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The Detection and Enhancement of Latent Fingermarks Using Infrared Chemical Imaging

ABSTRACT: The use of a new technique, Fourier transform infrared (FTIR) chemical imaging, has been demonstrated for the enhancement of latent fingermarks on a number of surfaces. Images of untreated fingermarks on glass backgrounds with excellent ridge detail were acquired using infrared chemical imaging. High quality fingermarks on glass backgrounds were also developed using ethyl cyanoacrylate (super glue) fuming and subsequent infrared chemical imaging. This new method allows the collection of images from backgrounds that traditionally pose problems for current fingermark detection methods. The background may, for example, be highly colored, have a complex pattern, or possess other pattern or image characteristics that make it difficult to separate fingermark ridges using traditional optical or luminescent visualization. One background that has proven to be a challenging surface for the development of latent fingermarks is the Australian polymer banknote. To demonstrate the power and applicability of infrared chemical imaging, fingermarks fumed with ethyl cyanoacrylate were successfully imaged from Australian polymer banknotes.

KEYWORDS: forensic science, chemical imaging, fingerprints, infrared, FTIR, hyperspectral imaging, cyanoacrylate

All fingermark detection techniques aim to create contrast between the ridge details of a latent fingermark and the background on which it is located. The majority of current methods rely on this contrast to be in the visible part of the electromagnetic spectrum, and thus, such methods encounter problems when background interferences such as printed images or patterns are present. Some of these problems can be overcome using traditional visible or fluorescence imaging techniques (e.g., alternate forensic light sources with appropriate barrier filters). Visible and fluorescence chemical (hyperspectral) imaging techniques have recently shown promise in addressing some of the more difficult problems (1,2). In these techniques, images are collected at many discrete wavelengths across the spectrum. Using this approach, wavelengths that give maximum ridge contrast can be found and chosen as the basis of fingermark images, or, where this gives unsatisfactory results, multivariate image analysis techniques can be employed to improve contrast (1,2). However, due to the very broad, overlapping bands that make up all visible absorbance and fluorescence spectra, it is not always possible to obtain acceptable fingermark images even using chemical imaging techniques in this region of the electromagnetic spectrum.

The vibrational spectra (infrared or Raman) of most carbon compounds consist of large numbers (often more than ten) of narrow, well-resolved bands which represent vibrational modes of discrete functional groups in these molecules. As a means of identifying and discriminating between different molecules, vibrational spectra are thus far more powerful than UV-visible methods. To date, this inherent feature of infrared (and Raman) spectra has not been utilized in the forensic visualization of fingermarks, although there have been several studies based on the infrared analysis of the chemical constituents of fingermarks (3,4). This is because until recently, infrared and Raman techniques provided no spatial information about a sample. Spatially resolved chemical information, however, is now accessible with the development of infrared chemical imaging (5–8). This paper describes the application of infrared chemical imaging to the visualization of fingermarks, with and without cyanoacrylate fuming, and it explores the future possibilities of this technique.

Instrumentation for Infrared Chemical Imaging

Infrared chemical imaging generally uses a focal plane array (FPA) detector that can be thought of as a large number (thousands) of discrete detectors (or pixels) laid out in a grid pattern (Digilab, Nicolet, Bruker instruments). In an alternative design (the Perkin Elmer Spectrum Spotlight instrument), a relatively small number of detectors (sixteen) is used in a zigzag pattern, under which the sample is scanned spatially using an automated microscope stage. In both designs, the instrument collects images that may consist of thousands of pixels, with a spectrum at each pixel. The best spatial resolution possible is of the order of 5 μm because of the wavelengths of light involved, so the smallest effective pixel size in infrared chemical images is usually about 5 μm.

By far the most common type of FPA detector used for mid-infrared chemical imaging is a 64×64 pixel mercury cadmium telluride (MCT) focal-plane array detector. This type of detector collects 4096 infrared spectra simultaneously into a file that can be thought of as a *datacube* (Fig. 1). The datacube ($x \times y \times$ wavenumber) can be visualized as a collection of images of the sample, with one image for each wavenumber resolution unit.

These images, or slices through the datacube, are often presented as "false color maps," formed by attributing an arbitrary color to each pixel according to the spectral intensity at the frequency (wavenumber value) selected. Most commonly, a color scale from high intensity (red) to low intensity (blue) is employed, but a grayscale also can be used.

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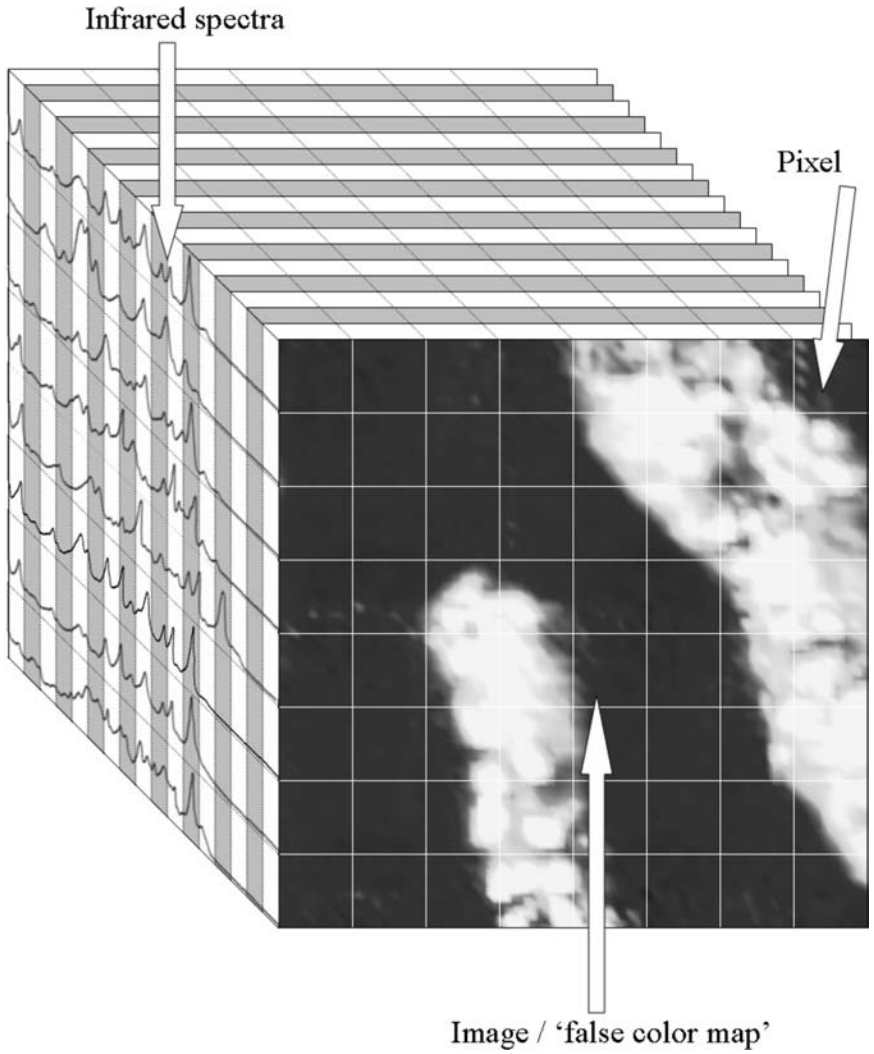

