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FACULTY OF CHEMISTRY
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RHEOLOGY OF HYALURONAN SOLUTIONS

REOLOGIE ROZTOKŮ HYALURONANU

DOKTORSKÁ PRÁCE
DOCTORAL THESIS

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Zadání dizertační práce

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Dizertační práce se odevzdává ve třech exemplářích na sekretariát ústavu a v elektronické formě vedoucímu dizertační práce. Toto zadání je přílohou dizertační práce.

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V Brně, dne 30.8.2005

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ABSTRACT

Present work is focused on rheological properties of hyaluronan solutions. It studies the solutions behavior in dependence on changing Mw and concentration. Also the effect of different solvents and the increasing pH on viscosity of HA solutions is described. In the second part, the effect of increasing temperature is discussed. Finally (but not less important) the dissolving of hyaluronan powder, the time stability of prepared solutions and presence of aggregates are studied. All of these experiments are very useful from the practical point of view, e.g. during the production, sterilization and storage of hyaluronan solution.

KEY WORDS

hyaluronan, rheology, viscosity

ABSTRAKT

Předložená práce se zabývá reologickými vlastnostmi roztoků hyaluronanu. Studuje chování hyaluronanových roztoků v závislosti na jejich Mw a koncentraci. Dále popisuje vliv prostředí několika rozpouštědel a vliv měnícího se pH na viskozitu hyaluronanových roztoků. V druhé části je studován vliv rostoucí teploty na viskozitu roztoků. V neposlední řadě je zkoumána správná příprava roztoků, jejich časová stabilita a tvorba agregátů. Všechny experimenty vycházejí z praktického upotřebení, např. při výrobě hyaluronanu, jeho sterilizaci a následném skladování roztoků.

KLÍČOVÁ SLOVA

hyaluronan, reologie, viskozita

CONTENT

1 INTRODUCTION

Hyaluronan is a high molecular weight unbranched glycosaminoglycan, composed of repeating disaccharides (β1-3 D-N-acetylglucosamine, β1-4 D-glucuronic acid). It is a widely distributed component of the extracellular matrix of vertebrate tissues.[1]

In the last 20 years, scientific attitudes have changed from regarding it only as a molecular cotton wool that fills certain extracellular spaces to ones that also view it as a center around which many matrix macromolecules are organized. A great range of biological functions has been imputed to the molecule, and it has importance from numerous physiological, clinical and diagnostic aspects. Its structural simplicity, span in molecular weight range and unique mode of synthesis mark it as a molecule of distinctive evolutionary significance. To date, no naturally acetylated, sulfated or other modified variants have been discovered.

Hyaluronan has many roles, some requiring its presence in minute quantities (*e.g.,* as a proteoglycan organizer in cartilage) whereas in others, it is the dominant structural entity (*e.g.,* its presence in vitreous, Wharton's jelly or synovial fluid). Thus, hyaluronan function may vary greatly depending on whether its interactions are predominantly with proteins in tertiary and quaternary organizations or with water and ions making viscous solutions or gels.

This work is focused on physical properties of wide range of molecular weight hyaluronan in solution, which means the range of studies Mw is approximately between 10 000 – 2 600 000 g/mol.

In theoretical part, the research on hyaluronan conformation and rheological measurements from the 1934, when the hyaluronan molecule was discovered, to these days is summarized.

The experimental part is concerned with the behavior of HA chains in solution and tries to compare the effect of Mw, concentration and pH of solvent on hyaluronan conformation in the first part. The second part is focused on the temperature stability of hyaluronan aqueous and phosphate solutions. Finally, because of the importance for many applications, the dissolving and time stability studies of HA in solution were done and the presence of aggregates was observed.

2 THEORETICAL BACKGROUND

2.1 Chemical structure of hyaluronan

Hyaluronan (also called hyaluronic acid or hyaluronate) is an anionic, non-sulfated glycosaminoglycan distributed widely throughout connective, epithelial, and neural tissues.

Its name, hyaluronic acid, is derived from hyalos (Greek for vitreous) and uronic acid because it was first isolated from the vitreous humour and possesses high uronic content.

The term hyaluronate refers to the conjugate base of hyaluronic acid. Because the molecule typically exists in vivo in its polyanionic form, it is most commonly referred to as hyaluronan.

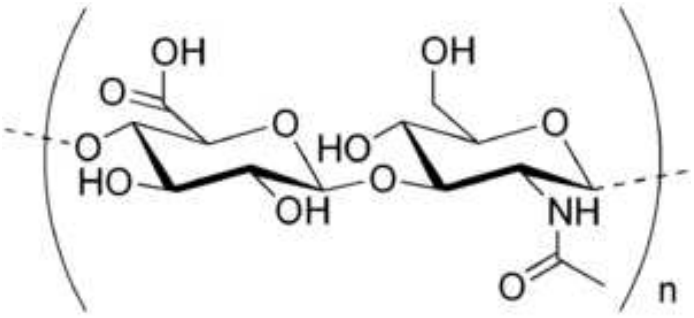

Fig. 1 The repeating disaccharide unit of hyaluronan

Hyaluronan is a polymer of disaccharides, themselves composed of D-glucuronic acid and D-N-acetylglycosamine, linked together via alternating β-1,4 and β-1,3 glycosidic bonds. Hyaluronan can be 25 000 disaccharide repeats in length. Polymers of hyaluronan can range in size from 5 000 to 20 000 g/mol in vivo. The average molecular weight in human synovial fluid is 3-4 million g/mol, and for example hyaluronan purified from human umbilical cord is 3 140 000 g/mol.[2]

