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Wetting and spreading of human blood: Recent advances and applications

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ABSTRACT

Investigation of the physical phenomena involved in blood interactions with real surfaces present new exciting challenges. The fluid mechanical properties of such a fluid is singular due its non-Newtonian and complex behaviour, depending on the surrounding ambient conditions and the donor/victim's blood biological properties. The fundamental research on the topic remains fairly recent; although it finds applications in fields such as forensic science, with bloodstain pattern analysis, or biomedical science with the prospect of disease detection from dried blood droplets. In this paper, we review the understanding that has been achieved by interpreting blood wetting, spreading and drying when in contact, ex-vivo, with non-coated surfaces. Ultimately, we highlight the applications with the most up to date research, future perspectives, and the need of advancing further in this topic for the benefit of researchers, engineers, bloodstain pattern analysts, and medical practitioners.

1. Introduction

The interaction of blood with foreign, non-coated, surfaces is an emerging research subject that finds various applications in fields such as forensic science or biomedical discipline. Although blood flow circulation is a major subject that was thoroughly studied, interest in blood ex-vivo, i.e. outside the body, and its interaction with a non-coated surface, is less significant. However the properties of blood as a complex, biological, colloidal fluid, differ from those of more commonly studied, pure or complex, fluids, stimulating a recent curiosity concerning the behaviour of blood with real porous and non-porous surfaces. While applied studies on the topic had already been made, in 2011 the work on the evaporation of blood droplets by Brutin et al. gave a fundamental insight into blood drying pattern dynamics [4]. This work was later completed by recent studies whose major findings are presented in Table 1. When blood is in contact with a substrate the two main interface transfers are first the wetting, and then the evaporation. While wetting accounts for the equilibrium of the various applied forces at the triple line (meeting point of blood, surface, and air), evaporation describes the phase change taking place after as recalled by the review of Sefiane et al. of 2011 [26]. These processes are dependent on variables such as ambient temperature, humidity, and pressure, wettability and roughness of the surface, time elapsed since blood deposition, volume and blood's clotting response. Indeed, when blood is outside the body, its properties change rapidly due to platelet activation leading to the coagulation cascade response. The importance of understanding this problem for forensic science and biomedical applications, appears to be crucial since it is used as a tool to obtain evidence in crime scene reconstitution or in medical diagnosis. The National Institute of Standards and Technology (NIST) has pointed out, in a very recent report, the urge of using valid scientific methods before presenting evidence in courtrooms [22]. This illustrates the demand that exists concerning this research. To respond, we investigated the current understanding of blood physical and mechanical properties, and the most up to to date advances in the field. In this paper, we present first the characteristics of blood, then its spreading behaviour over dry porous and non-porous surfaces, followed by its drying dynamics, and finally we review the physics of impacting droplets. At last, we discuss the implications that the understanding of blood dynamics on real surfaces has for applications, and the future challenges that research is confronted with.

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Table 1
References of special interest studies published over the last 3 years.

First author	Year	Discipline	Fundamental/applied science	Major findings
Hudevoca	2017	Haematology	Applied science	Feasibility of prenatal detection of haemophilia based on maternal blood droplet [12•].
Comiskey	2017	Forensic	Applied science	Theoretical model for predicting bloodstain patterns from back spatter from blunt bullet gunshot [7•].
Totesbury	2017	Forensic	Applied science	Dynamic of blood wetting on hard surfaces using a synthetic blood substitute [30].
Laux	2016	Acoustics	Fundamental science	Ultrasounds can be used in order to monitor the rheological properties of blood [20•].
Cho	2015	Forensic	Applied science	Differentiation between transfer patterns and spatter patterns onto fabrics [6•].
Laan	2015	Forensic	Fundamental science	Fluid dynamic model to estimate the point of origin of blood spatters, taking into account gravity and drag [18•].