FIG. 1—*Diagrammatic representation of "datacube" generated by focal plane array (FPA) detector.*

With a pixel size of about 5–6 μm, the infrared image produced by a 64 × 64 array is about 350 × 350 μm. Strategies for imaging larger samples, such as fingermarks, vary according to the instrument used. The Perkin Elmer Spectrum Spotlight instruments can image over an area limited only by the movement of the microscope stage (several centimeters in each direction), but they collect only 16 pixels' worth of data at each stage position. Larger sampling accessories on the Nicolet and Digilab instruments allow the rapid collection of images that may be several millimeters on each side, depending upon the size of the detector array used. However, these do not allow the imaging of a significant area of a fingermark with the typical 64 × 64 array size. An alternative is to use the combination of expanded field of view microscope optics (taking the image size up to about 700 × 700 μm) and tiling or *mosaicking* capabilities on the Digilab Stingray systems. With this approach, an infrared chemical image of a fingermark with adequate spectral signal-to-noise can be captured over a period of a few hours. Some trade-offs with spectral and spatial resolution can be made to reduce collection time and file-size.

Reagents for Infrared Chemical Imaging of Fingermarks

As mentioned, because of the large number of narrow, well-resolved absorbance bands that make up the infrared spectrum of organic (carbon-based) compounds, infrared chemical imaging offers potentially fewer problems with background interferences. This advantage can be exploited through the use of suitable reagents for the imaging of fingermarks. A suitable reagent for this application is one that:

- is easy to apply to evidentiary samples containing latent fingermarks
- selectively reacts with fingermark constituents
- contains an infrared vibrational frequency which is strong, isolated, and unique and thus not present in most backgrounds/surfaces

For the successful imaging of fingermarks (sufficient contrast between the ridges and the background), the chemical composition, and thus infrared spectrum, of the treated fingermark must be distinguishable from the infrared spectrum of a broad range of backgrounds/surfaces. This would be achievable if the infrared spectrum of the treated fingermark were to contain at least one spectral peak that is uncommon in the infrared spectrum of most surfaces.

Compounds which contain the cyano- or nitrile (C≡N) functional group are immediately obvious candidates for the infrared chemical imaging of fingermarks. Not only is the stretching frequency of this functional group isolated and usually free from interferences in the

spectrum at around 2200 cm^{-1}, but it is also present in one of the most commonly used fingermark detection reagents, cyanoacrylate (super glue).

This article evaluates infrared chemical imaging of fingermarks as a potential forensic technique, and it describes preliminary attempts to obtain infrared chemical images of both latent and chemically treated marks. The potential of the technique, linked with the use of proposed new reagents, is also discussed.

Materials and Methods

Latent fingermarks were placed on clean, dry glass microscope slides and freshly cleaned and dried circulated Australian polymer $5 banknotes. In one experiment, a fingermark was placed on an infrared reflective (metal oxide-coated) microscope slide (Kevley Technologies). Marks were prepared by thoroughly washing, rinsing, and drying hands before swiping a cleaned finger across an oily region of face (forehead, nose or neck) and finally placing the mark on the desired surface. Fresh latent fingermarks from a good donor were developed using a purpose-designed forensic cyanoacrylate fuming cabinet (Carter-Scott Design, Australia). Approximately 1 mL of ethyl cyanoacrylate (Selleys® Supa Glue) was used for each treatment. Glass slides were fumed until ridge development was obvious (an average of ten minutes), while polymer banknotes were fumed for an average of sixty minutes. Although ridge development on the banknotes was not visible to the naked eye at this point, a reference fingermark on a glass slide began to show signs of over-development at fuming times in excess of sixty minutes.

Infrared chemical imaging of fingermarks was carried out using a Digilab Stingray system, comprised of an FTS 7000 FTIR spectrometer, coupled with a UMA 600 infrared microscope with a Lancer 64 × 64 focal plane array (FPA) detector. Images and spectra were collected and processed with Digilab Win IR Pro software. All samples were imaged in reflection mode using the expanded field of view (EFOV) setting, in which each individual image tile is approximately 700 × 700 μm in size. Typically, 256 (16 × 16) tiles, with a pixel aggregation factor of 16, were collected, giving a total area imaged of 1.12 × 1.12 cm at a spatial resolution of about 44 μm. Image collection times using these parameters were typically of the order of four hours. The infrared spectra within each image were collected at 16 cm^{-1} resolution, using 64 co-added scans. Sample spectra were ratioed against background spectra so as to give log(1/reflectance) output, unless otherwise specified.