2.1.1 Structure of hyaluronan in aqueous solutions

The solution properties of HA have been investigated for about 60 years, without a clear consensus emerging. HA solutions have pronounced viscoelastic properties and the biophysical basis of its ´non-ideal´ behavior has been the sources of much interest and speculation. At neutral pH and physiological ionic strength much of the early work of the groups of Laurent and Balazs led to the conclusion that HA behaved as a stiffened random coil in solution with considerable local stiffness, and quite large persistence length.[3,4] Later the stiffening was proposed to be at least in part due to hydrogen bonding between adjacent saccharides, combined with some effect from the mutual electrostatic repulsion between carboxyl groups[5-8] and these proposals have been substantiated by later results using different techniques.[9-12]

Hascall et al. presented[13] that in a physiological solution, the backbone of a hyaluronan molecule is stiffened by a combination of the chemical structure of the disaccharide, internal hydrogen bonds, and interactions with solvent. The axial hydrogen atoms form a non-polar, relatively hydrophobic face while the equatorial side chains form a more polar, hydrophilic face, thereby creating a twisting ribbon structure. Consequently, a hyaluronan molecule assumes an expanded random coil structure in physiological solutions which occupies a very large domain (Fig. 2). The actual mass of hyaluronan within this domain is very low, ~0.1% (w/v) or less when the macromolecule is present at a very dilute concentration in saline. This means that the domains of individual molecules would overlap each other at concentrations of 1 mg hyaluronan per ml or higher.

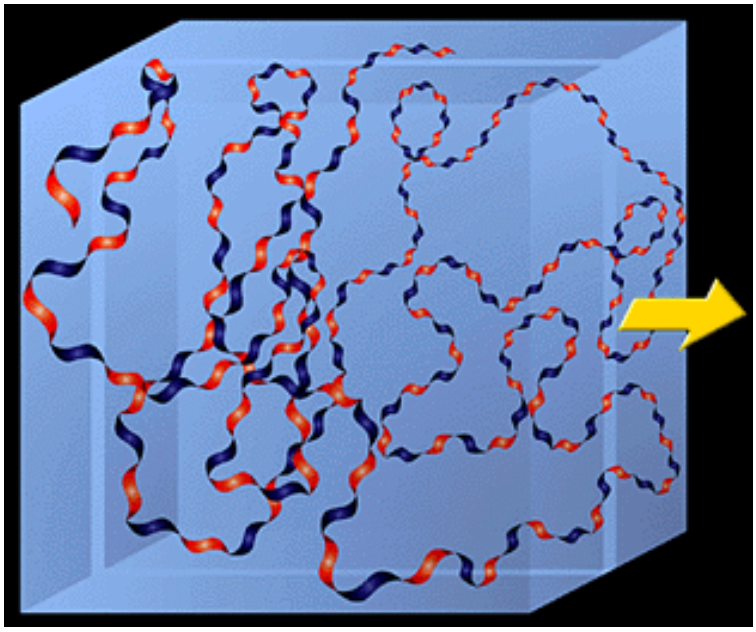

Fig. 2 Model of hyaluronan ribbon in a 3-dimensional domain. The light blue box represents the domain of the molecule in solution. The alternating blue and red strand represents the ribbon structure with blue (hydrophilic) and red (hydrophobic) faces.[13]

The domain structure of hyaluronan has interesting and important consequences. Small molecules such as water, electrolytes and nutrients can freely diffuse through the solvent within the domain. However, large molecules such as proteins will be partially excluded from the domain because of their hydrodynamic sizes in solution.[13]

The concentration of hyaluronan in tissues is often higher than would be expected if individual molecules maintained their expanded domain structures. In many cases the hyaluronan is organized into the extracellular matrix by specific interactions with other matrix macromolecules. However, high molecular weight hyaluronan at high concentration in solution (for example, $5 \cdot 10^6$ g/mol at concentrations above 0.1 mg/ml) can also form entangled molecular networks through steric interactions and self association between and within individual molecules. The latter can occur when a stretch of the hydrophobic face of the ribbon structure of the backbone interacts reversibly with the hydrophobic face on a

comparable stretch of hyaluronan on another molecule or in a different region of the same molecule. Such networks exhibit different properties than would isolated hyaluronan molecules. They can resist rapid, short-duration fluid flow through the network, thereby exhibiting elastic properties which can distribute load or shear forces within the network (Fig. 3).[13] On the other hand, slow fluid flow of longer duration can partially separate and align the molecules, allowing their movement and exhibiting viscous properties. Procedures for introducing covalent cross-links in hyaluronan matrices have been developed to create stable networks and semi-solid materials exhibiting pronounced viscoelastic properties.[13]

