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A Scanning Beam Time-Resolved Imaging System for Fingerprint Detection*

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ABSTRACT: A highly sensitive confocal scanning-beam system for time-resolved imaging of fingerprints is described. Time-resolved imaging is a relatively new forensic procedure for the detection and imaging of latent fingerprints on fluorescent substrates such as paper, cardboard, and fluorescent paint. Ordinary fluorescent imaging of latent fingerprints on these surfaces results in poor contrast. Instead, the specimens are treated with a phosphorescent dye that preferentially adheres to the fingerprint which allows time-resolved discrimination between the fingerprint phosphorescence and the background fluorescence. Time resolved images are obtained by synchronizing the digital sampling of the specimen luminescence with the on-off cycle of the chopped illumination beam. The merit of this technique is illustrated with high contrast images of fingerprints obtained from the fluorescent painted surface of a Coke™ can.

KEYWORDS: forensic science, fingerprints, confocal microscopy, confocal macroscopy, scanning laser imaging, fluorescence imaging, time-resolved fluorescence

Time-resolved imaging occupies a small but important niche among other methods of recording latent fingerprints. This niche is defined by the limitations of other techniques. The most widely used traditional methods are dusting with powder and development with ninhydrin (1). Dusting is limited to fingerprints on smooth surfaces (2). Ninhydrin, which is used on porous surfaces, reacts with the amino acids in the fingerprint to produce a blue-purple dye called Ruhemann's Purple. The quality of the image attainable by these methods is directly related to the amount of material deposited in the fingerprint: a weakly deposited fingerprint results in a low-contrast image.

Weak fingerprints can often be resolved by utilizing fluorescent compounds and selective light excitation such as laser excitation. Fluorescent dusting compounds are commercially available. Fluorescent dye staining is frequently employed together with cyanoacrylate fuming. Ruhemann's Purple can be treated with ZnCl, or other reagents, resulting in a fluorescent compound. Other processes such as use of 1, 8-diazafluorenone (DFO) can be applied to untreated fingerprints achieving the same end. A laser of appropriate wavelength is used to excite fluorescence in the treated fingerprints. Filters are used to limit the detection of light to the emission range of the fluorescent compound used. Ideally, good contrast is observed between the fingerprint and the background material, however, some materials (e.g., paints, plastics, and various adhesive tapes) demonstrate intense background fluorescence and cannot be imaged in this way. These surfaces are candidates for time-resolved imaging where long-lived luminescence (phosphorescence) from the fingerprints can be distinguished from the short-lived background fluorescence.

The imaging technique described in this paper combines methods from time resolved microscopy (3,4), confocal imaging (5), and scanning laser macroscopy (6,7). Time-resolved microscopy has advanced rapidly in the 1990s and several different approaches have been developed (8). One method involves a gain-modulated multi-element detector (9,10) such as a charged-coupled device (CCD) to obtain the entire image in one shot. Another approach involves confocal laser scanning microscopy where an image is acquired point by point using a single-element detector (11) such as a photomultiplier tube (PMT). In this way, imaging can be achieved by adapting single point lifetime resolved detectors and electronics to a new scanning optical setup. Time-resolved fluorescence measurements are performed using either the time or frequency domain (12). Time domain measurements involve pulsed light source excitation with intensity measurements of fluorescence emissions made as a function of time after the excitation pulse. Frequency domain measurements utilize modulated excitation sources which result in modulated fluorescence emissions with a phase lag. Fluorescence lifetimes can be determined by measuring the amplitude and phase lag of the emissions.

The instrument described in this paper uses an inexpensive confocal scanning laser approach in the time domain where a pulsed laser source is generated using a continuous wave laser coupled to a mechanical chopper wheel. Confocal optics provide a means for generating very clear, crisp images of luminescent specimens due to the confocal optical sectioning ability. PMT-based detection offers a highly sensitive and inexpensive way to detect very weakly luminescent specimens.

Materials and Methods

Specimen Preparation

The samples presented are fingerprints deposited on sections of Coke™ cans. Initially the specimens were fumed with cyanoacrylate ester (Superglue®). The cyanoacrylate polymerizes on the

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ridges of the fingerprint forming a white product which can be stained with fluorescent dye (13). The specimens were treated with a solution of EuTTAPhen (Europium ThenoylTrifluoroAcetone ortho-Phenanthroline). This compound deposits within the cyanoacrylate polymer. The absorption and emission spectra of EuTTAPhen are very similar to the spectra of the related compound TEC (Thenoyl Europium Chelate) (14). EuTTAPhen absorbs near 350 nm and emits in a narrow range centered about 614 nm (15). The luminescence lifetime of EuTTAPhen is reported to be between 0.3 and 0.6 ms. The long lifetime phosphorescence of these compounds makes them suitable for time-resolved imaging, especially low-cost chopper-based techniques.