Results and Discussion

Untreated Fingermarks

In order to assess both the potential advantages and limitations of infrared chemical imaging, untreated latent fingermark marks were imaged against plain backgrounds such as glass. Obtaining high quality images of untreated fingermarks did not always require the selection of particular infrared peaks. In some cases, the choice of certain frequencies for imaging gave excellent contrast purely because of the optical (rather than the chemical) properties of the sample at these frequencies. Ordinary glass is not an ideal background from which to collect infrared spectra, as it is very strongly absorbing. Thus, infrared spectra collected from plain glass surfaces often can be highly distorted and chemically uninterpretable. Despite this, fingermarks often can be imaged successfully by scanning through the sequence of images collected across the spectral range. Figure 2 shows an untreated fingermark on a plain glass microscope slide. The infrared image shown (Fig. 2*c*) was not formed using the area under a peak in the spectrum, but was formed simply by imaging the spectral intensity at a single frequency, namely 1188 cm^{-1} (Fig. 2*b*). While this is strictly not *chemical* imaging per se, it does illustrate the ability of the infrared technique to produce images even from non-ideal samples. The image was further improved by adjusting the contrast and brightness levels using image processing software (Fig. 2*d*).

The infrared spectra of many untreated fingermarks do show peaks due to C-H stretching vibrations at around 3000 cm^{-1}. These vibrations are common to most organic compounds, but aliphatic compounds such as fatty acid residues are the main source of C-H bonds in latent fingermarks. Peaks due to C-H stretches can thus be used to visualize fingermarks against some backgrounds, particularly those that do not contain C-H bonds. Figure 3 shows a small section of an untreated fingermark on an infrared reflective glass slide. The infrared spectra from the fingermark ridges in this image (Fig. 3*a*) show peaks at around 2900 cm^{-1}.

It is important to note that the success of this experiment relied on the absence of vibrational peaks from the background in this region of the infrared spectrum. In general, the C-H stretching vibration is neither sufficiently isolated nor free from interferences to have a practical application on a variety of surfaces. This spectral feature is shown here to be useful for infrared-reflective backgrounds (metals, coated glasses) but is unlikely to be as successful on other backgrounds such as polymer or ceramic substrates, because the infrared spectra of such substrates generally will contain their own C-H stretching vibrations that are likely to interfere with those of untreated fingermark constituents.

The infrared imaging of *untreated* latent fingermarks is limited to backgrounds that are absent from interferences in the C-H region. Examples of backgrounds other than glass that may yield similar results include metals, minerals, ceramics, and certain polymeric materials that do not contain C-H bonds (e.g., silicone based polymers). For fingermarks on other backgrounds, some type of chemical enhancement technique is required prior to infrared imaging, hence the attempts described in the following sections to image cyanoacrylate-fumed marks.

Ethyl Cyanoacrylate Fumed Fingermarks

A freshly deposited fingermark on a glass slide that was fumed with ethyl cyanoacrylate and subsequently visualized with infrared chemical imaging is shown in Fig. 4. This fingermark was visible to the naked eye, and a white light image of the mark is given in Fig. 4*a*. The promise of ordinary cyanoacrylates as the perfect infrared imaging reagents for fingermarks, owing to their C≡N (nitrile) functional group, was not realized. This is because the C≡N stretching vibration at around 2200 cm^{-1} in the liquid, monomeric cyanoacrylate actually disappears upon polymerization. This has been observed by both ourselves and other workers (9–11) using both infrared and Raman spectroscopy, and it has been attributed to intra- or inter-chain reactions of the nitrile groups as the polymer is curing. Despite this, it is still possible to find bands in the infrared spectrum of cured ethyl cyanoacrylate that can be used to visualize fingermarks on a number of backgrounds. In Fig. 4*c*, excellent contrast is observed between the fingermark ridge detail and the glass background when the intensity of the carbonyl (C=O) peak of the polymerized cyanoacrylate ester at ~1743 cm^{-1} (Fig. 4*b*) is used to form the image. Unlike the ubiquitous C-H stretching vibration used to image untreated fingermarks in Fig. 3, the carbonyl functional group used here is a less common constituent of possible backgrounds. Examples of backgrounds which would yield similar results for ethyl cyanoacrylate fumed fingermarks include glass, metals, certain polymers, minerals, and ceramics.