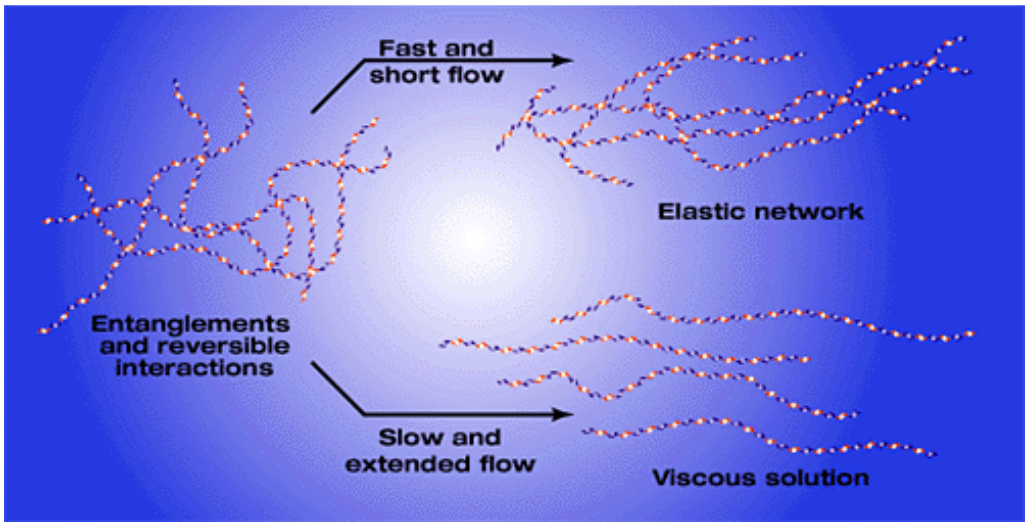

Fig. 3 Model demonstrating the viscous and elastic properties of hyaluronan solutions.[13]

However, this relatively simple model has in recent years been challenged by a proposal that HA chains self-associate and that this dominates the solution properties. The core evidence for this was in two strands. The first was that apparent association between HA chains was visualized in EM preparations and it was interpreted as anti-parallel double helices, bundles and ropes[14,15] and the second was that NMR spectra demonstrated an extended hydrogen-bonded system, a twofold helix with elements of co-operativity that included water bridges between neighboring sugar residues.[16,17] This structure seemed to account for chain stiffness and also for the observation that the high viscosity of HA reversibly and dramatically decreased at high pH.

However, the principal driver for this model of self-association was the observation that HA in a 2-fold helix could contain hydrophobic patches and these might provide sites for self-association between chains.[9] It was suggested that these patches could be the basis of interactions with lipid membranes and with proteins, and also of self-aggregation.

With the premise that HA may self-associate, but the interactions may be weak and transient, Hardingham et al. investigated HA properties in concentrated solutions and looked for evidence of self-association.[18] For this study they used a newly developed technique, confocal-FRAP. An important aspect, and indeed the value, of using confocal-FRAP is that it permitted analysis at concentrations of HA up to and far exceeding the critical concentration at which there is predicted molecular domain overlap.[19] This analysis was thus ideally suited

to investigations of entanglement and intermolecular chain-chain association, as these would be concentration-dependent and strongly favored at high concentration. Electrostatic and ionic effects on the HA network and its sensitivity to counter-ion type and valence were determined as these are known to greatly affect rheological and hydrodynamic properties. The results showed that in going from 0.5 M NaOH to de-ionized water, the apparent domains of HA chains were increased by more than 100 times and this most likely resulted from increased electrostatic interactions and hydrogen bond formation.[18]

The authors also suggested[18,19] that intramolecular hydrogen bonds and polyanionic properties of HA both contribute to provide a highly expanded macromolecular conformation. However, under physiological conditions of ionic strength the results predict the electrostatic effects to be modest.

To recapitulate it, HA in aqueous solutions exists as an extended random coil at low concentrations (<1 mg/ml),[20] allowing for free movement of the polymer chains.[21] At high concentrations (>1 mg/ml), a transient entanglement network arises where molecules entangle with each other and then disentangle after a period of time. This network is stabilized by hydrogen bonding and non-covalent intermolecular associations.[22] The network properties of HA at high concentration affect the viscoelasticity of the solution,[23] giving rise to enhanced viscosity and pronounced non-Newtonian behavior, manifested by a higher extent of shear thinning.[24-26]

Similar effects have been noted as the molecular weight of HA in solution is increased for solutions of the same concentration.[24] Solutions of HA of molecular weight of 3 000 000 g/mol showed increased magnitudes of the viscous and elastic components of the complex viscosity, η' and η'', respectively with frequency compared to solutions with HA of molecular weight of 500 000 g/mol at the same concentration.[27] However, the increase was more pronounced for the elastic component, η''.

Finally, Kobayashi et al.[28] indicated that a transient network is formed by entanglements of HA chains at high molecular weight and these entanglements were absent for HA at low molecular weight.

Similar trends were found in studies by Ambrosio et al.,[20] who indicated that in the case of high molecular weight HA (1 200 000 g/mol) a network structure is formed from entanglements, as opposed to the low molecular weight HA (150 000 g/mol) where entanglements are absent. The dynamic modulus G' and G'' exhibited cross-over for the higher molecular weight HA, in contrast to the low molecular weight HA that behaved like a viscous fluid throughout the range of frequencies examined.[29] Also, for the higher molecular weight HA, a lower cross-over frequency was observed at higher concentrations of HA. The authors postulated that the cross-over frequency corresponds to the polymer chains' disentanglement rate that is a function of their mobility, which is in turn affected by both the molecular weight and the concentration of HA in solution.

