dramatically in the intervening years, challenging the feasibility and practicality of an individual maintaining appropriate competency and expertise. Furthermore, the skills in analytical microscopy that enabled this approach, although enduring as an essential component of trace evidence analysis, could no longer stand alone. They had not lost their relevancy, but they had lost their sufficiency. The analytical methods routinely used in crime laboratories expanded, adding significant capabilities.

Today, the expertise required for a generalist practitioner in trace evidence analysis is daunting. The materials that can be encountered are innumerable and the corresponding methods of analysis are complex. The education and experience required to achieve analytical proficiency and dependable, responsible interpretation has become enormous. Pasteur’s admonition that ‘‘chance favors only those minds which are prepared’’ [35] though often referred to in the context of trace evidence analysis warns us that gaps in the individual’s expertise, widening with changes in manufacturing, product use and analytical methods will result in both missed and misinterpreted evidence.

Second generation approach: particle-type specialist practitioners

As the complexity of trace evidence analysis increased, a second approach emerged. This was one of data reduction–specializing in the detection and analysis of only a very few particle types that were recognized to occur prominently and frequently on evidentiary items. Specialization is a common response in many professions when there is a significant expansion in applicable scientific knowledge. Two major sources of this expansion affecting forensic trace evidence analysis in the mid-20th century have already been noted: rapid changes in how laboratory analyses were conducted and rapid changes in the range and complexity of the materials being analyzed. Initially, these brought two alternatives for specialization. Practitioners and laboratories with a generalized focus on particles could adopt specializations based on instrumentation, while others could adopt specializations based on the different particle type. In the 1970s, however, a third source of rapidly expanding knowledge also favored specialization by particle types: a growing body of research on the interpretation of trace evidence.

Prior to the 1970s there was little systematic research on either (1) how often different types of trace evidence (e.g. fibers, glass, paint) were encountered on items of evidence or (2) relative frequencies of specific varieties of these particles (e.g. blue cotton fibers vs. red rayon fibers). Quantitative data of this type (whether definitively determinable or not) are directly relevant to the interpretation of trace evidence.

When laboratory analysis finds a correspondence between crime scene and suspect specimens, questions of evidential weight immediately follow. For a very long time these questions were addressed by statements that the specimens could have shared a common origin, together with an expert’s assessment (based on experience) of whether the trace evidence material was common or rare. For example, some types of materials such as common soil minerals, or undyed cotton, were (appropriately) assessed of little or no significance because of their wide occurrence and their presence in most specimens [36]. Surveys of items representing the crime scene or suspect specimens, or accumulation of data from casework were means to provide a more definite foundation for these judgments. These studies began slowly, and were often motivated by efforts to determine the weight of evidence in a specific case. An early survey of glass fragments by Marris [39] is a good example. In the 1940s and 1950s, Kirk and colleagues studied the occurrence of colored wool fibers. Beginning in the 1970s, coincident with population surveys of emerging serological markers, published studies of this type became common. Examples are: for glass, [28-32] for paint, and [113–115] for fibers. Databases compiled from casework or comprehensive surveys, such as [116] for glass, also became available. Studies of the transfer and persistence of different trace evidence types such as soon followed, together with a growing body of literature focused on how the new, quantitative data should be used in interpretive processes.

The continued expansion of analytical and interpretive methods, together with increasing complexity in the composition of materials, resulted in the specialization of trace evidence into sub-disciplines of hairs, fibers, paint, glass and soil [28]. The time had passed when it was credible to approach all particle types using a single instrument (the microscope) to demonstrate a correspondence between crime scene and suspect specimens, and to rely on a single expert's experience to interpret the evidential weight of all types of traces.

Specializations in the analysis of hairs, fibers, paint, and glass and have emerged as discrete disciplines within (particle-based) forensic trace evidence analysis [29]. These divisions are consistently used in the literature, certification programs, proficiency testing, professional societies and analytical symposia. Alternative groupings are encountered (such as a combination of architectural paints with glass and other building materials) based on laboratory organization, shared educational foundations, or similar analytical methodologies. Additional disciplines of gunshot residue analysis (GSR), explosives analysis and ''general chemical unknowns'' include particle analysis along with liquid phase analyses. Once the principal focus of trace evidence shifted to discrete particle-type disciplines, targeted methods of specimen recovery and analysis followed. Methods for efficient recovery and preliminary analysis of fibers, for example, are different from those that work efficiently for fragments of glass. Analytical methods necessary to achieve credible discrimination among paints are different than those that achieve discrimination among fibers, and so forth. Standardization of these methods was necessary for sharing of data among laboratories, and for determining frequencies of corresponding specimens in available databases. The importance of standardization increased with expanded expectations of specific measurable and explicit foundations for interpretations [30].

Implementation of particle-type specializations within forensic laboratories has had three important effects. Firstly, there has been a shift to categorization of examination requests and cases by trace evidence type. It is not unusual for specific types of trace evidence to suggest themselves by case circumstances. (Typical examples are hair found in a victim's hand, the breaking of glass during a burglary, soil on a shovel used for burial, or paint flakes on a tool used for forced entry.)