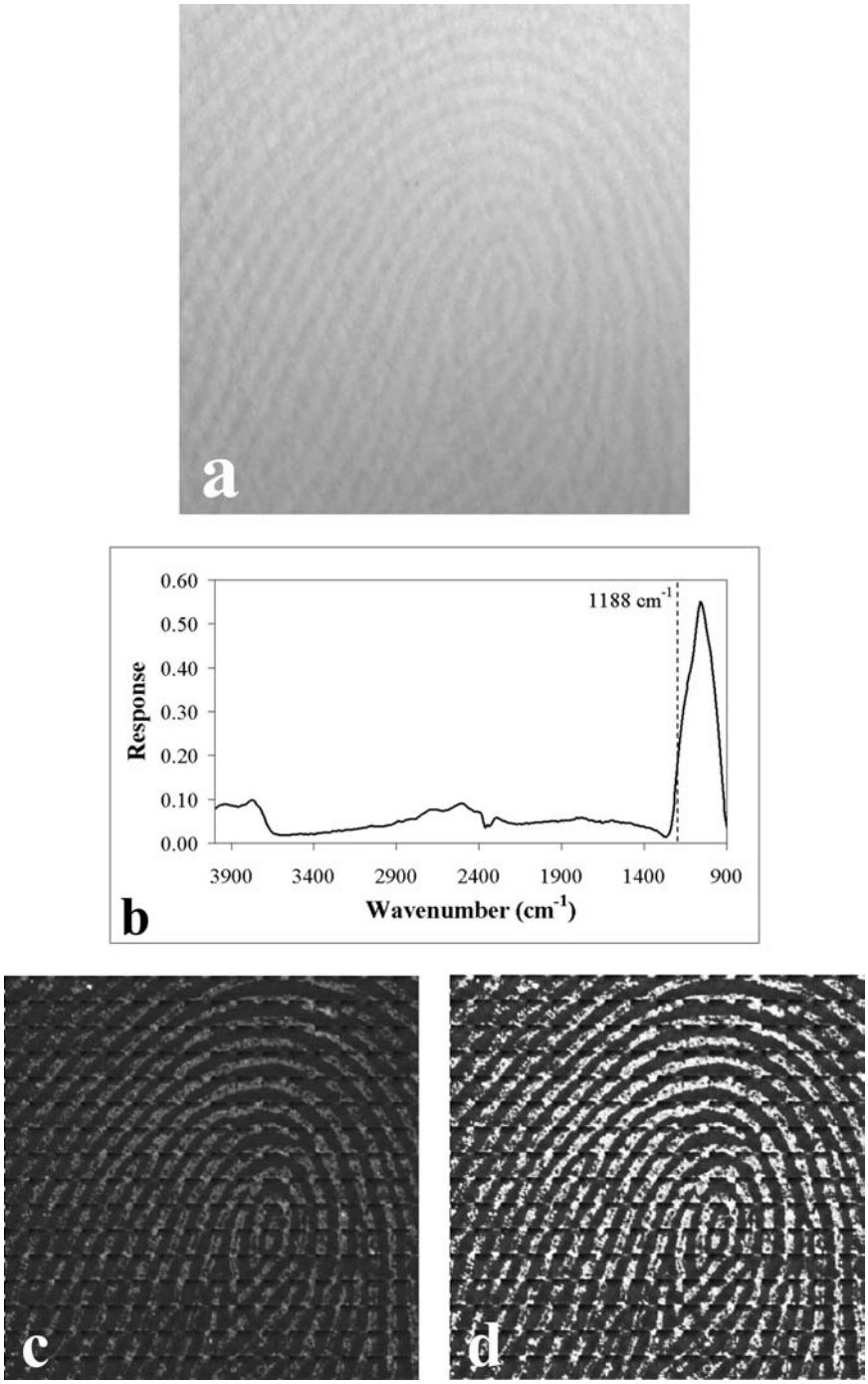

FIG. 2—*Untreated fingermark on glass slide: (a) White light photograph of untreated fingermark on glass slide. (b) Infrared spectrum showing imaging frequency at 1188 cm^{-1}. (c) Monochrome representation of infrared chemical image. (d) Figure 2c with contrast and brightness adjustment.*

Of these potential backgrounds, one of the most interesting to forensic scientists in Australia and New Zealand (and several other countries) is the polymer banknote. Polymer banknotes have been particularly difficult backgrounds for latent fingermark revelation (12). They possess a colored, uneven, patterned, and variable background. Furthermore, the material from which they are made does not behave as a typical porous surface like paper, nor like a non-porous surface like many plastics or glass. Instead, the polymer banknote surface is somewhere in between these extremes and is often classed as semi-porous. This makes the selection of a fingermark enhancement technique difficult. Conventional techniques for porous surfaces such as ninhydrin treatment, DFO treatment, or physical developer do not yield positive results on polymer banknotes. Cyanoacrylate fuming, the most common technique for fingermark enhancement on non-porous surfaces, also yields poor results.

Jones et al. describe the use of a combination of cyanoacrylate fuming, vacuum metal deposition (VMD), and luminescent staining on polymer surfaces in general and on banknotes in particular (12–14). To date, cyanoacrylate/VMD treatment remains the method of choice by the Australian Federal Police (AFP) for the revelation of fingermarks on polymer banknote substrates. VMD units are, however, expensive, and the technique requires significant experience for optimum results. Furthermore, the technique also requires

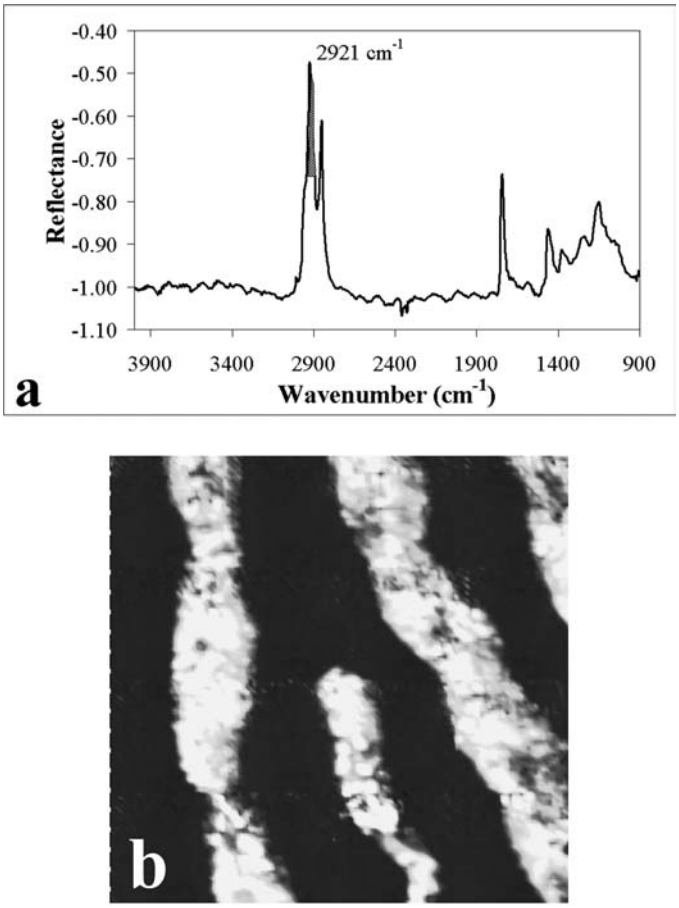

FIG. 3—*Small section of an untreated fingermark on an infrared reflective glass slide: (a) Infrared spectrum from fingermark ridge showing peak area at 2921 cm^{-1} used to generate image. (b) Monochrome representation of infrared chemical image.*

the application of luminescent staining (e.g., basic yellow 40 or rhodamine 6G) and subsequent visualization using an appropriate light source and luminescence imaging system (12).

The success of infrared chemical imaging of cyanoacrylate-fumed fingermarks on glass slides led to the attempt to image cyanoacrylate fumed marks on polymer banknotes. A fresh fingermark was deposited on a circulated but freshly cleaned Australian $5 polymer banknote. Marks were trialed on a number of different locations on the note. The best results are shown in Fig. 5, which demonstrates the power of this technique to image fingermarks against highly colored and complex backgrounds.