2.1.2 Dissolving of HA

In most of the literature, authors do not mention how they dissolved the hyaluronan samples.

The information about the dissolving of HA, which has been found in the literature, are summarized in the following table.

Tab.1 Processes of hyaluronan dissolving known from literature.

Sample (Mw, final concentration)	Solvent	Time of mixing	Type of mixing	Additional step	Ref.
?, ?	Water, buffer	Over night	Turning wheel	Dialysis over water (buffer) for 24 hours	30
?, 1 mg/ml	unbuffered 150mM NaCl	At least 2 days	?	-	31
?, ?	?	25℃ at least 12 h *	?	-	32
350 000 - 2200000, 0.11-11.47 mg/ml	pure water	At about 25℃ overnight	?	-	33
?, 1.2-2.0 mg/ml	pure water	stirred overnight at 4℃	?	Sonicated in a low-power US **	34

***** for the highest concentrations the time required to obtain perfect dissolution was longer than week

****** sonication at 30-40℃ after several hours of stirri ng led consistently to increasing diffusion coefficients

From the table, it can be clearly seen, that many authors make a little account of perspicuous description of HA dissolving. In the papers, the specification of Mw, concentration and type of mixing have been often omitted.

2.1.3 Aggregates

One of the earliest works dealing with hyaluronan aggregates was paper written by Schurz et al.[35] They found evidence for microgels in relatively fresh bovine vitreous humor

hyaluronate samples in pure water, which, remarkably, they stored for two years and subsequently measured by light scattering. After this lapse of time they reported that the microgels had fallen apart into a low molecular weight species.

Also Ribitzsch et al. studied the HA aggregates by light scattering.[30] They observed that the light scattering curves develop an oscillatory fine structure on a time scale of days for rooster comb hyaluronate in a variety of solvents. They concluded that the scattering form factor curves represented random-coil structure hyaluronate molecules with the superimposed oscillatory fine structure representing spherical aggregates of hyaluronate. In other words: hyaluronic acid in water exhibits a non-monotonous scattering function, which is explained in terms of multimerization leading to gel-like supermolecular particles. This tendency is highest in water, lower in buffer, and lowest in isotonic NaCl-solution + NaN_3. It means that ions have the tendency to suppress the aggregation. The aggregates are also disturbed by mechanical movement.

The possibility that HA associates in NaCl and $CaCl_2$ but not in KCl was suggested by the light scattering studies of Sheenan et al.,[36] but has been disputed by Månsson et al.[37]

Welsh et al. have discussed the possibility of breaking the aggregates by addition of shorter chains (about 60 disaccharide units). Longer or very short chains have no effect on it.[38]

The behavior of HA from two sources (bacterial and cock's combs) have been also studied by atomic force microscope (Fig. 4).[39] Long unbranched chains with evident intramolecular interactions have been observed on mica base.

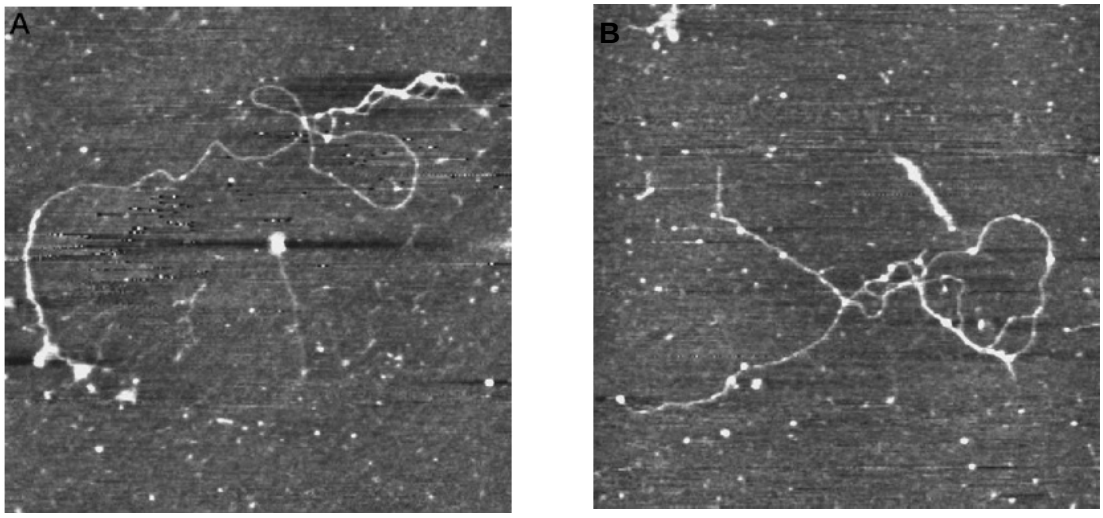

Fig.4 TMAFM image of an HA chain with extensive intramolecular self-association leading to a A) fenestrated structure B) meshwork structure

On the other hand, Gribbon et al. have found intramolecular association unimportant[40] and they have asserted that the behavior of concentrated solutions of HA is given by hydrodynamics and its chains entanglements. They have found no evidence for chain-chain association by mechanism such as hydrophobic patches contributing to the network

properties. Even at high concentration of HA in solution, the chains are still mobile without any gelation.

