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Permeability and wettability of bioresorbable nanofiber nonwoven membranes

Abstract: Nanofiber nonwoven membranes produced by electrospinning provide the possibility to adjust mechanical material parameters as well as simultaneously the biologically relevant properties - a fundamental aspect in developing new implants and medical devices. Wettability and permeability are also of great importance, as they have a decisive influence on the release of drugs, cell attachment, degradability and finally the nutrient supply of the surrounding tissue. Within this work the wettability and permeability of several electrospun poly-L-lactide nonwovens, including different additives, were investigated and a correlation to membrane morphology was found. A potential modification of the permeability by the fluid viscosity was also investigated. The results form a fundamental building block in the development of permeable biodegradable implants and medical devices.

Keywords: permeability, wettability, nanofiber, nonwoven, biodegradable, electrospinning, membrane

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1 Introduction

Electrospun nanofiber nonwovens represent a milestone in developing new materials. Their mechanical and biological properties can be modified by the polymer components and the spinning parameters [1]. Especially for medical applications matching the mechanical properties like Young's modulus or maximum tensile strength to desired functionality and even introduce anisotropies by adjusting the fiber direction can lead

to new functionalized or optimized devices. Furthermore, an adjustment of the wettability and the water permeability of the nonwovens is also indispensable, for instance in biodegradable implants, nanoparticle- and drug-delivery systems or corrosion-resistant coatings which have to seal and simultaneously be water permeable to a certain amount [1, 2].

According to Darcy's law the water permeability represents a constant which connects the pressure gradient over a structure with the fluid velocity:

$$\mathbf{u}_z = -\frac{\mu}{\eta} \cdot \frac{\partial p}{\partial z} \quad (1)$$

Here u_z denotes the fluid velocity in z-direction, η the dynamic viscosity of the fluid, $\partial p/\partial z$ the pressure gradient over the structure in z-direction and μ the permeability of the structure. In this context, permeability can be considered as a material parameter of the permeable structure. Depending on the porosity of the investigated structure the flow can also be turbulent, leading to a more complex relation between fluid velocity and pressure gradient. Furthermore, for nanofiber membranes porosity depends on the morphology which can be modified during applying a pressure to the membrane. In consequence, it needs to be investigated whether the water permeability of nanofiber membranes depends on the actual conditions like viscosity and the applied pressure gradient.

In this study the wettability and water permeability of bioresorbable nanofiber nonwoven membranes were investigated for different types of additives in the poly-L-lactide (PLLA) nonwovens. In addition, a potential modification of the permeability by the applied pressure gradient or the fluid viscosity was investigated.

2 Methods

2.1 Preparation of nanofiber membranes by electrospinning

Polymer solutions of 4 to 5 wt.% were obtained by dissolving PLLA (RESOMER L210, Evonik, Germany) in a mixture of chloroform and 2,2,2-trifluoroethanol (TFE) (1:4 v/v) at 37 °C. The 4 wt.% polymer solutions were loaded with

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12.5 wt.% of Triton X-100 (TX 100) or 1 wt.% of lecithin or 1 wt.% of lecithin and 1 wt.% of tetraethylammonium chloride (TEAC), respectively. Here the concentrations are with respect to the polymer weight. The 5 wt.% polymer solution was kept pure. The process of electrospinning was performed using the 4SPIN C4S LAB2 device (Contipro, Dolní Dobrouč, Czech Republic) which includes a custom-built rotating continual collector as well as a multi-jet capillary emitter with six or eight cannulas. All trials were performed at an emitter-collector distance of 15 cm, the applied voltage and the feed rate were chosen to be 18 to 30 kV and 100 $\mu\text{L}/\text{min}$ or 220 $\mu\text{L}/\text{min}$, depending on the number of cannulas. The spinning process was performed using ambient temperature of $22\text{ }^\circ\text{C} \pm 2\text{ }^\circ\text{C}$ and relative humidity of $25\% \pm 5\%$.

2.2 Electron microscopy

The morphology of the fabricated nonwoven membranes was investigated using a field emission scanning electron microscope (Quattro S, Thermo Fisher Scientific Inc., USA). The membranes were covered with a gold layer of a few nanometers (A2008, Agar Scientific Ltd, United Kingdom) to reduce charging during electron beam irradiation and subsequently investigated at identical magnification in low vacuum mode at 50 Pa with an acceleration voltage of 15 kV.

