



Study of petrolatum structure: Explaining its variable rheological behavior

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ABSTRACT

The rheological properties of petrolatum are dependent on both temperature and thermal history. How this thermal dependency can be explained is unclear. In the past it has been suggested that the structure of petrolatum consists of a three-dimensional crystalline network. This has been established using old microscopic techniques only. Therefore a study on the microstructure of petrolatum was conducted using rheometry, DSC, pulsed NMR, polarized light microscopy and synchrotron X-ray. The combination of these techniques show that petrolatum is composed of 21% solid material at room temperature. This consists of partly crystalline lamellar sheets which are packed in stacks. The occurrence of these lamellar sheets is temperature dependent and the number of lamellar stacks is dependent on thermal history. It was shown that rheological differences in petrolatum can be explained by the number of lamellar stacks present, where more lamellar stacks result in more rigid petrolatum.

1. Introduction

Petrolatum is one of the most commonly used materials in pharmaceutical and cosmetic ointments and creams. In 2014 approximately 80 million kg of petrolatum was used for pharmaceutical purposes worldwide (*Microcrystalline Wax and Petrolatum: Global Market Analysis and Opportunities*, 2018). Therefore it can be considered a major bulk product for pharmaceutical applications. For petrolatum and other semi solids physical characterization methods are used to describe its consistency. Since it is a viscoelastic material, meaning it combines both viscous and elastic characteristics, its rheological properties are complex. It behaves non-Newtonian and its structural properties are greatly dependent on temperature and applied shear. The rheological properties can be studied in more detail using oscillatory stress testing (Pandey and Ewing, 2008; Park and Song, 2010; van Heugten et al., 2017a,b). Significant differences in rheological properties exist both between petrolatum grades and different thermal treatments (van Heugten et al., 2017a,b).

Understanding what causes differences in rheological properties is essential to optimise manufacturing processes and formulations (Eccleston et al., 2000; van Heugten et al., 2017a,b). For creams a wide

range of studies is described explaining their rheological properties using techniques such as small angle and wide angle X-ray diffraction (SAXS and WAXS, respectively), differential scanning calorimetry (DSC), thermal gravimetric analysis (TGA) and both electronic and light microscopy (de Vringer et al., 1984; Eccleston, 1986; Junginger, 1984, 1997; de Vringer et al., 1987a,b). Since creams contain water, the focus in characterizing these products generally lies on the location of water within the formulation to define whether it is free or bound to structures within the cream. Others focus on the emulsifiers or other distinctive components within the cream. However this does not apply to petrolatum, since it contains no water or emulsifiers but merely consists of alkanes of varying size (Barry and Grace, 1971). Therefore it is more difficult to determine how differences in rheological properties for petrolatum can be explained.

In literature the explanation of differences in rheological properties for semi-solids is often attributed to the gel network paradigm (Eccleston et al., 2000). Such a gel network forms a viscoelastic continuous phase in emulsions. For petrolatum the structure is generally described as a two-phase system consisting of a three-dimensional crystalline network consisting of fibre-like crystals that encloses and immobilizes the liquid hydrocarbons (Barry and Grace, 1971; Pajor

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et al., 1967; Pandey and Ewing, 2008; Park and Song, 2010; Pena et al., 1994). No clear evidence exists of this three-dimensional crystalline structure. All cited papers conclude that such a structure may explain the complex rheological behaviour of petrolatum but direct evidence has not yet been described.

Nowadays new techniques exist to determine structures within materials such as petrolatum. Especially synchrotron X-ray scattering techniques can be powerful in studying structures at detailed level (Narayanan et al., 2017). This may finally elucidate the microstructure of petrolatum responsible for its greatly variable rheological properties.

Therefore we aim to study the nano-, micro- and macrostructure of petrolatum by synchrotron SAXS and WAXS methodologies combined with DSC, pulsed nuclear magnetic resonance (NMR), hot stage polarised light microscopy (HSPLM) and rheometry.

2. Materials and methods

2.1. Materials

Petrolatum (Snowwhite N, Sonneborn, Amsterdam, The Netherlands) and paraffin oil (Gustav Heess, Leonberg, Germany) were used.

2.2. Rheometry

A stress-controlled rheometer (TA instruments HR-2, Etten-Leur, The Netherlands) equipped with a peltier plate and a 40 mm sand-blasted parallel plate (TA-instruments plate geometry 40 mm) was used. Approximately 5 g of petrolatum was placed on the peltier plate before slowly lowering the upper plate to the preset trimming gap of 1050 μm . After trimming excessive petrolatum the geometry gap was set to 1000 μm .

