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Chemical contrast observed in thermal images of blood-stained fabrics exposed to steam†

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Thermal imaging is not ordinarily a good way to visualize chemical contrast. In recent work, however, we observed strong and reproducible images with chemical contrasts on blood-stained fabrics, especially on more hydrophobic fabrics like acrylic and polyester.

Our laboratory has been developing IR imaging tools to visualize blood and other bodily fluids on fabrics and other substrates using a thermal infrared camera.[1–3] Most of our work has involved infrared diffuse reflection because conventional thermal imaging depends primarily on the temperature of a solid object, with only a small contribution from its chemistry. Even very concentrated blood stains on fabrics showed very little contrast in ordinary thermal images in our experience, so reflection methods were our main focus.

Using infrared diffuse reflection, we have demonstrated the ability to visualize blood stains on some fabrics down to ∼100 times dilution of the blood with water. In an effort to observe even stronger signatures for blood on some fabrics, we sought to take advantage of the hydrophilic nature of blood proteins by exposing the samples to steam; our rationale was that blood proteins would adsorb more water than the surrounding fabric and the added water would increase the infrared reflection signature of bloodstains. It is well known that fabrics also adsorb/desorb water depending on humidity,[4,5] but some fabrics like acrylic and polyester are relatively hydrophobic compared to, for example, cotton. We thought the water-saturation approach might improve visibility of blood stains on the hydrophobic fabrics. To test this idea we obtained a simple hand garment steamer for about US$35 and began some proof of concept studies. The idea we were testing does appear to be true, but in the course of the studies a much more visually striking result was repeatedly obtained: strong heat signatures for blood stains appeared on these hydrophobic fabrics when exposed to steam. These thermographic effects are immediate, obvious, repeatable, and linked to the differing adsorption characteristics of the surface being imaged during steam exposure.

Fig. 1 shows photographs of two fabric samples for which thermal imaging data follow. Fig. 1A shows a coarse, dyed, unpatterned acrylic fabric on which letters were drawn using diluted rat blood three years previous to the experiments reported here. The symbol "I" in undiluted blood is easily observed. A letter "X" written with 10×, and a light "V" in 25× diluted blood are also observable to the eye. An "L" and a "C" drawn in 50× and 100× dilutions of blood with water are not visually observable. Rectangles surrounding the three most diluted symbols have been added to the picture to indicate where they lie on the fabric.

Fig. 1B shows a black polyester fabric with glittery skull-and-crossbones appliques on the opposite side clearly visible from both sides. This fabric has two handprints created by a latex-gloved hand; dashed outlines of the handprint locations have been added to aid the eye. The print on the right was made after dipping the gloved hand into blood diluted with water by a factor of 100. The print to the left was made after dipping the gloved hand into blood diluted by a factor of 1000. Neither handprint is visible on the fabric to the unaided eye.

The blood used in this work was taken from rats at the USC animal center; it was used fresh and not treated with preservatives. The water used for dilutions was ordinary purified water from a reverse osmosis unit with no added salts; it was not isotonic. The thermal camera used was a relatively low-cost (<$10k) FLIR Systems A315 camera operating at 60 Hz. Fabrics were exposed to steam from the hand-held steamer for approximately 10 s at a distance of ∼8 in.

Fig. 2 shows a sequence of 8 individual frames taken from a 45 s video record of the fabric in Fig. 1A before, during and after exposure to steam. All the images in Fig. 2 are autoscaled; vertical striations observed in the 0 s and 5 s images are camera noise observed due to the small temperature range in

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† Electronic supplementary information (ESI) available: Video files from which the frames of Fig. 2 and 3 were extracted. See DOI: 10.1039/c5an01413a