2.3 Permeability setup

The permeability was experimentally determined using a previously described setup [3]. In short, a hydraulic pump (Corio CD, JULABO GmbH, Germany) generates a constant flow and simultaneously controls the temperature of the fluid. The pressure drop over the membrane is determined using a pressure gauge (86A 3R-000000-005P G, Measurement Specialties Inc., USA) and the volumetric flow is measured using a Doppler sonography flow sensor (Leviflow LFS-008, Levitronix GmbH, Switzerland) in front of the sample chamber. The fluid temperature was set to $37\text{ }^\circ\text{C}$.

As test fluid a mixture of deionized water and glycerol was chosen and the concentration was modified to achieve different dynamic viscosities. For correlation between viscosity and concentration, the viscosity was determined using a commercial rheometer (RheoStress 1, Thermo Fisher Scientific Inc., USA). For the evaluation of the membrane permeability, three glycerol concentrations 0 wt.%, 20 wt.%, and 40 wt.% were chosen, which correspond to a dynamic viscosity of 0.937 mPa·s, 1.397 mPa·s, and 2.401 mPa·s, respectively.

2.4 Water contact angle

Measurements of the initial water contact angle were performed by sessile drop method on the nonwoven polymer surface using a mobile surface analyser (MSA, KRÜSS GmbH, Hamburg, Germany) with ADVANCE 1.9.2 software. The contact angles of water were determined against air, whereby droplets comprising a volume of $2\text{ }\mu\text{L}$ were deposited and measured within one second.

3 Results and discussion

3.1 Wetting the membranes

To investigate the wetting by the test fluid a pressure gradient was applied to the mounted membranes. The corresponding fluid velocities for the applied pressure gradients are plotted in Figure 1 using pure water as test fluid. As the pressure gradient increases, the fluid velocity suddenly changes its dependence on the pressure gradient. The observed changes occur instantaneously and mark the points at which the accessible area of the membranes is completely wetted, except for the membrane including lecithin and TEAC. This structure could not be wetted at all, resulting in zero fluid velocity for all applied pressure gradients. Figure 1 shows the observed changes occurring at 73, 92, and 137 $\text{Pa}\cdot\mu\text{m}^{-1}$ for membranes without additives, with TX 100 and with lecithin, respectively. To investigate the origin of this pressure gradient dependent wetting, the water contact angle was measured for all membranes (cf. **Table 1**). Within the obtained uncertainty the

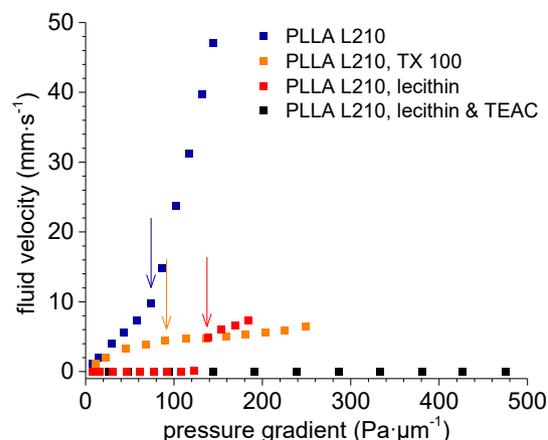


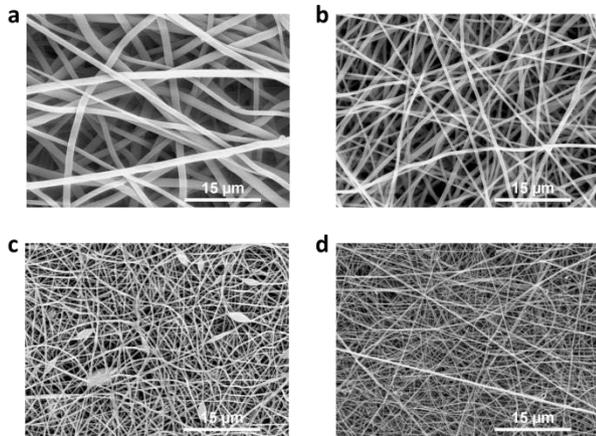
Figure 1: Fluid velocity during wetting of the membranes measured using pure water. After the complete wetting of the membranes the slope of the fluid velocity changes for each membrane. Point of complete wetting is indicated by the arrows. The membrane containing lecithin and TEAC was not wetted for the applied pressure gradients.