Secondly, there has been compartmentalization of laboratory activities, including the analyses themselves and the attendant management processes. Laboratory personnel perform (and are only trained and approved to perform) more standardized, modular tasks. Expertise can become very narrowly defined confined to the application of an explicit set of protocols. For example, one of our colleagues is currently trained and qualified to conduct examination and identification of general chemical unknowns in his laboratory. However, if his identification results in a finding of a particle of glass, he is no longer qualified, and the evidence must be transferred to another analyst. Likewise, if the particle is found to be a drug substance, a paint chip, or a fiber, these must be separated and transferred to appropriately qualified analysts within the laboratory. As another example, in one recent case pieces of tape were examined in five separate areas of a laboratory: hairs and fibers (for removal and analysis of adhering hairs and fibers), chemistry (for analysis of the tape adhesive and backing), trace evidence (for examination of fabric reinforcements in the tape); mineralogy (for examination of fiberglass reinforcements in the tape), and questioned documents (for physical fit of paper adhering to the tape). In such ways the particle specialist approach provides standardized results and interpretations, which address narrowly defined issues within narrowly defined case circumstances.

Thirdly, there has emerged a discrete choice of which (now particle-type specific) services are to be offered by the laboratory. There are identifiable costs and commitments associated with acquisition and maintenance of analytical instrumentation, corresponding personnel, and the directly associated processes of training, certification and accreditation. Should the laboratory support hair cases? Glass cases? Soil cases? Which of these provide the most services to the laboratory's constituency and help with legal decision-making in the most cases?

Evaluation of the effectiveness of established forensic trace evidence analysis methods

It is instructive to evaluate and contrast the effectiveness of the two established approaches to trace evidence analysis: the first generation generalist and the second generation particle-type specialist. Each has its own contributions and limitations.

The approach of the first generation generalist practitioner developed over a long time with a small set of expert-dependent tools. These tools could be chosen, applied and credibly controlled by an expert ''machinist,'' in response to the needs of individual cases. The quality was dependent on, but achievable by, an expert who could study a variety of commonly occurring particle types and address related interpretational issues. Unusual particle types, when present and relevant, could also be exploited, contingent on the range of the generalist practitioner's expertise. When the level of science required for credible analysis was lower, and when the courts and society were more tolerant of personal experience as a foundation for opinions, the general practitioner approach was an effective solution to forensic trace evidence analysis. The quality and coverage of this approach, though still employed, has been stressed by the expansion of particle types, their increased compositional complexity and associated requirements of improved analytical methods and interpretive skills. The contributions of the generalist practitioner approach are (1) a wide variety of particle types can be recognized and exploited for their potential as trace evidence, (2) their analysis provides a broad range of information that contributes to the solution of a broad range of problems, (3) effective case solutions can occur when the particle types, expertise and problem to be solved coincide, (4) the methods employed are relatively inexpensive and easy to set up, and (5) the technology can be directly integrated with case-specific problems by the cross-disciplinary expert ‘‘machinist,’’ ensuring practical application to the problem.

The major limitations of this approach are (1) required maintenance of an extraordinarily high level of individual expertise, (2) coverage limited to particle types that overlap this expertise, (3) technological developments continuing to decrease this overlap, (4) increasing probabilities of missed or misinterpreted evidence, and (5) variance with legal and scientific expectations favoring standardization and compartmentalization. For second generation particle-type specialist practitioners, analytical and interpretive methods are focused on a small group of specific, pre-defined particle types. This has allowed development of targeted recovery methods, analytical methods with increased discrimination, standardization of methodologies, and development of databases useful for interpretation. In laboratories this has resulted in differentiation of cases by trace evidence type; increased costs for analytical instrumentation and staffing; more modular, technician-level tasks; less direct integration of laboratory work; and discrete decisions regarding which capabilities to offer. These changes have severely restricted the range of particle types that are considered for analysis, which (in turn) severely limits both the range of problems that can be addressed and the possible contributions that can result.

The contributions of the particle-type specialist practitioner approach are (1) well-defined, predictable tasks, (2) more highly discriminating tools, (3) efficient solutions for recurring, pre-defined problems, (4) standardization of analytical methodologies, protocols, training, and quality management, (5) interpretational tools based on this standardization, and (6) meeting of increased legal and scientific expectations.

The major limitations of this approach are (1) a severely restricted range of problems that can be addressed and possible contributions that can result, (2) it is not adaptable or responsive to new problems, (3) most of the particles available as trace evidence are unexploited, (4) specialized tools and niche expertise are required, (5) methods and expertise can become very narrowly defined, and (6) there is no longer a cross-disciplinary ‘‘machinist’’ as an effective integrator of the technology with the practical application to the problem.

The limitations restricting the effectiveness of the two prevailing approaches to trace evidence work are the primary motivations for the writing this paper and define an opportunity for fundamental advancement. Would not it be nice if one could incorporate, rather than extinguish, the skills developed in the first generation and merge these with the technology developed in the second?

Current practices: recent changes and their impact

This section describes recent changes in the use of technology, their effect on the traditional approaches to trace evidence analysis, and the emergence of a third approach based on component processes.

