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Fibers Under Fire: Suggestions for Improving Their Use to Provide Forensic Evidence

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ABSTRACT: The current emphasis on DNA technology in forensic science has led many to believe that trace evidence examinations, including fibers, may be of little value. Reasons are given here to show that this is an erroneous assumption. In the face of this situation, fibers examiners have been challenged to consider ways in which they can improve the services they offer to the Criminal Justice System not only by increasing the efficiency of the examinations, but also by expressing the evidential value of the findings in a clearer way. The separate stages within fibers casework from evidence collection to report writing are critically examined. Suggestions are made on how improvements may be achieved. Areas where particular progress can be made include improving communication and exchange of information between the investigator and the scientist and streamlining analysis by using the latest equipment in conjunction with effective case management. In addition, ways of making better use of existing data pertaining to fiber frequencies, accumulating new data by using the resources of working groups, and improving training procedures with respect to evidence interpretation are discussed.

KEYWORDS: forensic science, criminalistics, fibers, examination, comparison, Fourier Transform Infrared-microscopy microspectrophotometry, sampling, fiber frequency, evidential value

Changes in the forensic world have meant that increased time, energy, and funding have been channeled into DNA analysis. DNA cannot provide decisive evidence in all types of forensic cases, because material containing DNA is simply not present in all cases. However, there is a school of thought that believes that the need for trace evidence examination has been substantially reduced. This is an erroneous assumption. De Forest (1), says "trace evidence has an important role to play in both the investigate and adjudicative phases of a case." Not all evidence categories lend themselves to a production line approach during laboratory analysis. Fiber cases are one example. Because of the extreme variance in the circumstances found from case to case, in the differing analytical approaches required, and the complexity of interpreting the results, a more individual treatment is required for trace evidence examinations. Unfortunately the flexibility needed sometimes makes following rigid written schemes of analysis impossible and, as pointed out by Chapin (2), this can be perceived as introducing subjectivity (a word carrying negative connotations). There is nothing remotely subjective about the details of the methodology permissible within these alternative approaches. Stringent quality assurance requirements for fiber examinations are based on Best Practice Guidelines produced by international working groups (3,4). The choice of method(s) however should be the responsibility of the analyst, who should apply his knowledge and experience to get the most discriminating result possible under a given set of circumstances. What is needed as a consequence of the current situation is a fresh approach to deal more effectively with the analytical side of fiber cases and to optimize the evaluation and reporting of fiber evidence.

Fibers are particularly important because they are are ubiquitous—we are surrounded by textiles in our daily lives. Their use as evidence in criminal cases is only limited by the extent of the investigator's imagination, provided that the necessary forensic support facilities are available. In addition, the textile population in a person's wardrobe and surroundings is based on personal taste and is therefore highly individual. It would be extremely unusual to pass a person on the street wearing exactly the same items as yourself from head to toe. In addition to this, fibers carried on clothing reflect the owners personal environment, and if transferred to other surfaces can provide a link back to their origin.

There will always be cases in which DNA cannot play a role, and in which crucial evidence may be brought to light by using fiber transfer examinations. In England and Wales the number of crime scenes where DNA is recovered is relatively low, circa 5% (K. Barnett: personal communication). Some examples are given here:

Terrorism/Armed Robbery—Fibers recovered from pockets can provide links to gloves and balaclavas carried in them; fibers from individuals can be found on weapons; fibers from individuals or locations can be found on explosive devices; fibers can be used to establish the usage of vehicles, to provide links between vehicles or to link conspirative living accommodations. Fibers matching masks or clothing may often be recovered from hair combings.

Homicide—When an unidentified body is recovered, examination of the clothing itself and the fiber population on it may provide information that will help to identify the deceased (5,6). Fibers on the body will bear witness to the last contacts. With a victim whose identity is already established, detailed recovery of fibers from the body (naked or clothed) using taping can identify groups of fibers foreign to the victim's own environment. These may have been transferred from the suspect or have been deposited during the last contact with textile items.

A method which allows for maximum recovery of transferred fibers from a body or scene while their distribution remains unal-

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tered is referred to as 1:1 taping. The area of one taping represents the same area on the surface from which the fibers are being recovered. The exact distribution of these fibers can help investigators reconstruct the events of a crime (5) and can provide investigative leads to a suspect and to their environment (6). The first action at the crime scene must be to assess whether other evidence could be lost if 1:1 taping is performed. Probably the most important consideration would be the loss of marks, e.g., fingerprints or shoemarks on the body. The decision to proceed must be that of the senior investigating officer after conferring with the appropriate scientific support personnel and/or forensic scientists.

While the use of 1:1 taping can undoubtedly yield valuable information leading to a substantially improved interpretation of the findings in accordance with the events of the case, logistical problems sometimes restrict its use. Because the fiber density will probably be reduced on most 1:1 tapings (with the exception of those from very good donor surfaces) searching time should not be increased. Automatic fiber finder systems may help to speed up tape searching in the future.

Rapes/Sexual Assaults—Fear of sexually transmitted diseases, especially AIDS, has probably led to an increased number of rape suspects using a condom. The successes of DNA analysis featured in the media may have increased awareness of DNA capability, which acts as an incentive to take precautions. There will always be some cases where no body fluids are transferred, detected or properly collected, although contact has taken place and in these cases it is often possible to demonstrate contact by fiber transfer.