There is no visible fingermark in the optical image (Fig. 5*a*) of the polymer banknote after cyanoacrylate fuming, yet the infrared chemical image of the same sample reveals excellent ridge detail down to the third level (Fig. 5*c*). Fig. 5*d* shows that an even better image can be achieved by simply adjusting the contrast and brightness.

The infrared spectrum of the polymer banknote background exhibits a relatively broad peak in the same area (around 1712 cm^{-1}) as the carbonyl peak in poly(ethyl cyanoacrylate). The carbonyl peak of poly(ethyl cyanoacrylate) appears as a shoulder at around 1760 cm^{-1} on this larger background peak (Fig. 5*b*). Despite this, these vibrational peaks are sufficiently resolved from each other to create contrast between the fumed fingermark ridges and the background surface.

The contrast obtained on areas of the polymer banknote without intaglio printing is significantly better than that obtained on intaglio

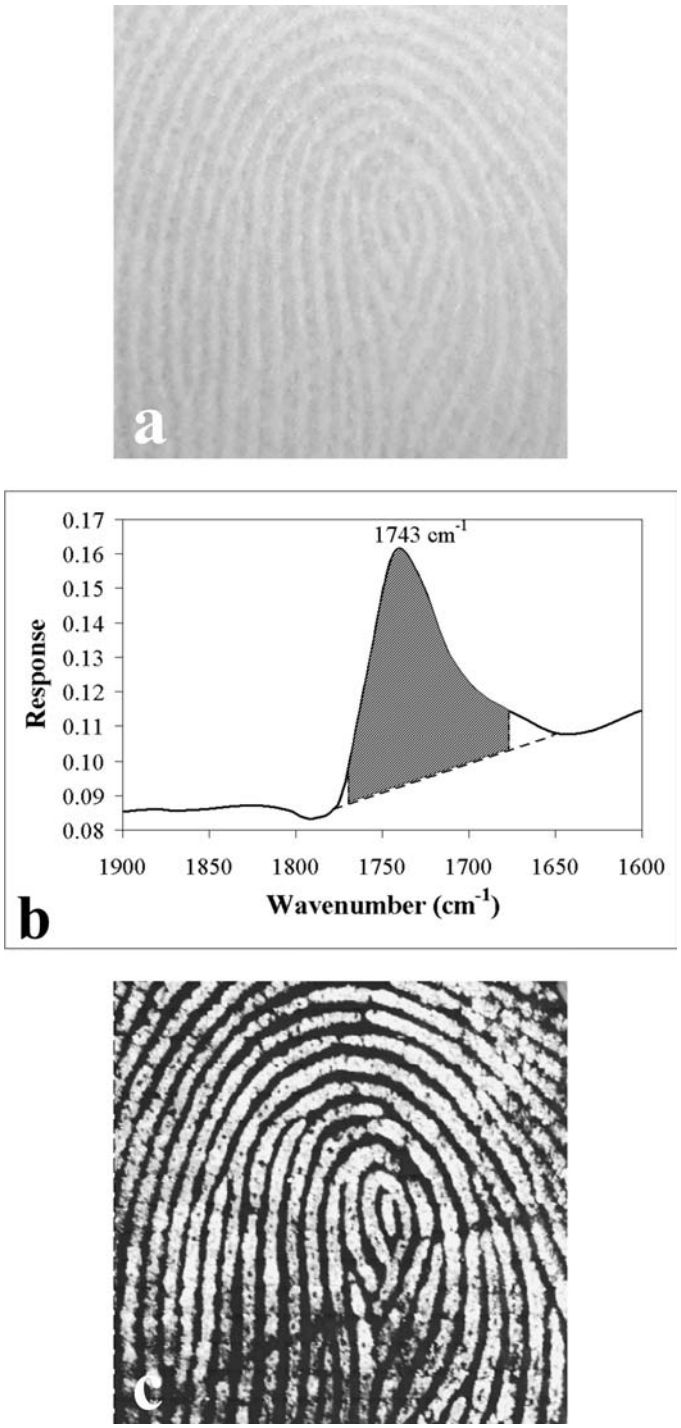

FIG. 4—*Ethyl cyanoacrylate fumed mark on glass slide: (a) White light photograph of ethyl cyanoacrylate fumed fingermark on glass slide. (b) Infrared spectrum of fingermark ridge showing peak area at 1743 cm^{-1} used to generate image. (c) Monochrome representation of infrared chemical image.*

printed areas of the note. This is demonstrated in Figs. 6 and 7. For the non-printed areas of the note, these images are of similar quality to those in Fig. 5. On the intaglio printed areas of the note, however, there is a significant drop in contrast, and the fingermark is at best only faintly visible on these areas.

There may be a number of reasons for this problem. Firstly, the fingermark may deposit differently on dissimilar areas of the note. The fingermark constituents transferred and those which are retained have been shown to differ, depending on the nature of the

