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Bloodstains on woven fabric: Simulations and experiments for quantifying the uncertainty on the impact and directional angles

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ABSTRACT

Bloodstain pattern analysis considers stains on various porous and non-porous surfaces, for the purpose of crime scene reconstruction. On non-porous surfaces, several studies relate the impact conditions of drops to the inspection of stain shapes. Stains on porous surfaces like fabrics have been relatively less explored. The phenomenon of imbibition of blood into the fabric after impact adds further complexity in retrieving information on the impacting conditions. The present work studies experimentally and numerically the formation of drip stains on a woven fabric. The proposed methodology first relies on Darcy's law to measure the imbibition characteristics of the fabric through a set of simple imbibition experiments. Next, the fabric properties are fed into a numerical model to predict the growth of the bloodstain after impact of a droplet. Experiments at different drop release heights and impact angles are compared with the numerical simulations. The uncertainties induced by the fabric on the determination of the impact and directional angles are explained and quantified.

1. Introduction

Bloodstain pattern analysis (BPA) is an area of forensic sciences that studies several fluid dynamics phenomena such as the impact, flight, break-up, imbibition, and drying of blood volumes [1]. An important problem in BPA is to determine the region in space from where the bloodspatter originated [2,3]. Therefore, knowledge about the interaction of blood with different substrates is essential for estimating the impacting conditions, i.e. the drop size, and the impact velocity, in terms of magnitude and direction. The direction of the impact is characterized by two angles, the impact angle and the directional angle [3,4].

The interaction of blood drops with non-porous substrates has been a subject of numerous investigations. Correlations between the impacting conditions of the drop with the stain size [5], and peripheral shape [5], have assisted in determining the size and velocity of the impacting drops. Most of these correlations depend on substrate characteristics [6], and are needed to reconstruct the ballistic trajectories of droplets [1], a reconstruction method that shows promise [7,8] to determine the region of origin more accurately than methods assuming that drops travel in straight lines.

However, the interaction of blood with porous substrates, such as fabrics, is complicated by the added effect of imbibition after impact. In the fluid dynamics community, the term imbibition refers to the capillary transport of fluid in a porous medium (here a fabric), which is driven by wetting forces, and resisted by viscous forces [1]. This transport mechanism is also called wicking, as for cotton threads that draw up wax in candles, called wicks [9]. Capillary transport that also involves absorption of the liquid in the porous medium (as blood in the cotton fabrics of this study) is called imbibition rather than wicking. Imbibition has been referred to as saturation in the SWGSTAIN recommended terminology [1,4].

An additional difficulty in crime scene reconstruction brought by imbibition, is a magnification and distortion of the stains that occurs during the time from their impact until drying. This deformation possibly masks important information about the impacting conditions of the drop. Imbibition dynamics depend on several factors such as fabric structure, imbibition properties of the fabric, humidity, moisture content of the fabric and temperature. For instance, bloodstain shape on fabrics has been found to depend on the number of laundering cycles [10,11] and on the presence of any underlying substrate (or the mounting procedure) [12]. Some of the aforementioned factors affect the fluid behavior during impact as well [13,14], which, consequently affects the final stain shape after imbibition.

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Nevertheless, recent studies have provided valuable insights in characterizing drop impact on fabrics, by differentiating contact and spatter stains on fabrics [15], determining drop volume [16], and characterizing drip stain dynamics [17]. However, further quantitative investigation into the imbibition process of blood in fabrics is required to better understand how the stain deforms after drop impact, a process relevant to the determination of the impact conditions of the drop.

In this paper, we demonstrate a methodology to determine the imbibition characteristics of blood in a woven fabric and consequently predict the growth of a stain after impact of a dripping drop. We model the fabric as a continuous porous medium and measure its permeability, using Darcy's law, from a set of imbibition experiments. The measured permeability values are then used in a numerical model of imbibition that predicts the final stain shape from a given shape of the drop after impact. Model results are compared with experiments for different drop release heights and impact angles. For situations where equal wetting occurs on both sides of the fabric, the model is able to predict the final shape of the stain given the volume of impacting drops. A map is proposed to quantify the uncertainty induced by imbibition in the determination of the impact and directional angles.

2. Methodology

2.1. Analytical models of imbibition

Darcy's law [18] describes the growth of the imbibition front in any porous medium, such as a fabric.

$$\vec{v_a} = -\frac{k}{\mu}\nabla p\ . \tag{1}$$

Here, $\vec{v_a}$ is the average discharge velocity through the fabric, k is the permeability of the fabric, μ is the blood's viscosity, and ∇p is the pressure gradient along the fabric. The fabric can be modeled as a 2D porous medium, since the thickness of the fabric is typically negligible compared to the two dimensions in the fabric plane. The flow velocity in the pores can be estimated by the equation:

$$\vec{v} = \frac{\vec{v_a}}{\varphi}\ , \tag{2}$$

where, $\vec{v}$ is the flow velocity in the pores, which is the same as the velocity of the imbibition front, and φ is a ratio of the volume of pores in the fabric to its total volume.