Volume/Petty Crime—Fibers evidence can also find application in burglary and car theft cases. Indeed many police forces, particularly in the North of England, have had great success in convicting car thieves. Clothing seized from suspects who have been apprehended quickly may be linked to the car interior by fiber transfer. By selecting appropriate "target" fibers (see page 72) the forensic work can be carried out successfully in minimum time. Fibers can also be used in connection with vehicles. It may be possible to establish who was driving in cases involving intoxication or lack of insurance, or in hit and run cases. This may be done not only by means of cross transfer of fibers between seats and clothing but, in the event of an accident, by fiber-plastic fusions (7–9). They may be useful in linking serial offences, e.g., identical fibers found at the point of entry of a number of burglaries.

Fiber examiners worldwide are taking stock of their situation and devising ways in which to offer improved service to law enforcement agencies. This applies not only to improving analytical procedures but also to introducing new approaches to case management.

In the laboratory, fiber examinations normally consist of the following processes:

a.) case assessment,
b.) trace evidence processing—involving recovery of transferred material and obtaining known representative samples for comparison,
c.) selection of the known "target" fibers,
d.) preparing known and recovered fibers for comparison,
e.) comparison of morphological features and optical properties of recovered and known fibers,
f.) confirmation of identity including polymer subclass where applicable,
g.) comparison of fiber finishing (dyes, optical brighteners, etc.),
h.) evaluation of the findings,
i.) report writing and testimony.

Case Management

The effective management of fibers cases can be broken down into four main areas. These begin at the *crime scene* where it is necessary:

a.) to maximize the information obtainable in a minimum amount of time.
b.) to carefully consider the aims of the forensic investigation, e.g., What may have happened here? Why is this evidence being collected? What can it show?
c.) to provide helpful information especially in the very early stages of the investigation (1).

The second stage is *Case assessment/acceptance*. This can be done effectively by:

a.) using a "hierarchy of propositions" approach (10–13) to discuss the case with full customer interaction.
b.) communicating the capabilities and limitations of fiber examinations to police and legal personnel.
c.) rejecting evidentially insignificant cases:
    1. involving very common fibers which have little or no evidential value, i.e., colorless cotton and polyester or indigo dyed cotton.
    2. involving looking for fiber transfers that will only confirm established facts.
    3. looking for fiber transfer in a domestic environment or under other circumstances where a legitimate transfer cannot be ruled out and it is not possible to make a reliable interpretation of the results.

There may be exceptional circumstances where 1 and 2 above will need to be carried out.

The *Analytical aspects* of a case can be optimized by adopting a particular strategy:

a.) choosing the best target fibers;
b.) using the most efficient search/recovery method;
c.) examining the most relevant exhibits first;
d.) using the most discriminating analytical techniques appropriate to the type of fibers involved in the case;
e.) solving the problem of representative sampling, i.e., deciding on the number of fibers to be tested at each stage of the analysis.

The fourth and final stage involves *Case Reporting:* The interpretation of the findings and the presentation of the evidence is critical to the successful conclusion of any case. The future success of fiber examinations in forensic science is inextricably linked with enhancing the product–the report, and its impact. In the past, fiber reports have often tended to be limited to simple first stage conclusion statements (the recovered fibers could have come from the known source) or to give no opinion on evidential value at all (the fibers found on *x* match those in *y*). They often confine themselves to the bare minimum of information (14) and experts have been shy of voicing opinions on fiber frequency. Small wonder that many observers form the opinion that fiber transfers are of little value as evidence. In the last ten years, a great deal more information about fiber frequency has become available (15)—the time has come to start using it.

How Can Improvements be Made?

Looking at the areas mentioned above in more detail, it is possible to suggest improvements in the different phases of casework up to and including the production of the report.

Case Assessment

One of the key issues in the future must be to achieve a better understanding of what can be achieved when a fibers examination is carried out. The capabilities and limitations of fiber examinations must be clearly communicated between the forensic scientist and the investigator. All encompassing, generalized requests for fiber transfer examinations in the hope that "something of forensic significance" will emerge, belong to the past. Fiber examinations cannot work miracles and forensic science laboratories no longer have the manpower resources to proceed in an unsystematic manner. The following maxims hold true:

a.) The effective interpretation of fibers evidence can be difficult even in simple cases.
b.) A simple result, e.g., focusing on cross transfer of a good target fiber(s) to key items is of more value than a complicated one, e.g., involving transfers of very low numbers of unremarkable fibers to many items, where the significance is not immediately clear; the evidential value is higher and the findings are easier for judge and juries to understand.
c.) Time spent on unsuitable cases delays work on more important ones; this is particularly critical in situations of understaffing.
d.) The results from unsuitable cases contribute to a negative image for fibers examination.

In the future, investigators must think very carefully about what they hope to demonstrate by means of fiber transfers and formulate their laboratory requests accordingly. The analyst needs as much background information as possible to be included in the request. This saves valuable time being lost through having to track down investigators. In the Forensic Science Service in England and Wales, and in other systems (especially those that charge for forensic examinations), the most fruitful line of examination is discussed in the light of the knowledge available, which will then be carried out at a certain cost. After the first stage of the examination, the results are discussed and the customer then decides if it would be worthwhile to carry out additional examinations for a further fee, or that further examinations would not add substantially to the case, in which situation the involvement of the laboratory terminates and a report is generated. While the costs in systems which charge for examinations are upfront, the costs may not be so blatant in other laboratory systems, but they still exist. Ultimately the taxpayer (including the analyst) will foot the bill, thus it is in everyone's interest to use a "best evidence" approach.