Optical Design

The fingerprint imaging system design is similar to that of a typical confocal MACROscope laser scanning system (16,17) but has the addition of a mechanical chopper. Design criteria included: Near UV excitation, detection at 614 nm, and scanning of areas large enough for a complete fingerprint. The prototype system, illustrated in Fig. 1, was assembled on a $4' \times 6'$ optical breadboard. The excitation is provided by an 18.5 mW, 325 nm HeCd laser (Omnichrome model 3056-15M). The absorption efficiency of EuTTPhen at 325 nm is about 40% of the maximum absorption efficiency which occurs at 350 nm. The beam is modulated with a mechanical chopper that utilizes an infrared emitter-detector pair to generate a synchronization signal. When operating at 300 Hz, the beam cutoff time is less than 25 μs. Once chopped, the excitation beam enters the beam expander (Optics for Research model ELU-25-5X-NUV) where it is expanded to a 6.5 mm beam. The expanded beam passes through the laser line filter and reflects off the dichroic beamsplitter (Omega Optical custom order: transmission for $\lambda > 375$ nm, reflection for $\lambda < 375$ nm) toward the XY scanners which are located at the front focal point of the scan lens. The XY scanners (Cambridge Instruments model 6350) can accommodate a 10 mm beam and have MgF coatings for good reflection of UV light. The scanned beam is then focused by the scan lens (Edmund Scientific 150 mm focal length fused-silica singlet) to a spot on the specimen. This combination of scan lens and beam size has a numerical aperture (NA) of 0.02 for which the theoretical diffraction limited spot size is ~20 μm. The actual spot size is closer to 30 μm due to aberrations related to the singlet lens. The luminescence from the excited spot is collimated by the scan lens and de-scanned, following the excitation beam-path in reverse except the visible wavelengths are transmitted by the dichroic beamsplitter. The transmitted beam passes through a long-pass filter that removes any remaining UV light. The detector lens focuses the beam to a point at which the aperture of the iris is centered. This point is confocal with the focused spot of the excitation beam. Thus the iris will only pass light originating from the focused spot. The light that remains is measured with the photo-multiplier tube (Hamamatsu model 2228) and amplified (Stanford Research Systems low-noise current preamplifier model SR570).

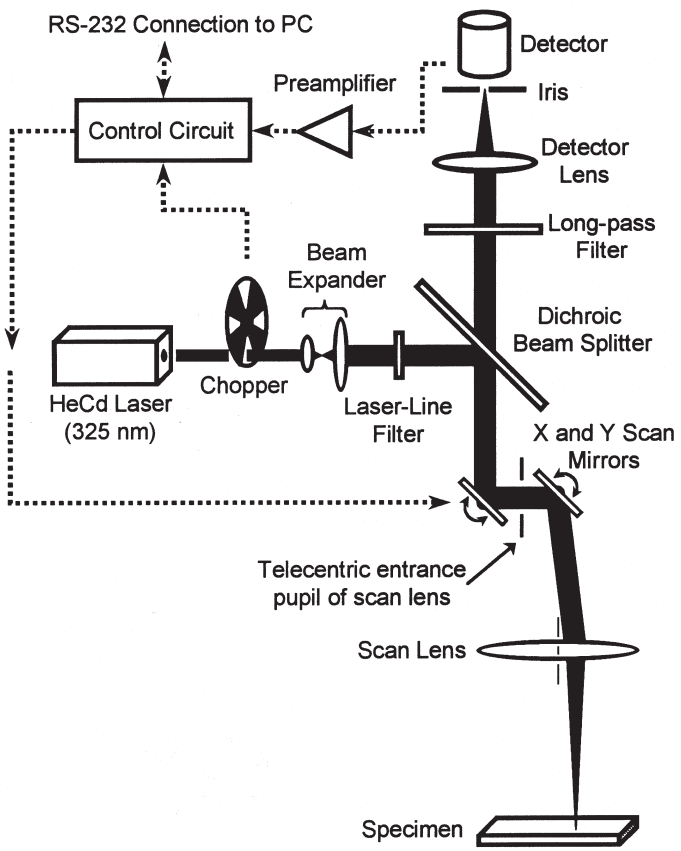


FIG. 1—*Schematic diagram of scanning-beam, time-resolved fingerprint imaging system.*

The optical system presented features telecentric scanning. The telecentric property causes the focused cone of light to remain parallel to the optic axis of the scan lens as it is scanned across the specimen. This is achieved by placing the scanning mirrors at the front focal point of the scan lens. Telecentric scanning is desirable since the magnification of the object is constant. In a non-telecentric system objects outside the focal plane can be distorted.