Ghosh et al. have found aggregates in HA solutions, which were possible to filter out using 0.45 μm filter or remove it by centrifugation.[41]

2.2 Rheology of hyaluronan

The first rheological measurements of HA were done by Gibbs et al [42] who measured the dynamic viscoelastic properties of its sodium salt over the frequency range. The effects of varying temperature, HA concentration, pH and ionic strength on the dynamic shear module were studied. It was shown that HA behaves as a non-Newtonian liquid.

Hyaluronate solutions at neutral pH and psychological ionic strength show high viscosity at relatively low concentrations, and also display substantial solid-like character, which is called viscoelastic behavior of hyaluronan solutions.[43] The influence of salt addition was studied and it was shown that according to increasing ionic strength, the electrostatic repulsions are suppressed and it may cause enhanced coupling. Increase in viscosity, at sufficiently high polymer concentration, was by the same authors also observed.

Rheological properties of hyaluronan solutions are related not only to the molecular weight or concentration, but also to the origin of the sample.[44] HA chains are free to move individually in dilute solution, but entangle with each other and form a temporary network in concentrated solutions. The overlap (critical) concentration C* of HA was reported to be about 1 mg/ml, and it is dependent on ionic strength, molecular weight and concentrations[21,45,46]

The rheological properties of sodium hyaluronate in phosphate-buffered saline were studied by Krause et al.[25] It behaved as a typical polyelectrolyte in the high-salt limit and there were no strong associations between NaHA chains under psychological conditions.

Effect of metal ions on flow profile of NaHA was studied by Knill et al.,[47] who obtained a result, that as the atomic number (atomic mass) of the metal ion increased, the Williamson zero shear viscosity decreased.

Zero Shear Viscosity, MW and Concentration

As shear rate approaches zero, a maximum viscosity number – zero shear viscosity – is reached. Zero shear rate viscosity has gained popularity in its use as a standard measure for the comparison of various HA products, especially those for ophthalmic use.[48] Zero shear viscosity is a function of MW and concentration. Bothner and Wik[49] studied the relation between zero shear viscosity of HA, and the product of HA concentration (mg/ml) x HA MW. Within the range of MW (1-4 $\cdot 10^6$ g/mol) and concentrations (10 and 20 mg/ml) investigated, there appeared to be a linear relation between their logarithmic functions. The authors concluded that a twofold increase in HA concentration or MW would result in a 10-fold increase in the zero shear viscosity (Fig.5).

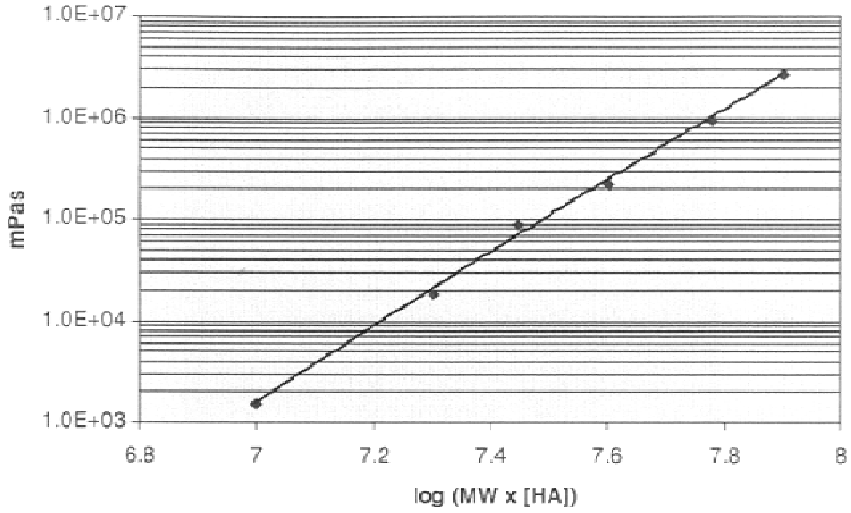

Fig. 5 The log of zero-shear viscosity plotted against the log of HA MW x [HA].