Recovery of Transferred Fibers

It has been shown that 97% of European laboratories and 78 of 104 laboratories (75%) surveyed in the United States use strips of adhesive tape to recover transferred fibers. Stereomicroscopy is used to search the tapes for targeted fibers. This technique is based on the method introduced by Max Frei-Sulzer in 1951 (16). Of the other recovery techniques available, scraping has been shown to be relatively inefficient (c.66% recovery) (17,18) and may cause a high level of background contamination in search rooms. The disadvantages of vacuuming far outweigh any advantages, confining its use to special circumstances. The "picking off" method of fiber removal is still acceptable when dealing with awkwardly shaped objects or when obvious tufts or "pills" of fibers can be seen adhering to items.

The searching of fiber tapings is an arduous task, but it is no more tedious and is certainly more efficient than searching through balls of fluff obtained as a result of scraping. There are two alternatives for reducing the labor involved. One is to search tapings more objectively, or more discriminatingly, starting with those likely to yield good results in accordance with the reported case circumstances and looking only for the best target fibers. For example, if a man (wearing a red pullover and blue denim jeans) grabs a woman (wearing a blue pullover and white trousers) from behind, it is sensible to first look at the tapes from the back of the woman's pullover for red fibers and the front of the man's pullover for blue fibers.

The key to a successful case is in selecting good target fibers. Crime scene teams must learn to assess the value of color, probable fiber composition, and sheddability of textile items connected with crime scenes and to advise investigating officers of possible associations accordingly. Ideally, investigating officers should have the opportunity to seek the advice of an experienced fibers specialist.

Within the laboratory, consideration must also be given in the future to being more selective in the choice of target fibers, and having confidence in their evidential value. Generally the best target fibers are:

a.) manmade fibers—they have a higher evidential value than natural ones.
b.) those which have the strongest colors, making them easily visible and thus saving searching time. Stronger colors also lend themselves better to color analysis using microspectrophotometry and offer the possibility of using thin-layer chromatography.
c.) those which shed best and which are likely to pervade a particular environment, thus offering the possibility of establishing not only primary but also secondary transfer.
d.) those which may be found in the most significant locations (e.g., on underclothes in rape cases).
e.) those displaying a color, polymer type, or a morphological feature that indicates reduced frequency in the general fiber population.

There will always be exceptions, e.g., a bright orange cotton dyed with a vat dye is far more unusual than many man-made fibers.

It is essential to ascertain that no source of the target fibers exists in the living environment of the person on whose clothing they are being sought, which would provide an alternative source of (legitimate) contact.

Another way to reduce the manual labor involved in searching tape lifts is to use an automatic fiber searching system. These systems have been comprehensively described by Biermann (19), and more specifically in a report on the use of the Foster and Freeman FX5 for fibers case work (20).

Theoretically the automatic search methods will speed up fiber recovery and release staff to carry out other tasks. The use of sheet feeder systems will allow large numbers of tapes to be searched overnight unattended. In practice, this situation has not yet been fully realized. Extensive tests have shown that when the instruments work correctly, they can save a great deal of time and they can search with high success rates. Unfortunately, they have been plagued with both software and hardware problems which have not yet been fully resolved.

The effective use of fiber finders will depend very much on the tapings being collected in a format in which they are immediately presentable to the instrument. In the future they may prove to be an indispensable aid to reducing searching time.

Analytical Work

Identification

The Oxford English Dictionary definition of "identify" is "to establish absolute sameness" . . . identical objects "agree in every detail." If a pair of fibers differ in composition, this will almost certainly be reflected by some visible difference either in color (the dyeing is likely to be affected) or in morphology (diameter, cross sectional shape, evidence of processing, e.g., texturizing, or in the distribution and size of delusterant particles). These characteristics describe fibers, but do not identify them chemically.

Accurate identification of fibers is critical to assessing their frequency of occurrence in the general fiber population, which will in turn affect their evidential value. It is no longer sufficient to describe man-made fibers by their basic generic class, e.g., regenerated cellulose, acrylic, modacrylic, or olefin as these types contain many subclasses.

It is necessary to know the exact composition of fibers for various reasons:

To Make Full Use of Discriminating Power—The description "a red round delustred synthetic fiber" means that the fiber might belong to any one of several generic varieties. "A red, round delustred acrylic fiber" is much more specific, and the description "a red, round delustred acrylic fiber made of acrylonitrile copolymerized with methylmethacrylate" has narrowed the field to such an extent that we can say we are dealing with a relatively rare fiber type.

Without knowing exactly what type of fiber is involved, false conclusions may be made about the shedding, transfer and retention properties of textiles made from it, which could lead to an interpretational error. This may be compounded by inaccurate assessments of the fiber frequency.

