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Impact of carpet construction on fluid penetration: The case of blood

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ABSTRACT

Bloodstains and bloodstain patterns are often observed at crime scenes and their analysis through bloodstain pattern analysis (BPA) can assist in reconstructing crime scenes. However, most published work related to BPA only deals with hard, non-porous surfaces and none of the studies have carefully characterized carpets. Soft and porous carpets are often encountered at crime scenes since they are common in American homes accounting for 51% of total U.S. flooring market; this has motivated the research described herein. To assess fluid penetration into tufted carpers, a new method for determining porosity and pore size distribution in tufted carpets has been developed for bloodstains on carpet. In this study, three kinds of nylon carpet were used: a low, a medium and a high face-weight carpet. Each carpet had an antistain treatment, which was removed from half of each carpet by steam-cleaning with a pH 12 NaOH solution. This resulted in six carpet samples. Yarn twist, carpet weight, pile height, water contact angles on carpets, water contact angles on individual fibers, and fiber cross-sectional shapes were characterized. Porosity and pore size distribution were analyzed using confocal laser scanning microscopy (CLSM). Porcine blood was used as a human blood substitute at three liquid volumes (30 μL, 10 μL, and 2 μL). Analysis showed that porous carpet construction and antistain finishing both affected penetration. The depth of blood penetration decreased with the increase of carpet face-weight but increased with increased drop height. The removal of antistain treatment increased blood penetration into the carpets and changed the pore size distribution. Effects of antistain treatment, porosity and pore size distribution of tufted carpet, and blood wicking behaviors on carpets were found to strongly affect blood penetration into the carpets.

1. Introduction

Blood at a crime scene may originate from events involving e.g. gunshot, nosebleed, blunt trauma, stabbing [1]. Blood is a complex, biologically active, non-Newtonian fluid whose main components are plasma, white blood cells, red blood cells, and colloids [2]. Non-Newtonian fluids have a non-linear relation between their shear stress and shear rate, and this relationship can be time-dependent [3].

Bloodstain pattern analysis (BPA) consists of collection, categorization and interpretation of blood stains and their patterns connected with a crime scene [5]. Bloodstains may have different shapes, which could be affected by gravity and height of release of dripping drops, drop trajectory, blood composition, blood viscosity, types of surface, substrate porosity and many other factors [1,5–7]. Bloodstain pattern analysis can help distinguish between them [5]. BPA is often used to help crime scene or accident reconstruction to determine what might have occurred and to provide a correct interpretation of evidence.

However, BPA is not straightforward because the physical relationship between blood impact and the resulting bloodstains is not fully understood. In most research cases, the stained surface was a flat, non-absorbing surface and the blood drops traveled independently in quiet air. Most studies of BPA have been performed on hard surfaces; only a few studies have focused on the interaction of blood and textiles [1,4,8–10]. Parameters such as textile (e.g. carpets, fabrics, clothing, towels, sheets, etc.) composition, porosity, absorbency, and finishing treatments of textiles should be considered when analyzing bloodstains and bloodstain patterns on textiles [4].

Some research has already been performed involving bloodstains on cloth and fabric [8], but little research has been done on porous carpets. According to The Carpet and Rug Institute (CRI), carpets account for 51% of the total U.S. flooring market [11]. At a real crime scene, carpet is a common porous and non-flat target

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[12]. The size and appearance of blood drops are influenced by the type of carpet surface since different kinds of surfaces can influence the impact of a droplet and therefore the resultant stain shape. To the best of the authors' knowledge, there have been no studies on the determination of drop impact conditions from examination of carpet stains. Although it may be possible to determine the quantity, spread, form and penetration of blood into a porous target, like carpets, it has not yet been reported. For example, blood may immediately flow into a carpet, staining the primary backing of the carpet. The stain in the backing could be larger than expected, even with a small blood pool unless the carpet has a fluorochemical antistain treatment. The backing of a carpet is important for crime scene reconstruction because it may preserve stain evidence despite vigorous washing from the top of the carpet.

The motivation for the studies described below is to understand bloodstain formation on complex, porous and absorbing surfaces such as carpets. Confocal laser scanning microscopy (CLSM) has been used extensively in this work since it can generate real-life 3D representations. It can also produce high-resolution and high-contrast images, with depth selectivity [13,14]. Below, a new, nondestructive method is described that has been applied to carpets to obtain the pore size distribution of carpets and to detect where the blood goes upon falling on a carpet.

