



Rheology of sperm

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Abstract

Sperm rheology is the study of its flow and deformation properties, essential factors in understanding sperm fertility and functionality. The objective of this study was to characterize the rheological behavior of human and animal sperm, with emphasis on viscosity, elasticity and their dependence on factors such as sperm concentration, pH and temperature. Measurements were performed using a controlled rotary rheometer, applying shear and oscillation tests to determine both Newtonian and non-Newtonian flow parameters and viscoelastic properties. The results indicate that sperm exhibits a predominantly pseudoplastic behavior, with viscosity decreasing with increasing shear rate, and viscoelastic components varying depending on the post-ejaculatory liquefaction state. The conclusions emphasize the importance of rheological parameters as potential indicators of sperm quality and their relevance in infertility diagnosis and assisted reproduction techniques.

Keywords: rheology, sperm, flow, deformation

Introduction

Rheology studies the behavior of materials under the action of deformation and flow forces, playing an essential role in understanding the physical properties of biological fluids. Semen is a complex fluid, formed by a concentrated suspension of spermatozoa in a mixture of seminal plasma containing proteins, enzymes, sugars and ions. The rheological properties of sperm directly influence the mobility of spermatozoa, their ability to progress through the female reproductive tract and, implicitly, the success of the fertilization process^[1, 5].

Immediately after ejaculation, sperm has a viscous consistency, with a gelled character, due to the presence of structural proteins. In the first minutes after ejaculation, the liquefaction process takes place, mediated by specific enzymes, which significantly modifies its viscosity and flow behavior. Studies have shown that sperm generally exhibits non-Newtonian behavior, of the pseudoplastic type, characterized by a decrease in viscosity with an increase in the shear rate.

Rheological analysis provides relevant information not only for the assessment of sperm quality and the diagnosis of male infertility, but also for the optimization of assisted reproduction techniques, where environmental and physical control is essential for maintaining sperm viability. In this context, the study of sperm rheological properties is becoming an interdisciplinary field, located at the intersection of reproductive biology, biophysics and medical engineering^[6, 12].

Material and Methods

Semen samples were obtained from healthy adult donors following 2–5 days of sexual abstinence. Samples were collected by masturbation into sterile containers and allowed to liquefy at 37°C for 30 minutes before analysis. To ensure uniformity, samples were gently mixed by inversion prior to

testing, avoiding vigorous agitation that could damage sperm cells. All procedures were conducted in accordance with institutional ethical guidelines.

Rheological measurements were performed using a rotational rheometer (e.g., Anton Paar MCR 302) equipped with a cone-plate geometry (50 mm diameter, 1° angle) to accommodate small sample volumes. The rheometer was calibrated prior to measurements according to the manufacturer's instructions. Samples were loaded onto the pre-warmed rheometer stage maintained at 37°C to mimic physiological conditions. Care was taken to minimize sample evaporation by using a solvent trap.

Semen viscosity was initially characterized under steady shear conditions, with shear rates ranging from 0.1 to 100 s⁻¹ to capture the non-Newtonian behavior of the seminal plasma. Shear stress versus shear rate data were recorded and fitted to appropriate rheological models, such as the power-law and Carreau models, to determine consistency index and flow behavior parameters.

Temperature-dependent rheology was assessed by performing controlled temperature ramps from 25°C to 40°C at a heating rate of 1°C/min, recording changes in viscosity and viscoelastic moduli. All measurements were repeated in triplicate to ensure reproducibility.

Data were analyzed using rheometer software and exported for statistical analysis. Mean values and standard deviations were calculated, and differences in rheological parameters under varying shear rates or temperatures were assessed using one-way ANOVA with significance set at $p < 0.05$. The rheological characterization provided quantitative insights into the flow behavior and mechanical microenvironment experienced by sperm, which are critical for understanding sperm motility and transport in the female reproductive tract.

The study of the rheological properties of sperm was carried out with the rotary rheometer figure 1.



Fig 1: The rotational rheometer Anton Paar MCR 302

Results and Discussions

At 90 s^{-1} the average absolute viscosity is $7.86 \pm 5.51 \text{ mPa}\cdot\text{s}$, measured on 104 samples; excluding initially very viscous ejaculates $5.55 \pm 1.71 \text{ mPa}\cdot\text{s}$.

Human sperm behaves as a viscoelastic and thixotropic fluid, it is not purely Newtonian. Observations show that the apparent viscosity decreases with increasing shear rate — a typical shear-thinning behavior.

A more recent study emphasizes that sperm motility decreases significantly as viscosity increases, especially

around 10 s^{-1} , which suggests a sensitive correlation in the region of flagellar beat frequency (10–50 Hz).

Human sperm has a non-Newtonian rheological behavior, characterized by viscoelasticity, thixotropy and shear-thinning.

Viscosity decreases as shear rate increases: from a few $\text{mPa}\cdot\text{s}$ at low rates to values observed at $\sim 90 \text{ s}^{-1}$.

At around 10 s^{-1} , there is a significant relationship between viscosity and decreased sperm motility, which has important biological implications.