Scanning beam imaging offers better sensitivity than other time-resolved methods. This is due to the intense focused-beam illumination of the specimen and sensitive single-point detection. Other methods generally illuminate the entire specimen (albeit with a more powerful light source). In these systems the detection is performed either with film or a gated CCD camera (18). These methods are quicker than the scanning beam method but lack its potential sensitivity.

Signal Processing

Scanner and data acquisition functions are performed by the control circuit in conjunction with a PC. The control circuit was designed and assembled in-house. The circuit is based on a 20 MHz DSP (Texas Instruments TMS320C5x DSP starter kit). Two 16 bit output buffers (74LS373 ICs) drive the X and Y scanners. A 2 MHz, 12 bit analog-to-digital converter (ILC Data Device Corporation model ADC-00300) receives input from the PMT via the preamplifier. A pair of Schmitt trigger inverters (74LS14 ICs) connected to an interrupt line of the DSP receive the chopper synchronization signal. The schmitt trigger inverters sharpen and debounce the high-low transition of the IR emitter-detector signal such that the transition occurs at a consistent fixed time before the on-off transition of the excitation beam. The RS-232 port is provided on the DSP board and is connected by a standard 9 pin serial cable to the PC.

Time-resolved imaging mode is used to resolve dim phosphorescent features that would otherwise be obscured by bright fluorescent backgrounds. In this mode, the chopper is turned on. The

scanning mirrors are moved along a grid that defines the image area and resolution. At each location on the grid, the luminescence is measured during a specific time interval with respect to the chopper on-off cycle.

Standard imaging mode is used to image total luminescence. The chopper is turned off, and a simple scan is performed during which the ADC is sampled. The result is stored as a TIFF (Tagged Image File Format) file.

Results and Discussion

Figure 2 shows a graph of the measured luminescence from a fingerprint ridge on sample B (Fig. 3f) before and after the on-off transition of the excitation beam. Because the ADC has limited dynamic range (12 bits) two data sets were merged to create this graph. The data for the period 300 μs before the transition to 80 μs after was recorded with the preamplifier set to 100 μA/V. The data for the remainder of the graph was taken with the preamplifier set to 1 μA/V. Thus accurate measurements spanning 2.5 orders of magnitude are presented. Immediately prior to the on-off transition of the mechanical chopper, the luminescence intensity is more or less constant. This is partially due to the constant intensity of the excited fluorescent background, and partially due to the asymptotic approach of the phosphorescence intensity to its equilibrium level. The intensity of the phosphorescence at equilibrium is a function of the intensity of the excitation beam, and of the concentration of the phosphorescent compound. The mechanical action of chopping the excitation beam requires 25 μs for completion. Commencing ~100 μs after the beginning of the chopper on-off transition ($t = 0$ μs), the luminescence begins to exhibit simple exponential decay characterized by a straight line of negative slope on the logarithmic plot. This indicates that during this period, the background fluorescence is negligible and the signal is dominated by the phosphorescence decay. The lifetime of this decay was calculated using linear regression and found to be 600 μs. The nonlinear region prior to this (25 μs to 100 μs) arises from background fluorescence and instrumental time constant limitations.

High resolution images were obtained of fingerprints on a Coke™ can using both standard imaging and time-resolved imaging modes (Fig. 3). Figure 3a and b show photographs of sections