2. Blood properties

2.1. Biological composition

Blood is categorised as a body fluid that accounts for roughly 7% of the human body weight. It has two main constituents: plasma, the fluid medium and blood cells, the colloids. Plasma is a water based solution, composed for 92% of water, which dissolves and transports organic and inorganic molecules, and for 8% of dissolved solutes [3]. The solutes are mainly sodium electrolytes; nutrients and organic wastes are found as well in diverse amounts, and finally the proteins, which account for 7–9% of the plasma. These proteins are albumins (80%), globulin (16%) and fibrinogen (4%) that are really important in blot clot formation. Fibrinogen is a globulin of very high molecular weight synthesised exclusively from the liver that can be precipitated easily. During coagulation, the fibrin coming from fibrinogen forms a web leading to the clot formation. The blood cells are divided into three categories, the red blood cells (RBCs) that transport oxygen and carbon dioxide, the white blood cells (WBCs) (neutrophils and monocytes, eosinophils, basophils and lymphocytes), and the platelets, which play an important role in the clotting response. Indeed platelets prevent bleeding by clumping and clotting vessel injuries. Thus all these constituents are main parameters to understand this complex, non-Newtonian, fluid, since an excess or a lack of these components would alter its wetting and its spreading.

2.2. Physical and rheological properties

Blood has a small density variation between 1020 and 1060 kg.m^{-3}, due to the differences in the individuals haematocrit level, which is defined as the ratio of RBCs volume to whole blood volume. The surface tension of blood is known to be similar to that of water, as shown by the work of Brutin et al. where they found $\theta = 69.8$ mN.m^{-1} as average statistical surface tension. Studies, such as the one of Chao et al. of 2014, account for the shear thinning properties of blood, since its viscosity decreases to a constant value at high shear rates ($\eta = 4.8$ mPa.s), although it spreads like Newtonian fluids of similar viscosity. Rheological properties of a liquid are determined by the liquid viscosity, μ, and the applied shear rate, $\dot{\gamma}$, according to the following relationship: $\mu = k\dot{\gamma}^{n-1}$, where $n<1$ corresponds to pseudoplastic fluids. This is in an agreement with previous measurements of blood rheology [5]. As described by Baskurt et al., the apparent viscosity depends on the existing shear forces, and is determined by its biological properties: haematocrit, plasma viscosity, RBCs aggregation, and the mechanical properties of RBCs[1]. Alteration of those properties, such as a noteworthy modification of the haematocrit value, accounts for the haemorheological variations. Additionally, the viscoelastic properties of blood come from the high deformability of the RBCs.

3. Spreading of complex fluids

For a lot of applications (such as painting, coating...), a smooth deposition is critical. However, only a few studies were published on the understanding of the influence of complex fluids on the dynamics of spreading. The most obvious way to improve spreading for aqueous solutions is to add surfactants to decrease the liquid-vapour interfacial tension and increase the initial spreading coefficient. Rafaï et al. in 2002 [24], firstly studied the super-spreading of aqueous surfactants drops on hydrophobic surfaces. The super-spreading is due to a large affinity of the surfactant molecules for the solid substrate. If the surfactant molecules are transported rapidly and efficiently over the (small) height of the droplet in order to saturate the solid surface, this entails a large surface tension gradient over a small distance, and consequently a large Marangoni force. This, in turn, leads to the linear time evolution of the radius. The difference with the 'classical' surfactants observed here is then either a difference in affinity for the solid substrate or a difference in the transport efficiency to that same substrate, a question that remains to be answered. In 2013, Bouzeid and Brutin [2] studied the influence of relative humidity (RH) on the spreading behaviour and pattern formation of a human blood droplet. The drops of blood of the same volume are deposited on an ultra-clean glass substrate and evaporated inside a humidity chamber with a controlled range of RH between 13.5% and 78.0%. Their experiments show that the contact angle decreases as a function of the RH which influences the final deposition pattern at the end of the evaporation process (Fig. 1). Due to the effect of RH on the contact angle of the drop of blood, initial evaporative rate is dependent of RH values. They observed cracks pattern at the end of the drying process which is due to the competition between the drying regime and the gelation inside the drop of blood. Indeed, at first, the Marangoni convection inside the droplet induces the transport of particles towards the rim, and thus favours evaporation at the triple line. This corresponds to a convective evaporation. Later, once the particles concentration reaches a critical point, gelation occurs, and evaporation occurs through the porous media. The transition between the purely convective evaporation regime and the gelation regime appears always at 65% of the total drying time. Thus, controlling evaporative rate by evaporating drops of blood at different RH levels impacts strongly the wettability properties and the final pattern of drying drops of blood. The influence of RH on the final pattern of a dried drop of human blood is of huge importance for biomedical applications where drops of blood are drying in an open atmosphere.