To determine the permeability of blood in the fabric, and to validate the proposed methodology, two sets of experiments are performed, corresponding to the following theoretical situations: (i) linear (1D) imbibition of blood into the fabric and (ii) radial (2D) imbibition of blood into the fabric.

For the linear (1D) case, imbibition follows Washburn law [19], which is briefly described here. Considering the pressure at the blood source (Fig. 1) to be negligible with respect to the capillary pressure inside the fabric (p_c), the capillary pressure in the fabric drives the flow, which is resisted by viscous forces. Consequently, Eq. (1) is written as:

$$\frac{dh_x}{dt} = \frac{k\ p_c}{\mu\varphi h_x}\ , \tag{3}$$

where, h_x is the position of the imbibition front from the source. After integration, the distance of the imbibition front from the source grows with the square root of time [19]:

$$h_x = \sqrt{\frac{2kp_c t}{\mu\varphi}}\ . \tag{4}$$

The fabric used in these experiments weaves yarns of two different diameters, called the warp and weft, along orthogonal directions [20]), so that the permeability values in either orthogonal direction are different. Such fabrics are called orthotropic. By applying appropriate coordinate transformation, imbibition in an orthotropic system can be expressed with respect to imbibition in an isotropic system (i.e. having same permeability in all the directions) [21,22]. In this transformed coordinate system, the radial position of the wetting front is given by Ref. [21]:

$$p_c\frac{k_e t}{\mu\varphi r_{se}^2} = \frac{r_f^2}{2r_{se}^2}\ln\left(\frac{r_f}{r_{se}}\right) + \frac{1}{4}\left(1-\left(\frac{r_f}{r_{se}}\right)^2\right)\ . \tag{5}$$

where, k_e is the equivalent permeability given by $k_e = \sqrt{k_{warp}k_{weft}}$, $r_{se} = \alpha^{0.25}r_s$, r_s is the radius of the source and $\alpha = k_{weft}/k_{warp}$, k_{warp} and k_{weft} are the permeabilities in the warp and weft direction-respectively, and r_f is the radius of the wetting front in the transformed coordinate system. The lengths of the axes of the wetting front in the original coordinates system are obtained as: $r_{warp} = r_f/\alpha^{0.25}$ and $r_{weft} = r_f\alpha^{0.25}$. For $\alpha = 1$, Eq. (5) converts to the solution for isotropic imbibition [21]:

$$p_c\frac{kt}{\mu\varphi r_s^2} = \frac{r_f^2}{2r_s^2}\ln\left(\frac{r_f}{r_s}\right) + \frac{1}{4}\left(1-\left(\frac{r_f}{r_s}\right)^2\right)\ . \tag{6}$$

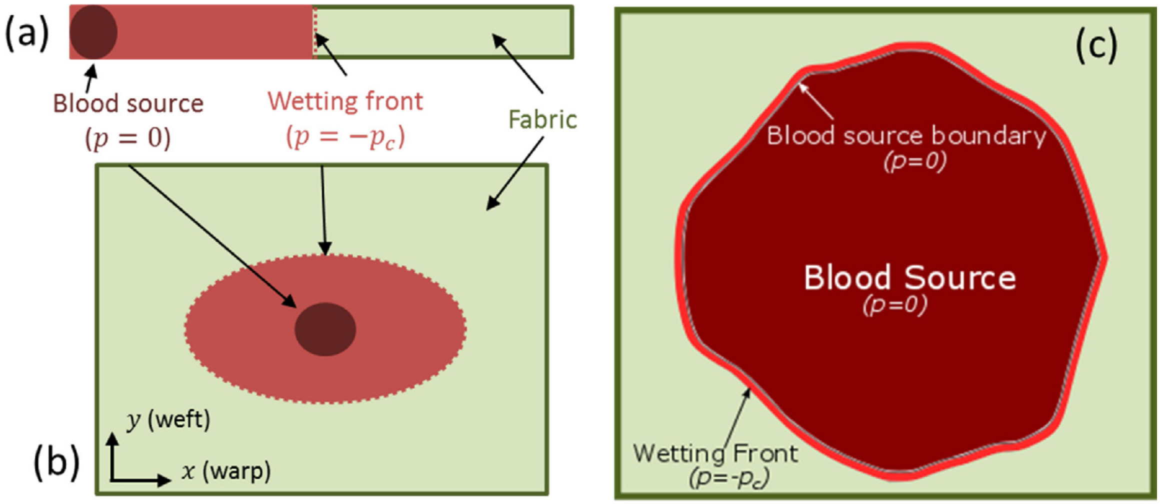

Fig. 1. Boundary conditions for analytical model (a) Linear imbibition, (b) Radial imbibition, (c) Numerical model.