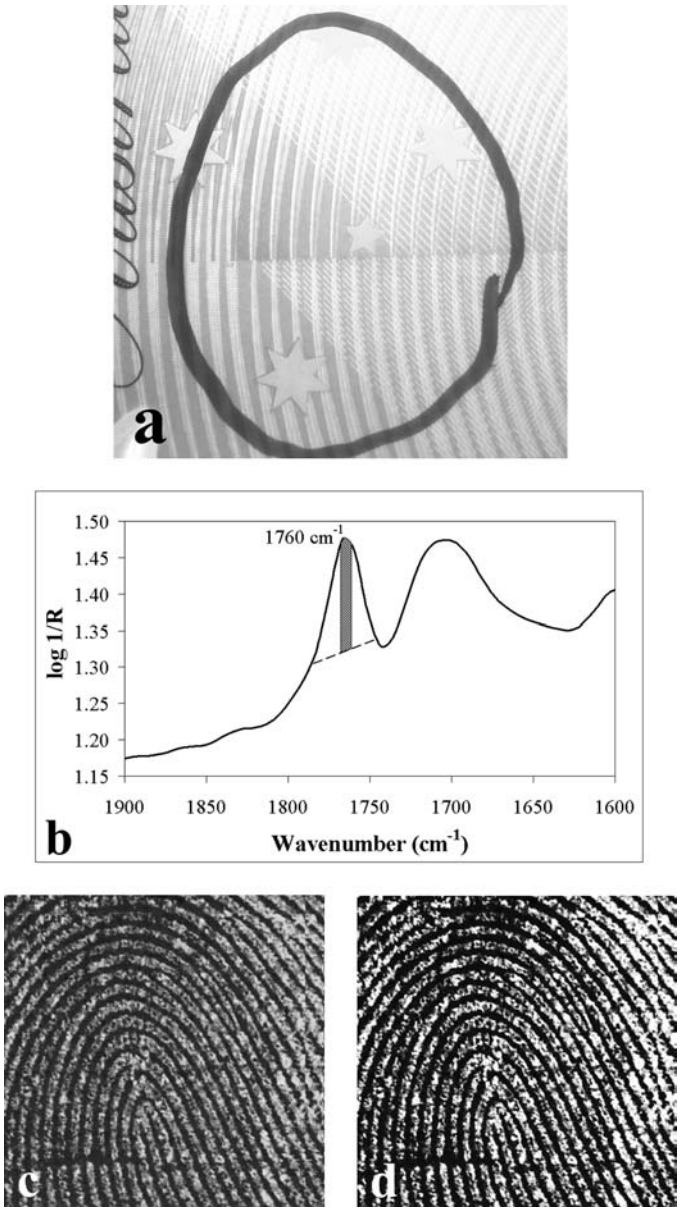

FIG. 5—*Ethyl cyanoacrylate fumed mark on $5 note: (a) White light photograph of ethyl cyanoacrylate fumed mark on $5 note. (b) Infrared spectrum of fingermark ridge showing peak area at 1760 cm^{-1} used to generate image. (c) Monochrome representation of infrared chemical image. (d) Figure 5c with contrast and brightness adjustment.*

substrate onto which they are transferred (14,15). Since the non-printed area of a polymer banknote is a different surface than the printed area, these variations in transfer may explain the differences seen in image contrast. Another possible explanation is that the type of fingermark constituents transferred and their relative abundance will, in turn, affect the extent of ethyl cyanoacrylate polymerization on the fingermark ridges.

The most likely explanation, however, for the observed differences is the variation in size and intensity of the interfering background infrared peak between printed areas and non-printed areas. The interfering background peak seen at around 1712 cm^{-1} in non-printed areas of the note is significantly larger and broader in the printed area of the note. This is demonstrated in Figs. 6*b* and 6*c*.

Figure 6*b* shows the infrared spectrum of a section of fingermark ridge on the non-printed section of the note. As in Fig. 5*b*, the carbonyl peak of the poly(ethyl cyanoacrylate) and the interfering background peak can be resolved clearly. This resolution is sufficient to allow the fingermark to be imaged in these areas of the note. In contrast, the infrared spectrum of the intaglio printed section of the same note (Fig. 6*c*) shows a very intense, broad background peak that envelops and masks the carbonyl peak of the poly(ethyl cyanoacrylate) (note the vertical scales of these two spectra).

Application of Alternate Spectral Transforms and Multivariate Processing Techniques

As demonstrated by Exline et al. (1), one of the features of chemical imaging is that by their nature, the images collected (datacubes) contain a large amount of information that may not be exploited completely simply by an examination of individual spectra or the viewing of images formed at single vibrational absorption bands. There are a number of different approaches that can be used to make better use of the available information. These can be roughly divided into (i) alternate spectral transforms and (ii) multivariate (hyperspectral) image classification techniques. Alternate spectral transforms include different ways of ratioing the sample and background spectra (single beam, absorbance, transmittance, reflectance, log(1/reflectance), etc.), as well as later mathematical transforms of the data in the spectral domain, such as taking derivatives of the spectra. For example, although absorbance spectra generally have band intensities that are proportional to concentration, transmittance spectra may be preferred in imaging applications because the non-linear scale tends to exaggerate the relative intensities of smaller bands. This would assist if contrast were dependent on the intensity of a smaller bands that may represent a constituent of a latent or treated fingermark. The second derivative of a spectrum has the useful property of having (negative) narrow peaks at the position of each peak in the original spectrum, even for peaks that only appeared originally as shoulders. Thus, hidden bands and shoulders can be resolved, which is an advantage if they can be used to visualize a fingermark.

Multivariate (hyperspectral) image classification techniques utilize multivariate statistical techniques, such as principal components analysis, or one of various cluster analysis techniques, to classify spectra, and therefore pixels, in a hyperspectral (chemical) image according to similarity. This approach is used commonly, for example, by remote sensing scientists to classify regions in satellite images (vegetation, land-use, soil and mineral types, etc.), typically using a very small number of near-IR and visible light wavelengths (16). Powerful image analysis software packages with hyperspectral capabilities, such as ENVI (Research Systems Inc), are available for this purpose and may be readily adapted for forensic applications, particularly where only image contrast is desired. Multivariate image analysis techniques also are being used in conjunction with chemical imaging in important bio-spectroscopic applications, such as the classification of abnormal cell types in cancer histopathology (17–19). Likewise, in the forensic sciences, multivariate image classification techniques are being used in packages such as ChemAnalyze (ChemImage Corp.) to obtain better contrast in visible light chemical imaging of questioned documents and fingermarks (1).

Two attempts were made to further enhance the ridge details of the fingermark shown in Fig. 7. In the first of these principal components imaging was attempted using the CytoSpec software package (http://www.cytospec.com/), while in the other, the second derivative transform was applied to all the spectra in the data set that make up the infrared chemical image. The latter technique proved effective in highlighting subtle spectral differences between the two peaks of interest (the one from cyanoacrylate and the one