It is unlikely, but possible, that fibers that have the same morphological features may differ, either in their polymer composition (e.g., they could be Nylon 6 or 66) or in their optical properties as a result of the manufacturing process. Visually identical polyester fibers may have a different birefringence due to a different degree of crystallinity produced during the spinning process. This can be detected by the use of polarized light or interference microscopy.

What criteria must be applied to methods used for fiber identification?

a.) Preferably, they should be nondestructive.
b.) They should be applicable to the smallest samples.
c.) They should be as discriminating as possible.
d.) They must be rapid.

Fortunately, the methods used for fiber identification in forensic science today generally fulfill these criteria and may be considered adequate. The primary methods used for identification are brightfield/polarized light microscopy and FTIR microscopy. These can be backed up by a "pool" of secondary methods that can be applied selectively when required in specific instances. These include interference microscopy, thermal microscopy, and the use of SEM-EDX and sometimes solubility testing. In order to achieve a high degree of discrimination it is not necessary to use a vast number of analytical methods; it's simply a question of choosing those that can most efficiently differentiate particular fibers. The main generic types of man-made fibers can be recognized at a glance by an experienced observer using polarized light microscopy. This can save much time in choosing the appropriate analytical method to confirm a positive identification.

To gain this experience, the value of a good reference collection containing authenticated samples cannot be overemphasized. It is vitally important that when staff are undergoing basic and advanced training, they see as wide a range of authenticated samples as possible. This wide range seems to be something lacking in many laboratories, even large, well-equipped ones. The correction of this deficiency would bring benefits in terms of saving analytical time, increasing accuracy, and improving discriminating power. Such collections are available commercially. An excellent collection of natural fibers is available from the Arbidar Company, Sula, MT 59871, USA ("Natural Fibers Research & Identification Kit") and a new collection containing 200 authenticated man-made fiber samples ("Forensic Fiber Reference Collection") is being marketed by Microtrace, 1750 Grandstand Place, Elgin, IL 60123.

Problems formerly associated with producing infrared spectra from man-made fibers, which were for the most part associated with preparation of the sample, have been overcome. FTIR-microscopy does not destroy the sample, but may change its physical form. There is no evidence so far of this affecting the spectrum. The technique is applicable to the smallest length of a single fiber (100 μm is enough), requires very little sample preparation and delivers information which, in most cases, cannot be bettered by any other technique currently in use. A sample can usually be prepared and run in 15 mins.

The technique cannot help with the identification of natural fibers, and here the ability to refer to reference samples becomes increasingly important. DNA analysis has already opened up new possibilities for identifying animal hairs/fur fibers. The individualization of domestic cats as reported by Menotti-Raymond and others (21) is just one example. FTIR-microscopy is also unable to differentiate between the various cellulosic man-made fibers, viscose, modal, lyocell, and cellulose diacetete and triacetate fibers cannot satisfactorily be distinguished using this technique. In these cases other techniques are necessary.

A survey (22) has shown that little use is being made of FTIR-microscopy to identify polymer subclasses, particularly in fibers containing acrylonitrile (23,24). This may be due to lack of reference material/reference spectra causing unfamiliarity with the spectral interpretation capability necessary to recognize polymer subgroups. It has also been noted from the results of trials held by the European Fibres Group and the Scientific Working Group for Materials (Fibers), which have required the use of FTIR-microscopy, that spectral quality often leaves much to be desired, which will adversely affect interpretation. Failure to correct these deficiencies means that not all available information relevant to the assessment of fiber frequency is being used. To attribute the same evidential value to all types of acrylic fibers is incorrect.

The use of microscopical Raman spectroscopy has been proposed for identification of man-made fibers (25,26). It offers the slight advantage that spectra can be run from fibers mounted on glass slides, as little interference occurs from the glass (however demounting and cleaning of recovered fibers may still have been required if UV-visible range microspectrophotometry has been carried out prior to FTIR). Raman can be applied to even smaller samples than those currently analyzed by FTIR (laser spot size 1 μm) and there are no sample presentation or preparation problems, but it does not offer any increased discrimination between generic types, and of course, at present, it is not possible or necessary to recover fiber fragments of this size. It has been suggested that Raman will be useful to obtain the spectra from fiber dyes, but with the exception of the limited work by Bourgeois and Church (27) and the Surface Enhanced Resonance Raman Scattering work of White (28) little convincing evidence of success has yet been forthcoming.

The Raman work of Bartick and Miller (25) reports particular difficulties in subgrouping acrylic fibers (which is not a problem when FTIR-microscopy is used). This area was not thoroughly investigated by Keen, White, and Fredericks (26), who concerned themselves mainly with polyamide and polyester fibers. Using the multivariate statistical technique of principal components analysis after recording four spectra from each fiber, these authors maintained that it is possible to distinguish between the products of different manufacturers. What has not been investigated is whether, over a period of time, variances may occur within the products of the same manufacturer, perhaps due to different batches of raw materials being used to prepare the resin, or due to different processes having been used after the fibers have been extruded, e.g., stretching, texturizing. The danger of trying to attribute fibers to a specific manufacturer is that it is necessary to be sure that no other manufacturer in the world is using an identical process. In these days of increasing globalization, plants producing (virtually) the same fiber product using the same technology may be scattered worldwide. The textiles made from these fibers, however, may be sold in quite different geographical areas from those where the fiber producers are located. The bottom line is that although research is continuing, Raman spectroscopy cannot currently offer anything more in the way of identification than can be achieved by other techniques, i.e., FTIR-microscopy, or in the case of dye analysis, spectrophotometry and thin-layer chromatography (TLC).