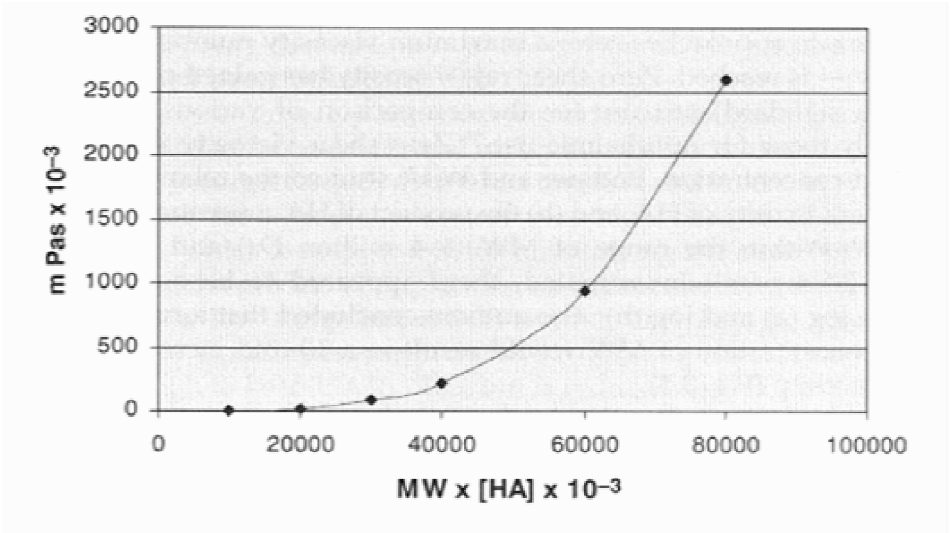

Fig. 6 Zero-shear viscosity of HA – a power function of HA MW x [HA]

Alternatively, if the zero shear rate viscosity is directly plotter against MW x [HA] without taking a logarithm, the viscosity appears to be a power function of MW x [HA]. It is not difficult to envision from the chart that a moderate increase of either MW or [HA] would greatly increase the zero shear viscosity (Fig.6).

Welsh et al. observed an interesting phenomenon that offered evidence that the intermolecular of HA is specific, rather than random entanglement.[50] It was found in their experiments that the dynamic viscosity of HA polymer (3500 disaccharide units) was decreased by an order of magnitude when an equal amount of HA oligosaccharides (60 disaccharide units) was added. This is incompatible with the „entanglement coupling“ theory for synthetic polymers, according to which the additional polymers should have increased the viscosity. The existence of cooperative interchain (interhelical) association and competitive inhibition of interchain (interhelical) binding of HA was therefore suggested. The HA segments were considered as occupying the binding junctions without contributing to the network.[32]

3 EXPERIMENTAL PART

3.1 Materials and methods

3.1.1 Chemicals

The summary of used chemicals with their batch numbers and producers are described in Table 2.

Tab. 2 Summary of used chemicals.

Chemicals	Batch number	Mw [g/mol]	Producer
Deuterium oxide 99.9%	MKBB2315		Aldrich
Sodium azide p.a.	42305090		Fluka
Sodium hyaluronate	verela T9001/070709	16 000	Contipro
	VLMW 080708-P1	39 900	Group
	HYA 141007	86 600	
	VLMW 190707-E1	102 600	
	verela 070909	133 000	
	verela 200409-E2	175 300	
	verela 251109/209-079	275 600	
	HA 250205-D1	750 000	
	HA 250205	1 400 000	
	HA 060306	1 690 000	
	HMW 160505	2 612 000	
Sodium chloride	K38062004 745		Merck
Sodium hydrogenphosphate dihydrate p.a.	0001434476		Sigma-Aldrich
Sodium dihydrogenphosphate dehydrate p.a.	PP/2009/10133		Lachner
Sodium hydroxide	SZBA0560UN1823		Sigma-Aldrich

3.1.2 Laboratory aids

Beakers (25, 50, 100 ml)

Volumetric flasks (250, 500 ml)

Magnetic stirrer RO 10 power

Pipette (25, 50 ml)

Plastic disposable pipettes

pH meter Ionolab

Ultrasound bath

3.1.3 Instruments

Rheology

AR G2 magnetic bearing rheometer developed by TA Instruments is a combined motor and transducer (CMT) instrument. The lower component of the measuring system is fixed, the upper component is attached to a shaft that can rotated by a torque produced by an induction motor. The constraint on the low torque performance of such an instrument is the friction between the rotating and the stationary components. An induction motor is therefore used not only because the rapidity and stability of its response, but more specifically to minimize the friction. But the rotating shaft has to be supported in some way, and this requires a bearing: another source of friction.

- used geometry:

  Double gap concentric cylinder - sample volume: 7.8 ml

  Cone and plate (60 mm, 1°) - sample volume: 1.0 ml

- used software:

for the instrument:

Rheology Advantage Instrument Control AR, product version V5.7.0

for data analysis:

Rheology Advantage Data Analysis, product version V5.7.13

Particle size:

Zetasizer Nano ZS is unique equipment that enables to measure static light scattering (SLS) and also dynamic light scattering (DLS) to provide characterization of HA.

DLS experiments were performed by Zetasize Nano ZS equipment with a helium neon laser operating at 633 nm with power 4.0 mW and avalanche photodiode detector, a computer-controlled and a temperature controlled sample cell. The temperature was 25 ± 0.1 °C.

The data were analyzed with DTS (Nano) 4.2 software by method of cumulants and CONTIN to obtain an average particles size and an approximate particle size distribution.

NMR

1D NMR spectra were measured by Bruker Avance III 500 MHz Ultrashield plus.

UV-VIS

UV-VIS spectra were measured by UV-VIS spectrophotometer Shimadzu UV-2401 PC.

Density

The density was measured by the digital densitometer Anton Paar DMA 4500. Each sample was degassed and measured at least two times at temperature 25℃.

Conductivity

The conductivity was measured by InoLab Cond 720 using the measuring cell TetraCon 325. The cell is composed of four graphite electrodes and its constant is 0,475 cm^{-1} with a relative error ±1.5 %.