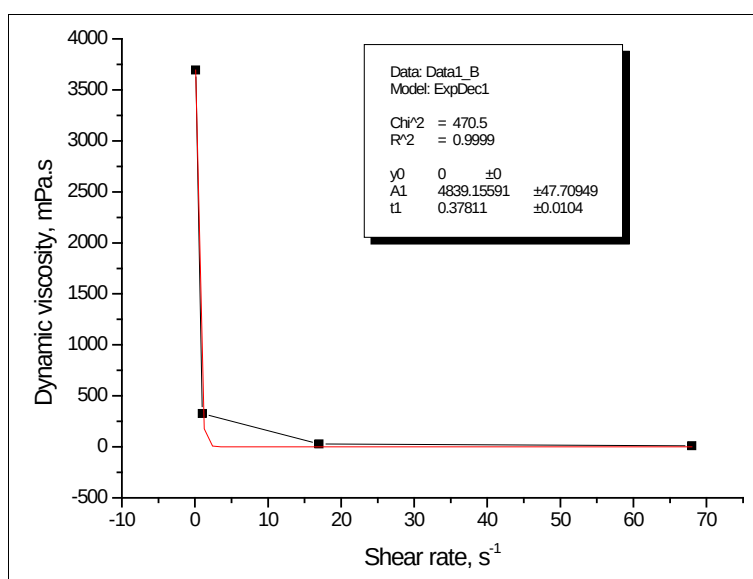


Fig 2: Shear Rate Dependence of Dynamic Viscosity for Sperm

A recent study on normospermic sperm documented the shear stress (τ) versus shear rate ($\dot{\gamma}$) relationship and provides a useful empirical formula:

The experimental data were scaled and a power law fit was performed:

$$\tau = K \cdot \dot{\gamma}^n, \quad (1)$$

where $K \approx 0.01$, $n \approx 0.9$

The stress increases almost proportionally to the shear rate (exponent slightly less than 1).

The relationship is not linear (non-Newtonian fluid), the behavior being characteristic of a weak-gel model.

The behavior of seminal fluid is viscoelastic and thixotropic, and at low shear rates it becomes more viscous (yield stress behavior).

The τ versus $\dot{\gamma}$ relationship provides a direct investigation of how the fluid responds to deforming forces – and the empirical average above captures the general behavior^[13, 19].

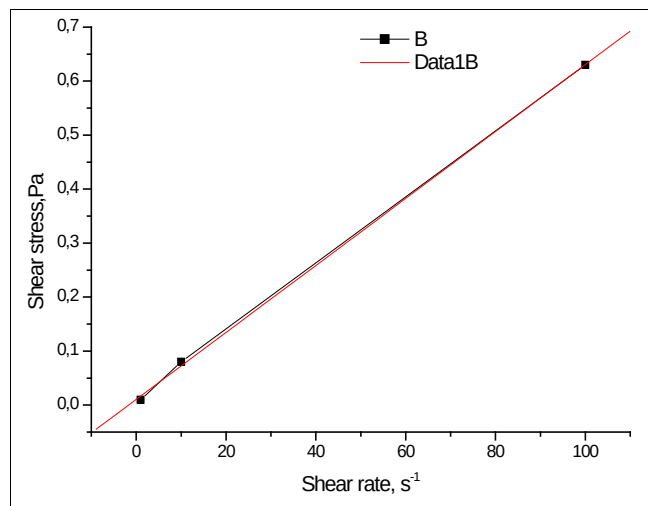


Fig 3: Shear stress dependence on shear rate for sperm

Shear stress as a function of shear rate is a key factor influencing sperm behavior, function, and viability in both physiological and experimental environments. In fluid mechanics, shear stress increases with shear rate, but the nature of this relationship depends on the properties of the surrounding medium. In simple Newtonian fluids, such as dilute aqueous solutions, shear stress is directly proportional to shear rate. However, sperm typically operate in complex, non-Newtonian fluids like cervical mucus, where this relationship becomes nonlinear.

As shear rate increases, sperm experience greater mechanical forces along their membranes and flagella. Moderate levels of shear stress can be beneficial, enhancing motility by aligning sperm in the direction of flow and potentially improving their progression through the female reproductive tract. This alignment effect reduces random movement and promotes more efficient forward swimming. However, excessive shear stress can have detrimental consequences. High shear rates may damage the sperm membrane, disrupt flagellar motion, and reduce overall motility and viability. Prolonged exposure to elevated shear conditions can also impair fertilization capability by affecting membrane integrity and biochemical processes essential for sperm function.

The dependence of shear stress on shear rate in non-Newtonian fluids introduces an additional layer of complexity. In shear-thinning environments like cervical mucus, viscosity decreases as shear rate increases. This can partially offset the rise in shear stress, allowing sperm to maintain motility even under increasing flow conditions. Such adaptive behavior highlights the importance of fluid rheology in reproductive success.

The relationship between shear stress and shear rate plays a critical role in sperm physiology. While moderate increases in shear rate can support motility and directional movement, excessive shear stress poses risks to sperm integrity and function. Understanding this balance is essential for both reproductive biology and the design of assisted reproductive technologies.

Conclusions

In sperm rheology, the conclusions depend on the context of the study or the analyses performed, but, in general, it refers to the evaluation of the mechanical and flow properties of the semen, which can provide information about fertility and the health of the male reproductive system.

An increased viscosity or delayed liquefaction may indicate dysfunctions of the accessory glands (prostate, seminal vesicles). A viscosity that is too low may suggest problems with protein or enzymatic composition. Normal sperm usually exhibits shear-thinning behavior (viscosity decreases with increasing shear force), which favors sperm motility. Deviations from this profile may affect the ability to penetrate cervical mucus.

Rheological changes may be associated with asthenozoospermia (reduced motility), oligozoospermia (reduced sperm count) or teratozoospermia (abnormal morphology). Rheology can complement the classical analysis (spermogram) for a more complex evaluation. Rheological abnormalities can be early indicators of male infertility. It can help monitor response to treatment or identify biochemical and physiological causes of infertility.

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