The use of Infrared Dichroic Ratio pattern recognition (29) has also been put forward as a means of individualizing the manufacturing source of polyester fibers. The comments made above also apply to this situation. In both cases the work was principally carried out on undyed fibers; forensic case work is very largely concerned with those that are dyed. The effects of consumer use, particularly due to heat or extensive wear, may cause spectral variation to occur from fiber within the same garment. The range of variation among the fibers in a particular textile would also have to be taken into account when attempting to assign a common origin to fibers from different sources.

Comparison

After establishing that recovered and known fibers have the same identity and do not display any forensically significant morphological or optical differences, the next step is to compare their dyeing and finishing. In the past, the traditional approach has been to use a comparison microscope to view known and recovered fibers simultaneously using brightfield and fluorescence microscopy. Fluorescence microscopy detects optical brighteners or fluorescence originating from the dye. If the fibers still match, the next stage would be to use microspectrophotometry (MSP) to examine fiber color and eliminate metameric matches. Microspectrophotometry has now been used in forensic fiber examinations for 25 years and can be considered an essential technique. In the ENFSI Best Practice Guidelines for fiber examination (4) its use is considered mandatory. If MSP is only carried out in the visible range of the spectrum, the use of fluorescence microscopy is highly recommended.

MSP may be used in the visible range (c.390 to 760 nm) of the spectrum only, or it may include the UV and visible ranges (c.240 to 760 nm). If the full range is chosen, it is necessary to remount the fibers to be examined on a quartz slide with quartz coverslip. However, if MSP is only carried out in the visible range, generally the fiber dyes should subsequently be examined using TLC, which is a complementary technique. Detailed procedures for dye classification, dye extraction for reactive and nonreactive dyes, and the appropriate eluent systems for TLC are available in (30).

Some fiber/dye combinations are more unusual than others (30). Classification of the dye class used in conjunction with FTIR increases the information available about the relative frequency of the fibers in question. This will allow the value of the evidence to be correctly weighted. In addition, information obtained from dye classification, dye batch variation (31) and FTIR may help establish a likely source of fibers found on the body or clothing of a murder victim, i.e., the fiber manufacturer and/or dyer. Even if large quantities of a colored fiber were produced, it may be possible to narrow the search to a particular dye batch, hence limiting the origin of the recovered fiber to a particular batch or batches. Further inquiries can reveal how much of the relevant batch was sold, to which garment manufacturers, how many garments were manufactured from it, and where they were sold. This type of intelligence work is on the increase in England and may, in the future, be very closely linked with the practice of 1:1 taping to provide important information as soon as possible after the onset of an inquiry.

A new range of microspectrophotometers has been developed for examining fiber color. The use of a diode array detector (DAD) or a charged coupled device (CCD) permits multichannel spectroscopy (MCS) where the spectrum is recorded simultaneously across the whole spectral range being scanned, instead of the data being accumulated in successive steps. The great advantage is that a spectrum can be acquired in less than a second, instead of the usual 2 min. Naturally, when it is necessary to record many spectra from control and recovered fibers, the time saving is considerable. DAD instruments are available from J & M in Aalen, Germany (also marketed by Zeiss in England), and CCDs can be obtained from SEE in Middleborough, MA, and the LOT-Oriel group in Darmstadt, Germany. Both can be attached to a variety of microscopes and used to record spectra in the UV and visible ranges.

This development has made it possible to use a work station approach for fiber examination, by mounting the multichannel spectrometer on a standard high power microscope, which is also equipped with polarized light and fluorescence facilities. Recovered fibers can be subjected to spectral analysis immediately following the preliminary microscopical examination and recording of morphological characteristics. All of the data generated can be directly entered and stored in a computer. In this way it is possible to scan a very large number of recovered fibers in a short space of time. They can then be sorted, using morphological and spectral characteristics, to see whether groups (or "collectives") of potential interest are present. The decision can then be made on whether to examine them in greater detail. This system is already in use at the Forensic Science Institute of the Federal German Police (BKA) but at present most laboratories are still using comparison microscopy as the first stage of the screening process.

Thus, the introduction of multichannel spectroscopy (MCS) has made it possible to change the traditional sequence of fiber examination where positive results from comparison microscopy are usually checked by a second scientist, requiring that two scientists therefore spend time in agreeing on the result of a subjective examination. When MCS is initially used, an objective result is obtained very quickly. Only spectrally matching fibers need to be compared and confirmed microscopically resulting in a considerable increase in efficiency. Diode array spectrophotometers offer the greatest potential for considerable time saving in fibers case work.

In addition to microscopy, spectroscopy (FTIR and Raman), and TLC there are other techniques that have been considered for comparative purposes:

Capillary Electrophoresis (CE)—This technique is not routinely used by any forensic laboratory in the world for fibers analysis. Laboratories in Australia, Austria, Finland, and the Netherlands have looked at the possibility of using the technique to examine textile dyes and some may have attempted on rare occasions to use it in casework. Many workers do not favor CE because, like TLC and HPLC, it is also a destructive technique. More importantly there are operational problems (32) that include: adapting the technique to handle small samples; finding an alternative to the organic solvents usually used to extract fiber dyes; preventing the equipment from becoming blocked and unusable; and finding a buffer system universally acceptable to all dye classes.