New technological advances and their potential contributions

Advances in analytical chemistry and information technology have tremendously increased our capabilities in materials analysis. The range of materials that can be unambiguously identified and comprehensively characterized is extraordinary, and there is unprecedented sensitivity, specificity, and efficiency. These developments have much to offer forensic science. Which tools should we use and how should we use them?

There are four major contributions that new technological advances can provide: (1) greater specificity and discrimination, (2) greater reliability, (3) broader application, and (4) greater efficiency. Greater specificity and discrimination are the result of more analytical information from the specimen itself and from a more comprehensive and relevant body of reference data. Examples are the use of LA-ICP-MS in the analysis of glass [31] and the use of

Raman micro spectroscopy in the analysis of paint [32].

Greater reliability results from methods that have less of a dependency on the contingencies of hands-on examination steps and observer subjectivity. These often accompany methods that minimize sample preparation, are semi-automated, and that provide objective, measurable analytical results. An example of minimization of sample preparation is the use of surface enhanced Raman spectroscopy for in situ analysis of fiber colorants [33]. Robotic methods of DNA analysis [34] are an example of semi-automated processing. Examples of objective, measurable results replacing subjective comparisons are the use of micro- spectrophotometry and multivariate statistical analysis for the measurement and comparison of dyed hair color [35,36] and similar methods applied to fiber dyes [37] and inks [38–40].

Broader application results when smaller specimen sizes can be accommodated or greater amounts of environmental alteration or dilution can be tolerated. Methods allowing micro-FTIR analysis or micro-Raman spectroscopy of individual particles [41] are good examples. Greater efficiency contributes directly to economy, but also increases the analytical throughput that allows more comprehensive collection of reference data that are needed for interpretation. Semi-automated particle analyses by SEM/EDS are a common example.

However, as we contemplate the potential contributions of new technologies, it is important to recognize that in a forensic context the advantages they offer are not intrinsically good. Whether or not increased specificity in the analysis (for example) represents an effective contribution necessarily depends on the particulars of the specific application, the impact on the full set of limitations, and the nature of any additional limitations that are introduced. Additional limitations from new technologies often include increased costs and restrictions on how broadly they can be applied (such as narrowly defined requirements on the types of specimens that can be accommodated).

Increased emphasis on scientific practices and standardization

A combination of factors, beginning in the 1990s, resulted in greater scientific and legal scrutiny of forensic science practices. Apart from forensic specializations within established professions (such as forensic medicine and toxicology), the broader scientific community became interested in the forensic sciences with the advent of DNA-based identification methods. During the same period, more intense interest within the legal community within the United States attended the redefinition of standards for the admissibility of scientific and technical evidence. Subsequent evaluation of traditional forensic science practices, including re-examination of evidence in cases where DNA analysis resulted in reversals of conviction [39], has prompted debate, criticism and fundamental scientific reviews. All of these have brought renewed emphasis on scientific practices and standardization within forensic science disciplines. Trace evidence examination is no exception.

Increased requisites for scientific practices and the increased attention of the scientific and legal communities are important changes promoting quality and reliability in the forensic science. Essential elements of all scientific practices include (1) a complete description of what was done, (2) documentation of analytical findings, and (3) a clearly articulated route from these findings to any conclusions that have been made. Standardized methods and objective measurements of known precision are two important means of achieving these elements. Standardized methodologies have well-defined input requirements and are designed to address well-defined problems with a known degree of specificity and reliability.

Impact of these changes on traditional approaches to forensic trace evidence analysis

Technological advances and increased emphasis on scientific practices have reduced the effectiveness and viability of the trace evidence generalist practitioner. Access to new technologies is itself an obstacle. Additionally, fewer particle types are addressed, costs are increased, and the integration of technologies is more challenging. Two of the limitations in coincide with the changes themselves: the continuing emergence of new technologies (increasing the education and experience required to achieve proficiency) and increasing legal and scientific expectations (favoring standardization and compartmentalization).

For the particle-type specialist approach, the recent changes are well-aligned and directly intensify both the contributions and the limitations. There is an added limitation of increasing costs. Whether or not there is a net improvement depends on the balance of the contributions and limitations in any specific context.

Conclusion

Particle traces have always been recognized as an important, highly informative source of physical evidence. The first generation generalist practitioner was effective in his day (when the level of science required for credible analysis was lower, and when the courts and society were more tolerant of personal experience as a foundation for opinions). This approach is no longer effective; the task is too complex to be managed within the limitations of the generalist approach.

The second generation particle-type specialist approach deals with the complexities of particle analysis by discarding all but a few of the most obvious, larger, and more frequently occurring particle types. This solves complexity at the expense of practicality. Cases must fit narrow, pre-defined criteria, resulting in low numbers of applicable cases and higher costs to maintain the capability. The component processes approach shows intriguing potential for specific improvements, but (1) it clearly cannot operate as a stand-alone capability and (2) its impact on either of the other two approaches is to intensify their limitations. None of the current approaches meet the overall objectives for trace evidence analysis.

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