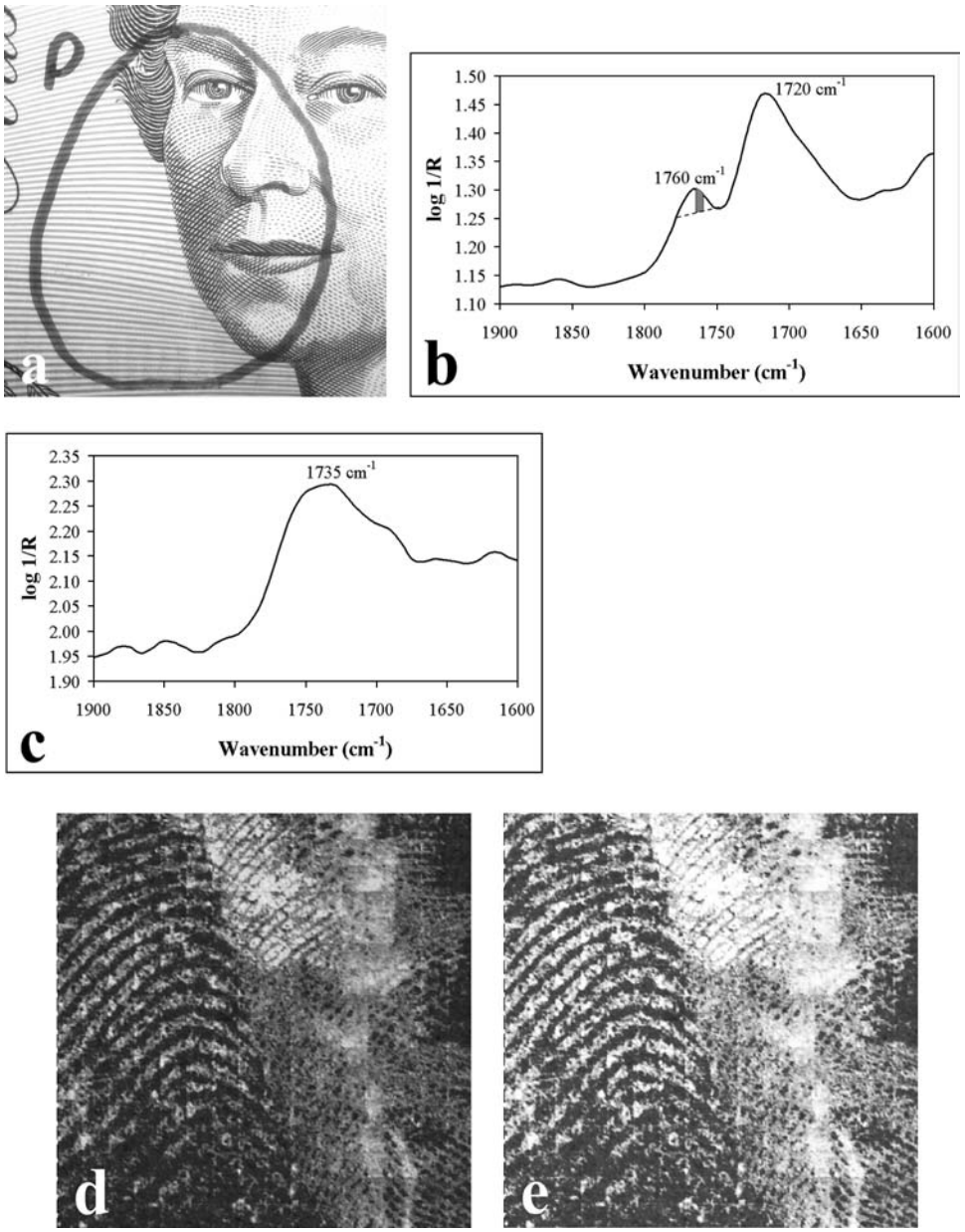

FIG. 6—*Ethyl cyanoacrylate fumed mark on $5 note: (a) White light photograph of ethyl cyanoacrylate fumed mark on $5 note. (b) Infrared spectrum of fingermark ridge on area of banknote free from raised intaglio printing showing peak area at 1760 cm^{-1} used to generate image. (c) Infrared spectrum of area of banknote with raised intaglio printing showing increase in size and intensity of interfering background peak. (d) Monochrome representation of infrared chemical image. (e) Figure 6d with contrast and brightness adjustment.*

from the background interference). The image formed after this data processing (Fig. 8*b*) clearly shows more ridge detail, particularly in the area previously obscured by the raised intaglio printing. For this particular dataset, although it did give greater contrast than the raw image data, supervised principal components imaging was unable to improve upon the second derivative image, whether it was applied to the raw data or to normalized, second derivative data.

Despite the improvements that can be obtained with further processing of the data, Figs. 6 and 7 demonstrate the problems associated with interfering peaks in the infrared spectrum of the background material and thus indicate the need for a fingermark reagent with a sufficiently intense and isolated infrared absorption band, if the full potential of this technique is to be realized. Potential reagents include those with an intense C≡N vibration. Work is underway in these laboratories to synthesize and isolate such reagents, applicable to a variety of fingermark substrate surfaces. If such reagents can be produced and utilized, the technique offers several advantages for fingermark visualization in difficult or high profile cases. These include the potential to visualize fingermarks with excellent contrast on almost any flat background and a reduction in the overall processing time or number of steps used for marks on difficult surfaces (relative to, for example, vacuum metal deposition techniques for polymer banknotes (12)). While infrared chemical imaging instrumentation is not currently common in forensic laboratories, the potential success of this preliminary work may lead to the development of less expensive and more accessible designs. Meanwhile, a full comparison of the technique with existing methods, using a variety of donors, surfaces, and fingermark ages, is underway, along with an examination of how it might fit into current latent fingermark enhancement sequences.