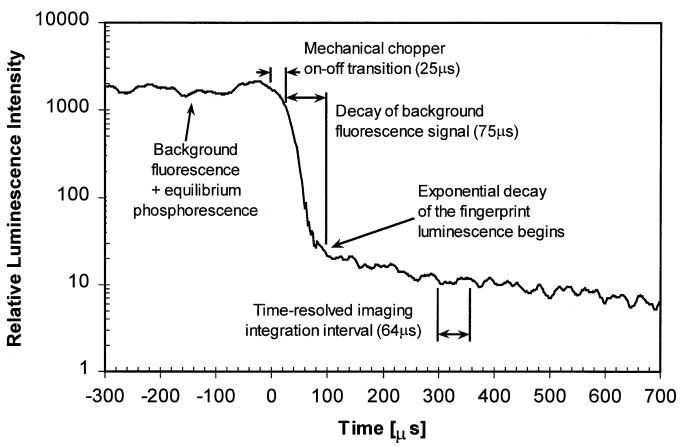
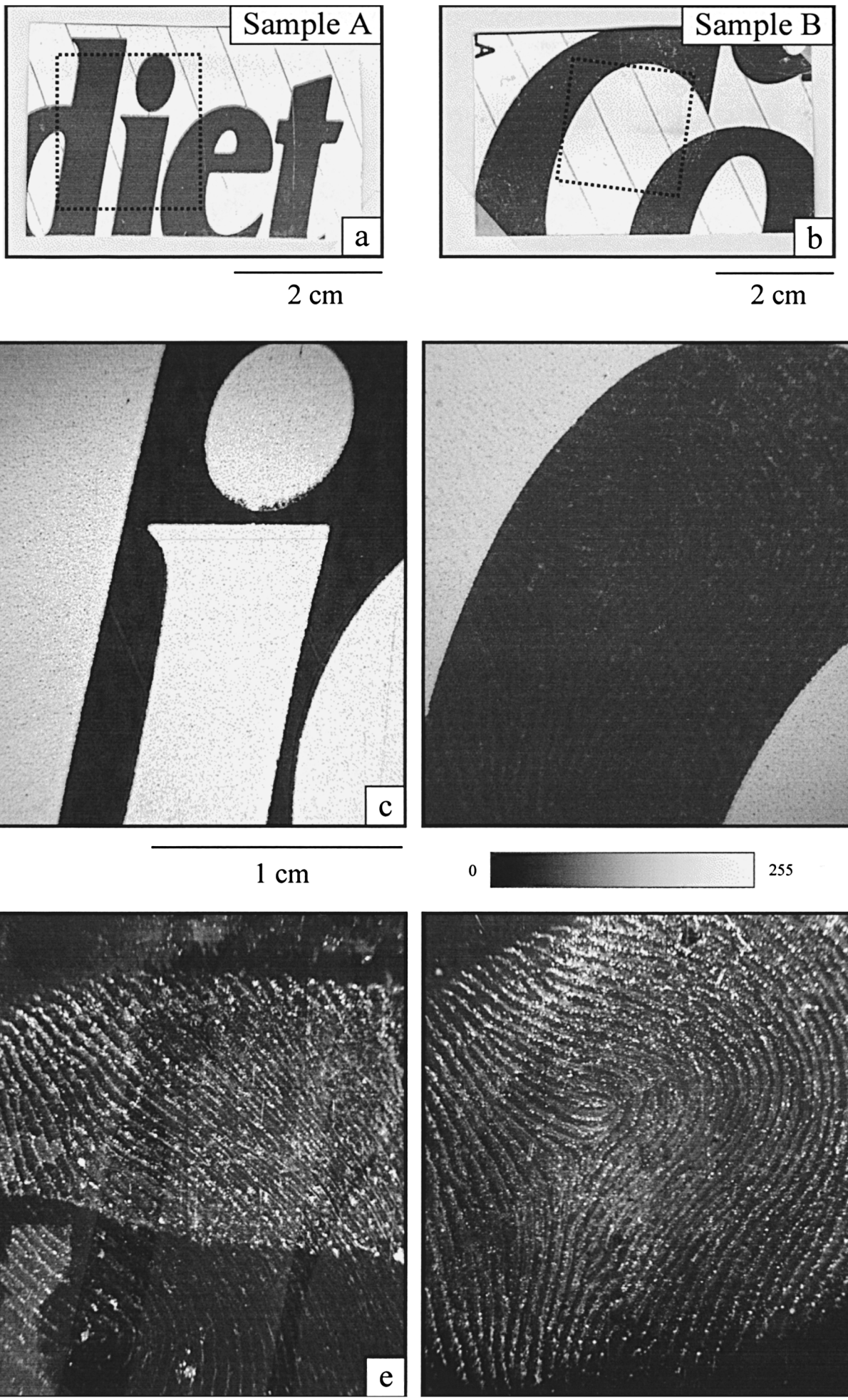


FIG. 2—*Recorded luminescence during the on-off transition of the mechanical chopper. The data was collected from a fingerprint ridge on sample B (see Fig. 3f). Two data sets were merged to create this graph (see text).*