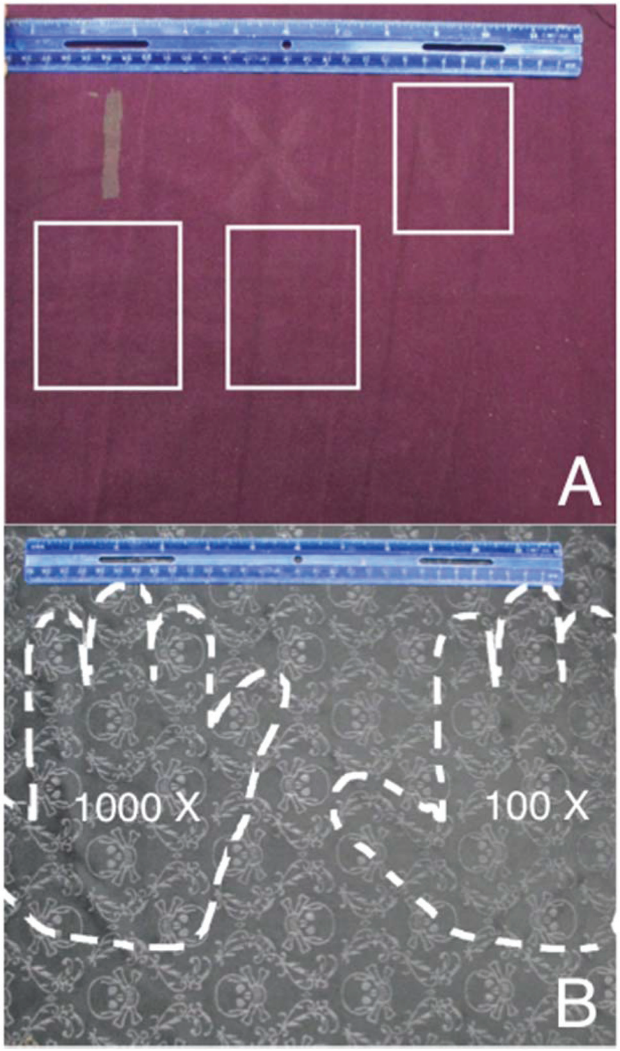

Fig. 1 Visible light images of bloodstained fabrics used in this study. (A) Acrylic fabric with symbols drawn in blood of varying dilution, (B) polyester fabric with latent handprints formed by a latex-gloved hand pressed into diluted blood solutions. A 12″ ruler is shown for scale.

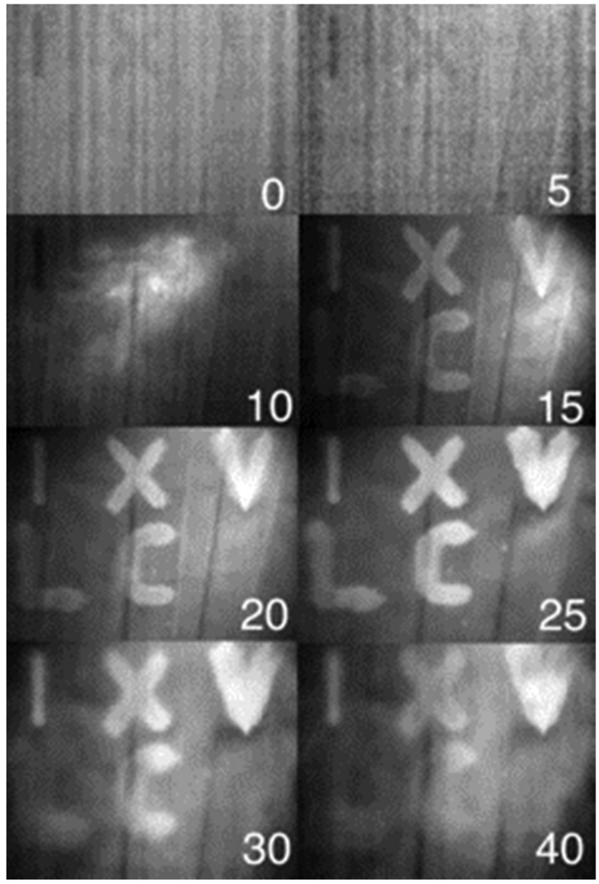

Fig. 2 Thermographic images excerpted from a video record of the acrylic fabric exposed to steam. These images are from the same fabric shown in Fig. 1A. The numbers in each frame show elapsed time (s) during the experiment.

the images before exposure to steam. Steam begins to strike the fabric 10 s into the experiment and ends 10 s later. Features (symbols, droplets, and "halos") appear in the thermal images of Fig. 2 immediately on exposure to steam in the locations where blood had been added. Despite the uneven distribution of water vapor by the steamer, the heating effect is similar across all letters, and thus not proportional to the amount of blood solids deposited in each of the letters, at least in this range of concentrations.