Table 1: Mean values of the water contact angle and fiber thickness of the investigated PLLA nanofiber membranes.

Polymer additives	Contact angle (°)	Fiber thickness (nm)
none	132.5 ± 13.5	1129 ± 375
TX 100	12.7 ± 2.8	531 ± 116
lecithin	135.3 ± 1.9	325 ± 96
lecithin & TEAC	139.1 ± 72.8	165 ± 32

contact angle does not differ for the investigated membranes, except for the membrane including the surfactant TX 100. Accordingly, the differences in the wettability are probably not correlated to the initial water contact angle.

Next the membranes morphology was analyzed by means of electron microscopy. A clear difference in the fiber diameter and thus also in the effective interface roughness was found (cf. **Error! Reference source not found.**2). When comparing the pressure gradients required to wet the membranes and the averaged fiber diameter of the corresponding membrane, it becomes apparent that a change in the wetting at low pressure gradients is probably correlated to a large fiber diameter (cf. Table 1). Similar effects were recently found by comparing membranes consisting of different polymers with larger fiber dimensions [4]. Note that, a smaller fiber diameter is commonly associated with smaller vacancies between the fibers.

**Figure 2:** Electron micrograph sections of the investigated PLLA nanofiber nonwovens **a** without additives, **b** with TX 100, **c** with lecithin, and **d** with lecithin and TEAC.

3.2 Permeability of the membranes

After wetting the membranes, the fluid velocity measurements were repeated (cf. Figure 3 a-c). Subsequently, the slope of each dataset was determined by linear regression followed by

calculating the permeability according to Equation $\mathbf{u}_z = -\frac{\mu}{\eta} \cdot \frac{\partial p}{\partial z}$ (1). The exact values of the permeability can be found in Table 2. It should be noted that no permeability could be determined for the membranes containing lecithin and TEAC as well as for the membrane with lecithin at a viscosity of 1.397 mPa·s due to the lack of wetting. Apart from a distinct difference for all types of membranes, the permeability tends to increase with increasing fluid viscosity for each membrane.

One possible reason for this effect could be that Darcy's law (cf. Equation $\mathbf{u}_z = -\frac{\mu}{\eta} \cdot \frac{\partial p}{\partial z}$ (1)) is not valid for the investigated membranes using the present experimental parameters. Potentially due to turbulent flow within the membranes during the entire measurement or because of deformation initiated by the applied pressure gradients also causing turbulent flow or just a change in fiber fraction.

An indication of this is provided by the partly non-linear characteristic of the fluid velocities shown in Figure 3 a-c. However, since the porosity of electrospun membranes as well as the fiber morphology can only be estimated, no clear statement can be made whether laminar or turbulent flow is present in the conducted experiments.

Nonetheless, Figure 3 d-f shows the thicknesses for the investigated membranes. Within the existing uncertainties, no irreversible change in thickness can be detected. Thus, the observed non-linearity of the fluid velocity and the associated variation of the permeability for different viscosities is probably caused by a change in the thickness and morphology of the membranes during the measurement [5].

Table 2: Water permeability μ for the investigated membranes with respect to the dynamic viscosity η of the test fluid.

Polymer additives	μ (m ²)		
	$\eta = 0.937$ (mPa s)	$\eta = 1.397$ (mPa s)	$\eta = 2.401$ (mPa s)
none	23.98 · 10 ⁻¹⁴	81.02 · 10 ⁻¹⁴	95.80 · 10 ⁻¹⁴
TX 100	1.90 · 10 ⁻¹⁴	3.51 · 10 ⁻¹⁴	13.35 · 10 ⁻¹⁴
lecithin	2.86 · 10 ⁻¹⁴	-	4.78 · 10 ⁻¹⁴

4 Conclusion

Within this study nanofiber membranes consisting of biodegradable PLLA nonwovens were investigated with respect to their wettability and water permeability. The nanofiber membranes showed a distinct correlation of the pressure gradient needed for wetting and the fiber dimensions of the corresponding membrane [4], whereas no difference in

the initial water contact angle for the investigated membranes was observed.