High Performance Liquid Chromatography (HPLC)—This technique was considered a number of years ago as being a possible replacement for TLC (33). It still suffers from similar problems to CE. Sample size, blockages in the system, sample carry over between runs, and the number of different buffer systems necessary to cover the different dye classes encountered make it a cumbersome technique to use.

Pyrolysis Gas Chromatography (PyGC)—This technique can be used to identify man-made fibers (34) but the results obtained are generally no better, and have been known to be worse, than those obtained by FTIR. Obtaining reproducible results from the same instrument or between instruments in different laboratories can be a problem.

Mass Spectrometry (MS)—Work on mass spectrometry linked systems is going on in the Forensic Science Service in England and Wales and as a joint project between ecb Online Analysen-Technik GmbH and the BKA in Germany. There is potential in this area and results have already been obtained from single fibers. The aim is to identify the dye components on a single fiber and then to link them to a particular dye. Although the task of building a database of mass spectra from dyes used worldwide may turn out to be an impossible one, MS may provide valuable comparative information.

The techniques being used around the world in forensic science for fiber examination are the concensus of the FBI sponsored Scientific Working Group for Materials (Fibers) and the European Network of Forensic Science Institutes (ENFSI) European Fibers Group as being the most discriminating methods currently available.

Sampling

Sampling is another issue relevant to expenditure of time affecting two stages in fiber examinations.

a.) How many potentially matching fibers should be recovered and mounted?
b.) On how many of these is it necessary to carry out all additional tests when comparing them with the known sample?

First, once a number of matching fibers has been recovered from a specific item, the question arises—is it necessary to search all remaining tapings, in the hope that a few more may turn up? If target fibers have already been recovered in relatively high numbers, to what extent will the evidential value be increased by locating a few more? It is not possible to make a general rule, the situation must be considered on a case by case basis. Recovery of as many transferred fibers as possible may provide the following information:

a.) A clearer picture of the events may emerge by localizing the findings, for example when 1:1 taping is used. This can only apply if the object being taped *has not been disturbed* since the crime took place. If exhibits have been packaged and submitted to the laboratory for taping, the chances are that some redistribution of fibers will have occurred, so that only if a notable majority of fibers are found in a particular area will this be of interest.
b.) The total number of fibers (in a particular area) on an item may help to assess whether a primary or secondary transfer has taken place. The key questions are—how many fibers are likely to have been shed from the donor item? (this number can only be estimated) and, What percentage of this is represented by the number of recovered fibers? The issue of persistence is important: how many fibers would be expected to have remained on the garment? The use of live transfer experiments, replicating case circumstances as accurately as possible, may provide enlightening information. If time permits, live transfer trials will nearly always yield information that is interesting and useful, even if only in a general sense.

In the second stage regarding how many fibers should be completely analyzed, the question is—on what percentage of recovered fibers (whose composition and morphology microscopically match the known sample) is it necessary to carry out additional examinations (FTIR, MSP, TLC) before the results obtained from a random sample can be said to apply to the remainder of the unexamined population with a known degree of confidence? The problem has been addressed in relation to trace evidence by Faber et al. (35), who provided some guidelines. The problem is related to the discriminating power of the techniques used for the examinations. These authors base their choice of sample size on the following criteria: "the sample size *n* should be the minimum number such that if all the fibers in the sample match, then it can be stated with (say) a 95% confidence level that (say) at least 80% of the total population (0.8 *N*) matches." An additional concern is to choose values for the confidence level and minimum number of matching fibers in the population which are practically significant.

Solving this problem may influence fiber examinations in the future. The lower the number of samples required to fulfill the necessary sampling criteria, the greater the saving in analytical time. It is important to be able to show that the same analytical steps have been carried out, with the same results on identifiable control and recovered fibers.

More on Selection of Target Fibers

As a result of ever-increasing research into fiber frequencies, more information will become available about subgroups of fibers within "blocks of color" e.g., grey polyester, blue acrylic, etc., and it may be possible to be more specific about choice of target fibers. If it can be shown that certain spectra occur very often because they originate from dyes that are used in great quantity like sulphur black 1, or reactive black 5 on black cotton (36); it may become increasingly obvious that it is usually not worth including such fibers in a transfer examination as their evidential value is extremely limited. Conversely, this type of research helps to increase the value of fibers whose dyes produce uncommon spectra.