In addition to the symbols that had been intentionally added to the fabric in the past, several small (~2 mm) bright spots appear on the fabric near the letter "C" (*e.g.*, at 15 s, 20 s, and 25 s), representing what may be accidental blood spatter during production of the sample that had been previously unobserved *via* reflection measurement, or some other contamination of the sample. Also, the "V" and other symbols show "halos" around them. When the fabrics are heated by conventional means such as touching them with a warm object, the thermal imprint of the warm object does not spread and form a halo, but simply fades with time. Neither is a halo observed with the high-concentration symbols in Fig. 2 ("I" and "X"). Our interpretation of the halos is that they are caused by vapor interacting with blood solids that wicked into the fabric around the stains made with low viscosity, more dilute blood solutions.

There are vertical linear features observable in the images of Fig. 2 that are readily traced to previous folds in the fabric also visible in Fig. 1A, and that we attribute to uneven exposure of the fabric to steam along these creases.

After the exposure to water vapor ends at 20 s in Fig. 2, the boundaries of the letters become indistinct as the letters begin to cool. As the experiment was repeated numerous times, the observed contrast between the clean fabric and the bloodstains diminished but remained visible. During the cool-down phase of the experiment, the bloodstained regions appeared to cool slightly below the temperature of the surrounding fabric, leaving them with a slight negative contrast compared to the surrounding material. This is observed in the first two images of Fig. 2, since the experiment had been repeated several times before the data of Fig. 2 was collected.

A thermal image sequence for the polyester fabric (Fig. 1B) is shown in Fig. 3. Exposure to water vapor begins 10 s in to the experiment, and ends at 20 s. Before exposure, neither the skull-and-crossbones applique pattern nor the handprints are visible in thermal IR images. The blood handprints begin to appear as soon as vapor exposure begins and reach maximum contrast near 13 s.

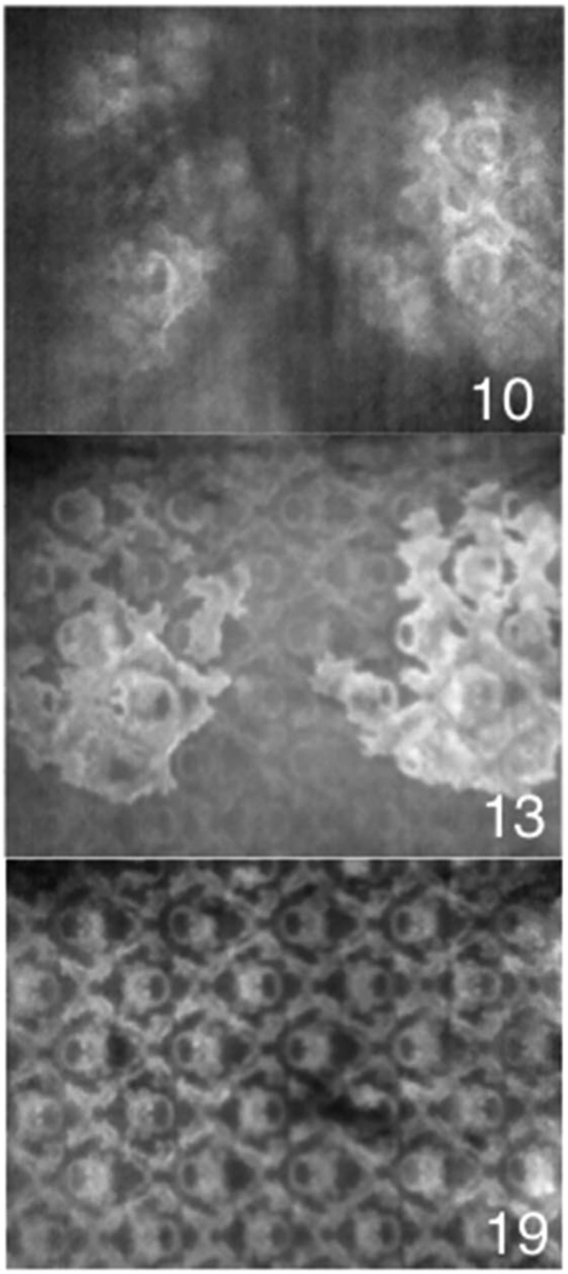

Fig. 3 Thermographic images excerpted from a video record of the polyester fabric exposed to steam. These images are from the same fabric shown in Fig. 1B. The numbers in each frame show elapsed time (s) during the experiment.