The linear viscoelastic region (LVR), meaning the range of stresses within which the structure of the sample is not destroyed (Pandey and Ewing, 2008), was determined using oscillatory stress sweep (OSS) experiments in a wide stress range (1–2000 Pa) at 25, 35, 45 and 55 °C. Temperature ramps were conducted within the LVR of 55 °C at a heating and cooling rate of 5 °C/min between 25 and 75 °C. Petrolatum yield stress after slow and fast cooling was determined using a conditioning temperature ramp of 0.1 or 10 °C/min and a OSS similar to the LVR measurements after this temperature ramp. Yield stress was defined as the point where the storage and loss modulus lines cross. Data was analyzed using Trios v3.3.0.4055 software.

2.3. Differential scanning calorimetry (DSC)

DSC measurements were conducted on a TA Instruments Discovery DSC (TA Instruments, Etten-Leur, The Netherlands). 5–8 mg of petrolatum was placed in DSC hermetic aluminum pans and the sample was conditioned at 10 °C for 10 min, next, the sample was heated at 5 °C/min to 70 °C and subsequently cooled to 10 °C at 5 °C/min. Data was analyzed using Trios v3.3.0.4055 software.

2.4. Solid fat content (SFC)

Petrolatum was transferred to a glass NMR tube and stored at room temperature for two weeks. Before measurement the sample was conditioned in waterbaths (Lauda Ecoline RE104, New Jersey, USA) at 10, 15, 20, 25, 30, 35 and 40 °C for 30 min. Afterwards, pulsed NMR (Bruker Minispec MQ20, Leiderdorp, The Netherlands) was used according to the direct method (Coupland, 2001).

2.5. Hot stage polarised light microscopy (HSPLM)

A small amount of sample was applied to a glass slide. All samples were analyzed at a 100 \times magnification on a Nikon Eclipse TE2000-U

microscope (Nikon Instruments Europe BV, Amsterdam, The Netherlands). The samples were assessed at different temperatures. The sample was heated to 25 °C, then 35 °C and 50 °C and finally cooled back to 25 °C. The estimated average heating rate was 4 °C/min, the estimated average cooling rate was 2 °C/min. Pictures were analyzed using ImageFocus v 3.0.0.2.

2.6. Synchrotron small- and wide-angle X-ray scattering

For small- and wide-angle X-ray scattering (SAXS and WAXS) measurements, a small amount of sample was transferred to 80 mm glass capillaries with a diameter of 1 mm and wall thickness of 0.01 mm (Hilgenberg GmbH, Malsfeld, Germany). The sample was heated homogeneously in an oven to 75 °C to remove stresses caused by sample loading. One sample was melted and cooled directly by removing it from the oven at an estimated cooling rate of 10 °C/min. Another sample was allowed to cool to room temperature at a programmed cooling rate of 0.1 °C/min in an oven. Both samples were incubated at room temperature for at least 2 weeks prior to the measurements. After collecting the SAXS/WAXS data for the two samples at room temperature, the fast cooled sample was subject to a thermal treatment protocol as in the rheological measurements.

SAXS and WAXS patterns were obtained at the DUBBLE beamline at the European Synchrotron Radiation Facility in Grenoble (Borsboom et al., 1998). The SAXS sample-to-detector distance was kept at 1.5 m and X-rays with a wavelength of 0.1 nm were used to measure the scattering. A Pilatus 1 M detector was used to record small-angle (λ) scattering profiles. WAXS profiles were recorded using a Pilatus 300 K detector. Background corrections were applied on all azimuthally (integrated across all angles) integrated profiles. Background correction was obtained from scattering recorded from capillaries filled with paraffin oil.

In the SAXS profiles the scattering wavevector q is plotted against the corresponding intensity (I). This scattering wavevector can be viewed as the resolution with which the sample is observed and is calculated using Eq. (1), in which λ is the wavelength of the X-rays and θ the angle of the X-rays.

$$q = \frac{4\pi}{\lambda} \sin \frac{\theta}{2} \quad (1)$$

2.7. Data analysis

2.7.1. Kratky plot

Before peak analysis, SAXS profiles were multiplied by q^2 to compensate for the inverse square decay (Kratky plot). Such a Kratky plot extracts the slope from the data thereby making the interpretation of the data more reliable since the determination of a peak maximum is more accurate (Glatter and Kratky, 1982).

2.7.2. Porod invariant and peak width σ

Of these Kratky plots the first peaks were integrated as a measure for the amount of material structured in lamellar sheets. This peak integrant corresponds to the so called Porod invariant (Q) (Glatter and Kratky, 1982). A Gaussian curve was fit to each peak and the peak width σ was taken directly from this fitted Gaussian. This peak width is a measure for the degree of periodic order. This corresponds to the number of lamellar sheets in a stack (Glatter and Kratky, 1982). A high peak width reflects a small degree of periodic order and thus a low number of lamellar sheets in a stack.

2.7.3. Crystal lattice, crystallinity and crystallite size

WAXS peak positions were obtained from the azimuthally integrated WAXS profiles from the peak maxima. From these peak positions the type of crystal lattice was determined. For the amount of crystalline material in the sample, the WAXS profiles were multiplied

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