(A and B, respectively) from the Coke™. The red lettering appears dark in the white background. The samples were treated with cyanoacrylate and EuTTAPhen as described. In each case the scanned grid was 1000 × 1000 pixels, and covered an area 20 mm square with a pixel spacing of 20 μm. This spacing allows for slight oversampling of the specimen since the focused spot diameter is somewhat greater than 20 μm. Because the scanning rate is limited by the chopping rate (300 Hz), each scan of one million points took about an hour to complete. When the total luminescence of a specimen is scanned using the standard imaging mode the image is dominated by the fluorescence of the painted surface (Figs. 3c and 3d). The fluorescence is particularly bright in the regions containing painted red lettering. Here all traces of the fingerprint ridges are obscured. The white painted regions are less fluorescent. In these regions, it is possible to resolve the ridges if sufficiently sensitive detection is available; but the images will be of poor contrast, and require post-processing. When scanned using time-resolved mode the fingerprints are clearly visible in both red and white regions of the specimens (Fig. 3e and 3f). The ridges of sample B (Fig. 3f) appear slightly brighter in the red paint regions than the white. This is not observed on sample A (Fig. 3e). On sample A, the distribution of phosphorescent material is non-uniform. This suggests a problem occurred when treating the samples with EuTTAPhen since non-uniform fuming of cyanoacrylate would seem unlikely. On both specimens, the background is brighter on the red paint than on the white. This indicates a small amount of cyanoacrylate has polymerized on the red paint and absorbed the europium complex.

The resolution of the images is sufficient for identification of fingerprints by the ridge pattern. However, the resolution is insufficient for clear imaging of the fingerprint pores. Changes to the optical design are necessary to facilitate higher resolution imaging. The singlet scan lens has aberrations, which increase the diameter of the focused spot: it can be replaced with a multi-element laser scan lens designed for flat-field scanning of large areas which would unfortunately increase the cost of the instrument significantly. To achieve a resolution of 10 μm a minimum NA of 0.04 would be required. Ideally, this lens should be color corrected for both the excitation wavelength (325 nm) and emission wavelength (614 nm). Alternative laser sources with lines closer to the EuTTAPhen absorption maxima (350 nm) should be considered. A great deal of miniaturization can be achieved as inexpensive solid state lasers in the blue and UV become available. In the present system, the laser occupies nearly half the instruments space. The time required to record a time-resolved image could be reduced by making changes to system components and to the timing of the sampling. A higher power laser could potentially reduce the time needed to excite the phosphorescence to under 100 μs. Presently, the excitation period is 1500 μs. Increasing the NA of the scan lens would improve the light collection efficiency and thereby reduce the luminescence intensity necessary for imaging. This would further reduce the necessary duration of the excitation pulse. The actual time necessary for measuring the phosphorescence is dependent on its signal to noise ratio. Presently good results are obtained by averaging the signal for 64 μs. This could be reduced if the improvements to the excitation and measurement of the phosphorescence result in an increase in the signal. With all the stated modifications implemented, the period of the chopper cycle could be significantly reduced, possibly to less than 250 μs. A 512 × 512 pixel image could be scanned in less than 90 s.


Sample A
diet
a
2 cm
Sample B
b
2 cm
c
d
1 cm
0
255
e
f

Conclusions

A novel confocal scanning beam time-resolved MACROscope imaging system achieves good contrast when imaging EuTTAPhen treated fingerprints on fluorescent backgrounds. Currently, the instrument is capable of resolving fingerprints. With better focusing optics, the resolution can be improved to allow imaging of fingerprint pores on suitable specimens. Confocal optics allow this instrument to produce high-quality, crisp fluorescence images by picking out details only near the focal plane and rejecting the background. Due to its high sensitivity, use of the beam scanning technique is sure to expand, especially since rare-earth-based fingerprint treatments are in the offering (19,20).

The prototype instrument described in this paper was not intended to be portable nor used in the field. The merits of this instrument are its high sensitivity, simplicity, and low cost. Compared to CCD camera-based methods, the scanning process is slow; but significantly less expensive. The parts cost for a time-resolved MACROscope is less than $20,000 while the cost for a time-gated CCD camera alone is in excess of $30,000. Imaging speeds can be increased by at least and order of magnitude by utilizing pulsed solid state lasers and superior imaging optics, while still maintaining the cost under CCD-based systems. A commercial and consequently portable version of this instrument would be less expensive and more sensitive than its CCD-based counterpart.

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FIG. 3—*Fingerprints on the surface of a Coke™ can. (*a*) and (*b*) are photographs. (*c*) and (*d*) are total luminescence images scanned in standard imaging mode. (*e*) and (*f*) are time-resolved images of the same areas as (*c*) and (*d*) respectively. The brightness of these images was adjusted prior to publication but no contrast enhancement was performed.*