2. Materials and methods

2.1. Carpets

Three typical-quality carpets were chosen: a commercial grade low face weight carpet, Core Competency, a medium face weight home carpet, Cozy, and a high face weight home carpet, Peaceful Moments II (S). Since the quality and price is typically proportional to the face weight, these carpets provide a sample of carpets found in homes corresponding to low, medium and high living standards. Thus, in the remaining of this manuscript, we will refer to the carpets with their face weight. The manufacturer-supplied information is shown in Table 1.

2.2. Steam cleaning of carpets

Upon receipt, the carpets were cut in half and one half was steam-cleaned to remove its antistain treatment. A pH 12 solution of NaOH was prepared by diluting pH 14 NaOH 100 times by adding 1 mL into 100 mL deionized water. This solution was diluted 100 times more by following the same procedure a second time. Finally the pH value was tested using MColorpHast™ PH-indicator strips to verify that the pH was 12. A MC1275 Heavy-Duty Steam Cleaner was filled with the pH 12 NaOH solution and the carpet was steamed. A Ridgid® ProVac Wet/Dry Vacuum Cleaner was used to remove residual cleaning solution.

2.3. Analysis of carpets

The carpet weight per unit area was measured using ATOM SE Swingbeam Clicker Press and die cutter to cut samples 10.2 cm × 10.2 cm (4 inch × 4 inch) from the carpets and weighting the samples according to ASTM D5848-10e1 Standard Test Method for Mass per Unit Area of Pile Yarn Floor Coverings [15]. A Tucsen camera microscope was calibrated and used to measure the pile height.

Contact angles on carpets and contact angles on individual fibers were measured using a Meiji stereo-microscope (Meiji Techno, EMZ-13TR, Saitama, Japan). To obtain contact angles on carpets, carpets were cut to the desired size, and then a 10 μL Hamilton Company syringe was used to drop deionized water onto the surface of the carpets. A Canon EOS camera (Canon, EOS EF-S-18-55IS, Lake Success, NY, USA) was installed onto the camera adapter of the microscope to capture the images seen in the microscope. Upon dropping deionized water onto the carpet, images were captured as soon as possible. To obtain contact angles on individual fibers, a sprayer containing deionized water was used to spray tiny water drops onto individual fibers, which were placed between the ends of a U-shaped slot. A wetted wipe was placed very close to the fibers to reduce the evaporation rate and the entire system was placed under the objective lens of a microscope. Images of the drops were captured by the camera and processed using Adobe Photoshop software to obtain the contact angles.

Confocal laser scanning microscopy (LEXT 3D Measuring Laser Microscope OLS4000, Olympus Corporation, Waltham, MA, USA) was used to measure the carpet pore size distribution and porosity. All experiments were conducted at 21 ± 1 °C and 65 ± 2% relative humidity. The pore shapes were divided into three groups: round, intermediate and elongated [16,17]. The effective radius of pores can be calculated by [18]:

$$r = \frac{2A}{P}$$

where A is the pore cross-section and P is the perimeter of the pore as measured with the confocal laser scanning microscope and ImageJ processing of the images. In the case of a cylindrical pore, the effective radius equals the radius of a cylinder. Another measure of the shape is the circularity:

$$I = \frac{4\pi A}{P^2}$$

For a perfect circular pore, $I = 1.0$. For this study, round pores were defined as pores with $I \geq 0.5$, intermediate pores had $0.19 \leq I < 0.5$, and pores with $I < 0.19$ were classified as elongated pores.

2.4. Blood

Porcine blood was used to simulate human blood while evaluating wetting and wicking in the carpets. Fresh, whole, EDTA

Table 1
Basic information of carpets.

Face weight level and designation in this study	Low	Medium	High
Manufacturer	TrafficMASTER	SoftSpring	Shaw
Name	Core Competency	Cozy	Peaceful Moments II (S)
Model #	0198D-42-12	HDC7777101	HDD5757105
Color	Cake batter	French buff	Soft sun
Carpet fiber	100% nylon	100% BCF nylon	100% BCF nylon
Density, g/m^3 (oz./cubic yd.)	50,580 (1364)	98,040 (2644)	123,200 (3323)
Face weight, g/m^2 (oz./sq.yd.)	1020 (30)	1490 (43.9)	2306 (68)
Pile height, mm (inch)	5.58 (0.22)	12.7 (0.5)	19 (0.75)
PAR rating	3.35	3.5	4.25
Gauge[a], mm (inch)	9.52 (0.375)	2.54 (0.1)	2.54 (0.1)

[a] Gauge is the distance between tufting needles and hence between the tufts in a tufted carpet.