After a few seconds more, the applique pattern emerges while the handprints are still visible. The applique pattern is dominant afterwards; faster kinetics enabled the handprints to be observed before the applique heated.

In both experiments reported here, the bloodstained regions of the fabric seemed to become hotter than the clean fabric when exposed to steam. A three-point calibration for fabric temperature was performed to determine the magnitude of the thermal response. For the acrylic fabric shown in Fig. 2, a typical highest temperature reached during exposure to vapor was 5.5 °C for the clean fabric. The clean polyester fabric showed a temperature rise of 1.4 °C. Temperature differentials between the blood-stained areas and the unstained fabric are a bit more difficult to assess quantitatively since they have a dependence on emissivity that has not yet been measured; the order of magnitude of the temperature differential appears to be 2 °C or less in each case.

The stains observed in Fig. 1–3 ranged from undiluted blood to blood diluted by 1000× with clean water. A trained forensic scientist with the South Carolina State Law Enforcement Division (SLED, Columbia, SC) using two alternate light sources for blood detection was able to observe stains we created down to 100× dilution on the unpatterned acrylic fabric. Neither handprint on the polyester fabric was detected by the investigator, even though the investigators knew they were present from having observed a repetition of the vapor exposure experiment in person.

Textile literature studies have previously shown how fabrics adsorb water as a function of humidity.[6–12] More importantly, we have not been the first to observe exothermic effects in infrared imaging of fabrics exposed to water and water vapor.[12,13] In retrospect it is not surprising that exposure to water might yield chemical contrasts in systems where two materials have very different water adsorption behavior. But the fact that the observation is so immediate and strong, even when a blood stain has been diluted 100 times or more, is an observation that suggests this type of imaging may have a role in forensic analysis along with other types of alternate light source methods.

Conclusions

In our work, we happened to observe thermal-imaging chemical contrast in forensic samples with which we were already working. For this reason, one question that has been posed by SLED and others is whether the exposure to steam prevents genetic analysis of the sample. Temperature measurements tell us that under the conditions of testing used for Fig. 2 and 3, sample temperatures increase by less than 10 °C. Since much DNA analysis involves amplification for extended periods at much higher temperatures, it seemed likely that DNA evidence would be preserved. We tested this hypothesis with help from staff at SLED (not reported in detail here); results show that

DNA can be efficiently extracted from bloodstains after imaging *via* steam thermography.

It seems likely that this method can also be adapted to observing chemical contrast in other systems where a coating might behave differently from an uncoated surface, or where a sample is heterogeneous, or where a rare chemical defect in a process might exhibit a very different adsorption profile. For example, although blood is difficult to observe on cotton by this method because both materials have similar adsorption/desorption isotherms with respect to water, hydrophobic stains on cotton are easy to observe (they appear dark on a cotton background which is bright). Further, there does not appear to be any reason to think that water/steam is unique in its ability to create image contrast of this type; anything that can be dosed in vapour form at high concentrations might enable a chemical contrast to be observed.

We identify six possible mechanisms that can explain the observation of apparent thermal contrast under the conditions of Fig. 2 and 3: (1) differential heat transfer from the hot gas stream; (2) differential radiant heating; (3) differential condensation of water vapor; (4) differential adsorption of water vapor; (5) differential deposition of hot droplets; and (6) differential emissivity. Preliminary experiments show that all of these mechanisms may be in play, but that differential adsorption and differential emissivity are probably the most important. We are continuing to try to understand the complete origins of the effect. To this end, we are examining the emissivity of fabrics as well as kinetic and other aspects of the adsorption phenomenon with the goal of extending the method to hydrophilic stains on fabrics that are also hydrophilic (like cotton). Despite their similar uptake of water, the kinetics of the process may be different and enable a measurement, for instance. Also, there may be positions on the adsorption/desorption curve as a function of humidity that are better for distinguishing one material from another in specific cases – such as a plateau region of one material at a humidity level of strong uptake in another.

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