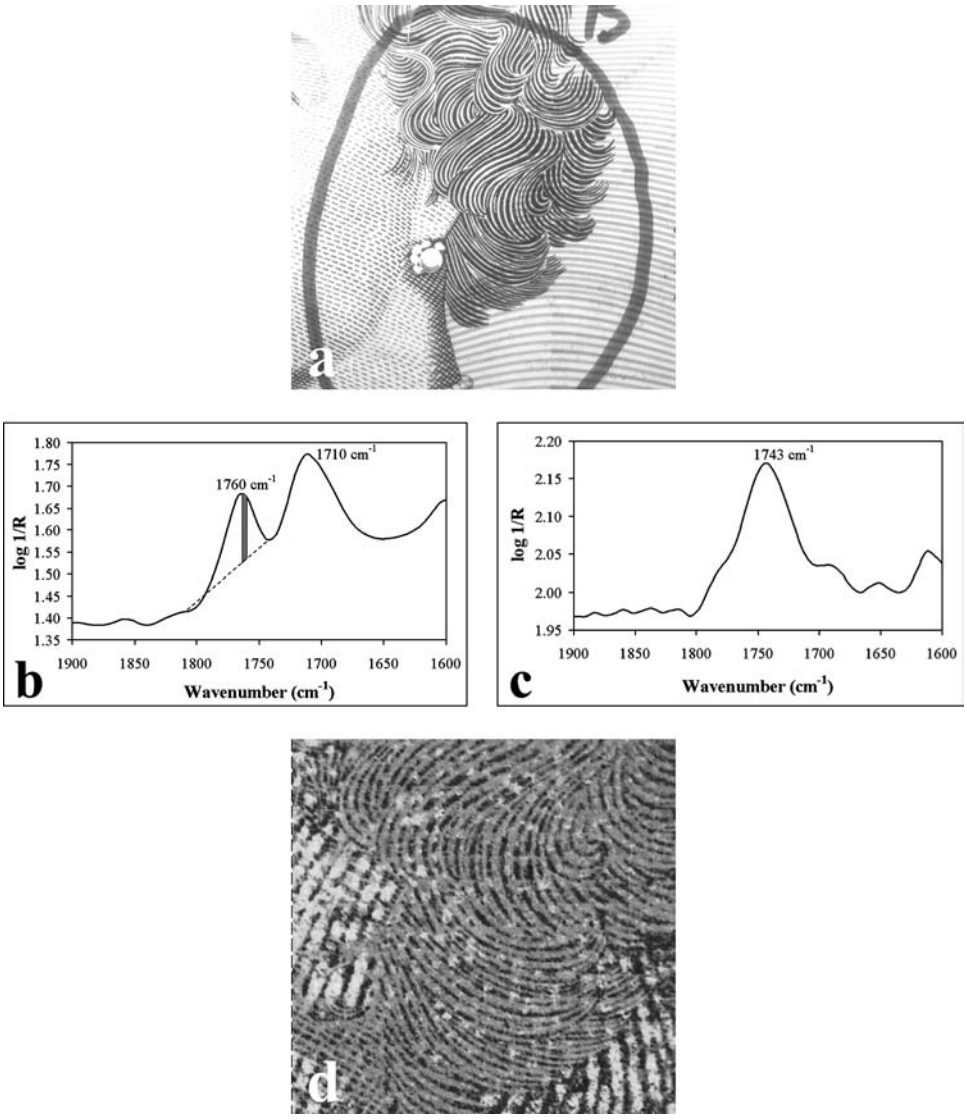

FIG. 7—*Ethyl cyanoacrylate fumed mark on $5 note: (a) White light photograph of ethyl cyanoacrylate fumed mark on $5 note. (b) Infrared spectrum of fingermark ridge on area of banknote free from raised intaglio printing showing peak area at 1760 cm^{-1} used to generate image. (c) Infrared spectrum of area of banknote with raised intaglio printing. (d) Monochrome representation of infrared chemical image.*

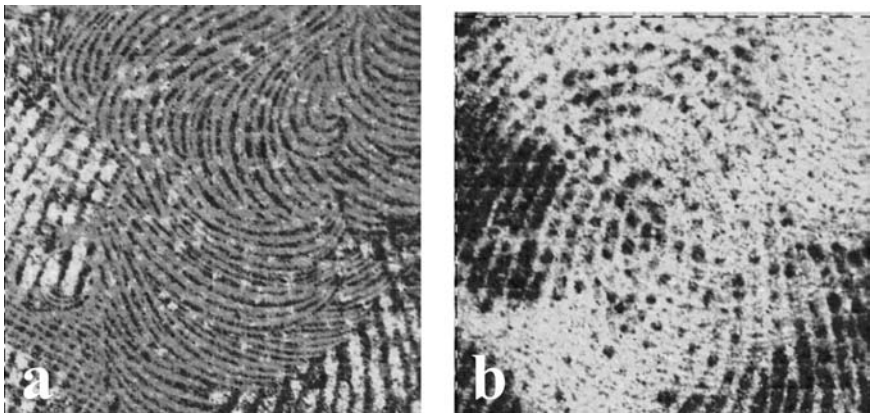

FIG. 8—*Infrared chemical image from Fig. 7d (a) before and (b) after second derivative processing of spectra.*

Practical Considerations and Limitations of the Method

The forensic practitioner considering infrared chemical imaging as a technique for the enhancement of fingermarks will be curious about some of its practical aspects. The availability of this type of instrumentation is currently not high, mainly due to the relative novelty of the technology and the cost of purchasing a system that must include an FTIR bench, an infrared microscope, and a focal plane array (or other imaging) detector. However, we are currently

observing trends that we believe will contribute to a surge in the popularity of infrared chemical imaging equipment. One of these is that infrared microscopes are now being manufactured in such a way that imaging detectors (such as FPAs) become merely optional extras that can be added onto a system at a later date. Thus, recent purchasers of infrared microscopes will find that they can upgrade to imaging capabilities without buying new instruments. Another trend is that the base hardware required for infrared chemical imaging (i.e., the FTIR spectrometer) is becoming less expensive due to technological improvements. As an example of this step-scan FTIR is no longer required for imaging, particularly where the detector array is 64×64 pixels or smaller.

Most of the technical limitations of infrared chemical imaging are simply those normally encountered in conventional infrared microscopy. Indeed, an infrared microscopist needs little extra training ($\sim$one day) to be able to collect chemical images, although multivariate image analysis, where required, requires more experience. The most significant imaging-specific limitations that apply to the enhancement of fingermarks are collection times (see Materials and Method) and sample size. Work in our laboratory has seen the former reduced significantly even during the preparation of this article, so that a *full* fingermark can be imaged in four hours, depending on the available chemical contrast. The maximum size of a single image varies according to manufacturer (it is 4.5×4.5 cm for our Digilab system), but so long as infrared microscopes are being used, there will be an upper limit dictated by the extent of travel of the microscope stage (4.5×8.0 cm in our case).

Acknowledgments

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