The question has been posed (37) whether in some circumstances it is worth using cotton as a target fiber at all. Cotton fibers of certain colors, grey/black dyed with sulphur black, turquoise, and even some blues can be very hard to distinguish from one another within their own group, making it difficult or even impossible to come to any conclusions, let alone decide whether or not spectra from recovered fibers match those in a known sample. Factors in favor of rejecting cotton target fibers are:

a.) The recovery of cotton (unless mercerized) from tapings depends solely on color (unlike manmade fibers), therefore many more potential hits are recovered.
b.) Even with the help of MCS, sorting of a large number of recovered fibers for "collectives" takes longer—spectra must be run from all fibers in color groups, as in this situation the spectra offer the only effective sort characteristic after color and fluorescence.
c.) Within sorted spectral groups, very careful comparative brightfield and fluorescence examinations are necessary to confirm the matches. These can be complicated by the extreme range of depth of dyeing effects and fluorescence variation that can be found within cotton samples.
d.) Spectral variation within known samples may be extreme, sometimes making it difficult to decide if a particular recovered fiber lies within the range of variation or not. To answer this question reliably, it may be necessary to run far in excess of the usual ten spectra from the known sample.
e.) For those examiners who do not have access to a microspectrophotometer, difficulties may be encountered in extracting sufficient dye for thin layer chromatography, meaning that an objective color comparison is ruled out. In the case of ingrain (rarely seen) vat and sulphur dyes there is no accepted method of extraction. However, occasionally dyes in these classes may "bleed" into an extractant, yielding a solution that is suitable for TLC.

All of these aspects will increase the examination time if they are to be properly dealt with.

On the other hand, there may be circumstances where examiners definitely should look for evidence of transferred cottons:

a.) when they are of an unusual color, e.g., purple or orange, or have an unusual spectrum within a more common color class;
b.) where it may be possible to show that they are present in a particularly case-relevant location where this variety of fiber would not normally be found (in high numbers);
c.) when they are present in the donor textile in conjunction with manmade fibers (especially if these are of an infrequent type);
d.) where there is no alternative, i.e., all of the garments in a particular case are cotton—unfortunately the consumption of cotton worldwide is far in excess of that of any other fiber type.

Assessment of Evidential Value

The ultimate test of fibers evidence depends on how the evidential value of the findings is assessed, expressed by the examiner, and perceived by the Court. The evidence must be succinctly presented in an unbiased and understandable manner. The structure and content of the report is very important. Of fiber examiners surveyed in Europe, 78% (14) thought that reports should contain an interpretive summary.

Whether or not a Bayesian approach is used to present fibers evidence, the issue of fiber frequency plays a dominant role in assessing the evidential value of fibers. In every country, and perhaps in some cases geographical region, there will be a specific rank order for the frequency of occurrence of the different generic varieties of man-made fiber. Within this order, other factors like morphological features, polymer composition, sales figures, etc. then start to play a role. The evidential value of fibers may be enhanced by many other factors affecting fiber frequency of which scientists need to be fully aware. Any unusual chemical, physical or morphological properties, or special features caused by processing, damage or environmental factors will tend to increase evidential value (15). Eventually, it should be possible to fit all of the fragments of information relating to fiber frequency together like the pieces of a jigsaw puzzle, to build up a complete picture. These factors can be divided into those which influence the numerator and the denominator respectively in the two opposing hypotheses that are used in Bayes theorem to calculate the Likelihood Ratio (Jackson: personal communication). Fiber transfer, persistence, and sheddability will influence the numerator and data on the frequency of color and morphological features, plus information from target fiber and population studies together with production figures will influence the denominator.

Perhaps the greatest advantage of Bayes theorem is that it provides a model for incorporating the most relevant objective knowledge currently available into evidence evaluation and forces the examiner to consider other factors relating to the case other than just the results of the laboratory examination. A recent collaborative test exercise (38) carried out by the European Fibres Group showed that the use of Bayes theorem is not yet widespread in reporting fiber evidence, but that some laboratories in Europe are learning to consider competing hypotheses which offer alternative explanations for the findings, and then to give opinions using a verbal probability scale. It may also be helpful to the overall evaluation of case findings to consider different issues within the same scenario separately.

A survey carried out in 1998 (22) on the evidential value of fibers and on the interpretation of evidence in fiber cases involving 50 fiber examiners from Europe and 29 from North America clearly showed that fiber frequencies are being overestimated. This can lead to good evidence being severely undervalued. The reason for this may be partially due to inexperience but can probably be traced back to inadequate training. Few fiber examiners appeared knowledgeable about how different combinations of morphological characteristics (cross section/delusterant) or different polymer compositions can affect the relative frequency of subgroups within one generic class of man-made fiber. This has already been referred to earlier in connection with the use of infrared spectroscopy to subgrouping acrylic fibers.

These problems need to be rectified if the impact of fiber evidence is to be improved. Additional training will provide examiners with the confidence to make distinctions about the evidential value of man-made fibers to reflect their high degree of polymorphism. That there is no formalized training with respect to evidential value was apparent in the survey by reading the opinions of different examiners within the same laboratory/system when asked questions about fiber frequencies (22).

Without exception, all respondents felt that they would benefit from attending workshops on the interpretation of fiber evidence (if they were available). Greater cooperation between experienced fibers case workers and proponents of Bayesian theory in writing realistic examples applying the Bayesian approach to casework would be very helpful.

With respect to interpretation of fiber evidence, most deficiencies could be corrected by better training and by accumulating more data relevant to fiber frequencies. Training should include:

a.) greater intra and inter laboratory discussion about fiber frequencies and inclusion of a section dedicated to evidence interpretation;
b.) required reading to familiarize fiber examiners with relevant published data and textile journals and encourage them to develop contacts within the fiber industry;
c.) test samples aimed at improving analytical ability and competency to recognize subgroups within generic classes and to relate to their frequency;
d.) information about fiber production, dyeing, and finishing;
e.) the application of Bayes theorem to interpreting fiber evidence;
f.) report writing.