Surface tension

The surface tension was measured by the Digital Tensiometer K9 using Wilhelmy Plate Method, which is an universal method especially suited to check surface tension over long time intervals. A vertical plate of known perimeter is attached to a balance, and the force due to wetting is measured.

3.1.4 Methods

3.1.4.1 Preparation of HA solutions for the effect of Mw, c, solvent and T (chap. 4.2-4.4)

All solutions were prepared by dissolving appropriate amount of hyaluronan powder in the proper solvent at ambient temperature during mechanical stirring for at least 6 hours. During the night, the samples were stored in the fridge at temperature about 4℃.

0.1 M Phosphate buffer, pH = 5, 6, 7, 8

0.1M solutions of sodium dihydrogenphosphate dihydrate and sodium hydrogenphosphate dodecahydrate were prepared in demineralised water. After dissolving, the solution of sodium hydrogenphosphate dodecahydrate was added dropwise to the solution of sodium dihydrogenphosphate dihydrate (or conversely) until the pH reached the require value. The pH was measured at the ambient temperature 25℃ by pH meter Inolab.

Physiological solution

Physiological solution is 0.9% (w/v) solution of NaCl and was prepared by dissolving of a calculated amount of NaCl in demineralised water. The solution was stirred for at least one hour and stored in a fridge.

3.1.4.2 Preparation of HA solutions for other physical chemical methods (chap. 4.5)

Samples for zeta sizer

Sample concentration for DLS was 10.0 $g.l^{-1}$. Solutions were measured after filtration through the 0.2 µm Fisher Brand, mixed esters of cellulose membranes of syringe filters. For measurements, 1 ml of sample was putted into disposable sizing cuvette.

Samples for NMR

The samples for NMR were prepared by dissolving 10 mg of HA powder in 0.75 ml of D_2O (99.9%) and were stirred overnight.

Samples for UV-VIS

Sample concentration for measuring UV-VIS spectra was 10.0 $g.l^{-1}$ and only one solvent - HA in PBS (pH 7) was chosen.

Samples for dissolving and time-stability studies (chap. 4.1 and 4.6)

A special attention was paid to preparation samples for dissolving studies.

Preparation of solutions

All solutions were prepared by dissolving hyaluronan powder in distilled water at ambient temperature during mechanical stirring for at most 72 hours. The additions of powder samples to the solvents were done under strictly controlled conditions. The injection water was filtered throw the 0.22 µm filter. The solutions were placed on a mechanical stirrer and were mixed at room temperature at 300 rpm.

0.1 M Phosphate buffer, pH = 7.0

15.6 g of sodium dihydrogenphosphate dihydrate was dissolved in 1000 ml of demineralised water and 71.6 g of sodium hydrogenphosphate dodecahydrate was dissolved in 2000 ml of demineralised water. After dissolving, the solution of sodium hydrogenphosphate dodecahydrate was added dropwise to the solution of sodium dihydrogenphosphate dihydrate until the pH reached 7.00. The pH was measured at the ambient temperature 25℃ by pH meter Inolab.

Ultrasound degradation

The 1% solutions of HA in phosphate buffer or demineralised water with addition of NaN_3 were immersed into ultrasound bath. The power of the ultrasound was 72 W and samples stand in the bath for 10, 20 and 30 minutes.

Samples for zeta sizer

Sample concentration for DLS was 1.0 $g.l^{-1}$. It was prepared before measurement by dilution the stock solution after investigation, that was continuously stirred (10 $g.l^{-1}$), in water or phosphate buffer solution with addition of sodium azide. Dissolution was necessary for

providing Brownian motion in solution. Solutions were measured after filtration or not filtered. Filtration was performed by 0.2 µm Fisher Brand, mixed esters of cellulose membranes of syringe filters. For measurements 1 ml of sample was putted into disposable sizing cuvette.

Process of dissolving

The solutions were prepared as was mentioned above and the samples were taken in predetermined time period (Tabs. 3-5).

Tab.3 The mixing process of 0.15% aqueous solution HA 060306 with addition of 0.02% NaN_3.

TIME

SAMPLING NUMBER

Sampling number	Time of mixing 1 [h]	Time of storing in a refrigerator 1 [h]	Mixing 2 [h]	Refrigerator 2 [h]	Mixing 3 [h]	Refrigerator 3 [h]	Mixing 4 [h]
1	1.5	-	-	-	-	-	-
2	3.5	-	-	-	-	-	-
3	5.5	-	-	-	-	-	-
4	8.5	-	-	-	-	-	-
5	8.5	16	1	-	-	-	-
6	8.5	16	2	-	-	-	-
7	8.5	16	5	-	-	-	-
8	8.5	16	9	15	1	-	-
9	8.5	16	9	15	15	-	-
10	8.5	16	9	15	8	16	1
11	8.5	16	9	15	8	16	5

Tab.4 The mixing process of 1.0% aqueous solution HA 250205-D1 with addition of 0.05% NaN_3.