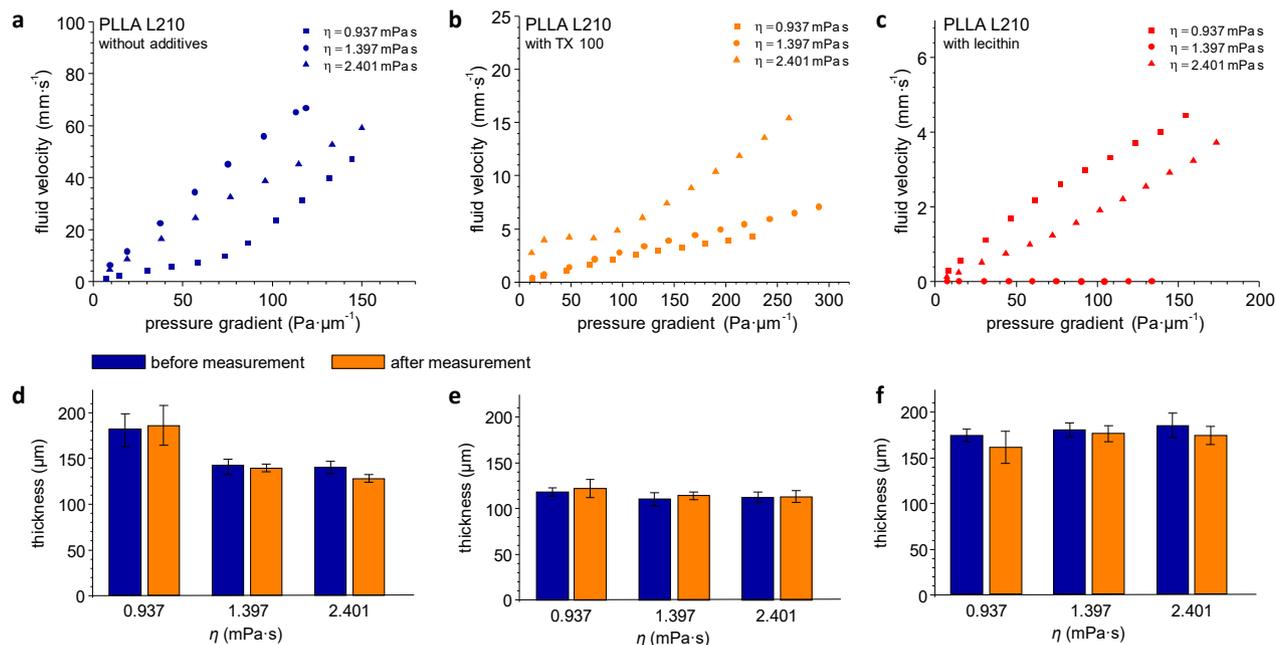


Figure 3: Fluid velocity as a function of the applied pressure gradient for **a** PLLA L210 without additives, **b** with TX 100, and **c** with lecithin. The slope was determined by linear regression and used to calculate the permeability. For each type of membrane, the shown data includes the measurements for a fluid viscosity of 0.937 mPa·s, 1.397 mPa·s, and 2.401 mPa·s. Through the membrane consisting of PLLA L210 with lecithin and TEAC no fluid velocity could be measured. After performing the measurements no distinct variation in the thickness was found for the membranes made of PLLA **d** without additives, **e** with TX 100, and **f** with lecithin.

Furthermore, it was shown that besides the different wettability there is also a clear variation in water permeability. Therefore, for the investigated electrospun membranes the permeability cannot be considered as a constant parameter according to Darcy's law. Since no irreversible change in thickness was observed, it is supposed that the membrane changes its permeability during the presence of a pressure gradient. It has also been shown that the permeability varies with fluid viscosity. Especially, for their degradability and when used as drug- and nanoparticle-delivery systems [1] or corrosion resistance coating [2], the wettability as well as the viscosity-dependent permeability of the nonwovens are of decisive importance. Thus, the results presented here form the substantial basis for the development of new permeable and semi-permeable implants and medical devices consisting of biodegradable nanofiber membranes.

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