Data accumulation is time consuming, but is not technically demanding. Careful record keeping using case work and/or other samples can be used to amass very valuable data on morphological characters/polymer subgroups in a relatively short time. If research is beyond the resources of individual laboratories, the best approach appears to be to develop joint projects using the resources of working groups like the FBI sponsored Scientific Working Group for Materials (Fibers) or the ENFSI European Fibres Group and then to combine the results. It will be critical for the results of such projects to be published, as court-going scientists must be able to reinforce opinions with references to factual data. The best way of coping with a larger project, like establishing a frequency data base similar to those in existence in Europe (Adams et al., personal communication), (39) is probably to do so on a regional basis, establishing an information center accessible to scientists from various laboratories. Such a center could also provide assistance with industrial enquiries.

Conclusion

There will always be cases where fibers evidence can be used to good effect, sometimes fibers may represent the only type of physical evidence available. An increasing emphasis on the use of DNA technology has emphasized the need for a new approach toward fibers as a means of providing evidence in forensic investigations. Recent surveys carried out by international working groups have highlighted existing deficiencies, and at the same time suggested ways in which they can be corrected.

Progress can be made by improving:

a.) awareness of the potential of fiber evidence;
b.) the use of fibers to provide investigative information particularly in the initial stages of a case;
c.) exchange of information between the customer and the forensic scientist;
d.) case management;
e.) streamlining of the analysis and knowing which techniques to use and when to use them;
f.) use of existing data pertinent to evidence evaluation;
g.) accumulation of more data relating to fiber frequencies;
h.) training on report writing and better presentation of the evidence;
i.) "willingness to present personal opinions based on pertinent facts, and to defend them" (2);
j.) consideration of using a Bayesian approach to evidence evaluation;
k.) the degree of specialized training undergone by examiners.

Case management is a critical issue. Some fiber examinations are so complex and exhibit such variability that effective case assessment can only be carried out by a person who has specialized knowledge and experience, which will enable them to ask the right questions and to steer the examination accordingly. The case manager needs to be fully versed not only in the analytical possibilities but also well acquainted with the pieces that make up the evidential value jigsaw puzzle as discussed earlier. A recent survey (14) showed that 68% of trace evidence examiners in North America spend less than 25% of their time examining fibers; this reinforced the findings of an earlier survey showing that for 59% of examiners the time spent was between 5 to 20%. To put this in perspective—a potential car buyer probably would not seek advice about buying a new car from a salesman who spent 80% of his time selling bananas! A greater degree of specialization can only pay dividends. While some law enforcement customers may be restricted to area crime labs, others are not and may choose to go where they get the best service.

In terms of the financial outlay spent in training staff and equipping DNA analytical facilities, the objectives listed above could be realized at minimal expense. It is possible to make objective assessments of fiber frequency. Being able to give objective opinions on frequency is of overwhelming benefit to fiber evidence, even in the current situation where accurate color data cannot be taken into account. It is difficult to store more than a limited amount of color data and in searching it is necessary to use spectra as well as complementary chromaticity coordinate values. This has further resource implications. It would be a great advantage if more laboratories had access to frequency data. It does not require extraordinary mental ability or special facilities to acquire it; just time, dedication and, knowledge of data storage and retrieval. It is a mistake to say that without numbers, fibers evidence is useless and that opinions are less valid. This has already been effectively demonstrated by population and target fiber studies (15).

In his article on "the tyranny of numbers" (40), Houck in common with Chapin (2) expresses the concern that the public and the courts (because of their experiences with DNA evidence) now expect fiber examiners to use mathematics and statistics. The large number of variable factors which must be considered in evaluating fibers evidence often require inductive (common sense) rather than the deductive (mathematical) logic which generally appeals to jurors and lay-people. Houck (40) mentions that a major problem is that "trace material populations may change at least as fast, if not sometimes faster than they can be sampled." This is not completely correct. It does apply to recovered fibers (random fiber populations found on various surfaces) but not to known textile materials, where, because of long term production processes, chemical and morphological characters will remain constant over long periods, although fashion colors may change. The type of fibers used to produce various textiles also remains constant because the items depend on the fibers displaying certain properties. In these cases, reliable frequency data can be collected and is useful insofar that fiber frequency in "recovered fiber" populations will reflect that in known textile populations.

In the nascent stage of development of the use of frequency figures in fibers evidence, some objective data is better than none. The use of available data [Adams: personal communication] (39) to provide helpful information in relation to interpretation of fibers evidence is acceptable, provided its limitations are made clear. The fact that a particular fiber type has never been encountered at a crime scene (40) does not make it rare. Anyone may turn to crime. The fiber frequency problem is therefore not related to previous offenses, but to the general fiber population. With the advantage of objective data, it is not a question of whether fibers can provide good evidence in criminal cases, but rather whether the will is there to use them. Peter DeForest states that "part of the explanation of the underutilization of trace evidence is attributable to lack of awareness on the part of both investigators and forensic scientists of the potentials of trace evidence." The impetus to overcome this situation lies partially with fiber examiners themselves—they must be able to convince both managers and law enforcement officers of the need to retain the capability, and by improving education and data collection, learn to exploit the full potential of this form of forensic evidence.

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