TIME

SAMPLING NUMBER

Sampling number	Time of mixing 1 [h]	Time of storing in a refrigerator 1 [h]	Mixing 2 [h]	Refrigerator 2 [h]	Mixing 3 [h]	Refrigerator 3 [h]	Mixing 4 [h]
1	4	-	-	-	-	-	-
2	6	-	-	-	-	-	-
3	8	-	-	-	-	-	-
4	10	-	-	-	-	-	-
5	11	16	0.5	-	-	-	-
6	11	16	6.5	-	-	-	-
7	11	16	7.5	16	1	-	-
8	11	16	7.5	16	7	-	-
9	11	16	7.5	16	8	16	1

Tab.5 The mixing process of 1.0% solution HA 250205-D1 in 0.1M phosphate buffer with addition of 0.05% NaN_3.

TIME

SAMPLING NUMBER

Sampling number	Time of mixing 1 [h]	Time of storing in a refrigerator 1 [h]	Mixing 2 [h]	Refrigerator 2 [h]	Mixing 3 [h]
1	2	-	-	-	-
2	4	-	-	-	-
3	6	-	-	-	-
4	8	-	-	-	-
5	9	16	1	-	-
6	9	16	7	-	-
7	9	16	8	16	1

3.1.4.3 Rheology

Each sample was measured at least three times and the average value of zero shear viscosity was calculated

Used methods

1. Stepped flow - applies successive shear values, data are sampled at the end of each value.

2. Temperature ramp – holds the shear constant while ramping the temperature, samples at defined intervals.

Used rheological models

The basic rheological equations, used for describing hyaluronan solutions flow, are mentioned bellow.[51]

Newtonian model

This model describes the simplest type of flow behavior, namely that where the materials viscosity is constant, independent of applied shear. The model is expressed in terms of the shear stress/shear rate relationship.

$$\sigma = \eta \cdot \dot{\gamma} \qquad \text{(eq.1)}$$

The Cross model

To obtain a model for a general flow curve, over a wide range of shears, requires a equation with at least four parameters. The Cross model is a good example of this type of equation. It predicts behavior consisting of low and high shear plateau's, with a shear thinning region between in. The Cross model uses shear rate as the independent variable. The Ellis model can be used as an equivalent using shear stress. The viscosity of many suspensions could be described by the equation of the form:

$$\frac{\eta - \eta_\infty}{\eta_0 - \eta_\infty} = \frac{1}{1 + (K \cdot \dot{\gamma})^m}, \qquad \text{(eq.2)}$$

where η_0 and η_∞ are the dynamic viscosity of the solution [Pa.s] at very low and high shear rates, respectively. K and m are constant parameters, generally called as consistency and flow index, respectively. K is constant expressed in seconds and m is dimensionless constant. The reciprocal, 1/K give us a critical shear rate that proves a useful indicator of the onset shear rate for shear thinning. K and m can be related to texture, application properties, pumping, mixing and pouring characteristics and many other everyday flow processes which often occur in the shear thinning region the fluid’s flow behaviour.

4 RESULTS AND DISCUSSION

This part is divided into 6 chapters. In the beginning, to be sure the solutions are good, the dissolution of HA powder is studied, while this topic is not discussed in the literature. The second chapter deals with the best conditions and adjustment of rheometer for the next rheological measurements. In following chapters the effect of concentration of the solution, Mw of HA, pH, type of the solvent and temperature on HA viscosity is described step by step. To confirm HA quality, other physical methods, such as particle size measurements, NMR, UV-VIS, were used. Finally, the time stability of HA solutions and presence of aggregates is study in the last part.

4.1 Dissolution of HA powder

The dissolution of any polysaccharide and especially of hyaluronic acid is not as easy as it would be expected. The dissolution depends on many factors, for example temperature, speed of rotation, concentration of final solution, Mw of the polysaccharide, the way of adding the powder sample, the size of solution surface and a few others.

The dissolution of HA powder and preparation of HA solutions generally is not satisfactorily described in literature (Tab. 1), it was studied at the beginning of present work, to be sure to have good solutions without any aggregates or not dissolves particles. Three molecular weights and two solvents (demineralised water and 0.1M PBS, pH 7) were tested and the solutions were prepared according to procedure described earlier.

The results were taken into consideration during preparation of all solutions that were mixed at least 24-48 hours in dependency on their MW. More detailed study, using particle size measurements, conductivity and surface tension, is at the end of present work in Chap. 4.6.

4.2 Preliminary rheological measurements

The range of acceptable shear rates was determined by testing one HA sample (Mw 86 600 g/mol). Consequently, the range of measured shear rates was chosen (depending up the measured Mw) from 0.1 – 10 000 s^{-1}.

According to the temperatures commonly used in the production of hyaluronan, the temperature range was chosen from 15 to 90 ℃. The best shear rate for the temperature ramp was found with the same sample of HYA. The shear rate should be chosen from the first Newtonian plateau that is for this sample in range 5-1000 s^{-1}.

Three measurements with the shear rates of 10, 100 and 1000 s^{-1} were done. The shear rate of 10s^{-1} was too low to get relevant data. On the other hand, shear rate 1000 s^{-1} caused the decrease of viscosity because of the degradation of the sample by too high shear, not only because of the increasing temperature. This implied that the shear rate 100s^{-1} would be the best for our measurements.

4.3 The flow curves

This chapter includes the main results of the present work, the flow curves measurements. It means dependence of dynamic viscosity on increasing shear rate of hyaluronan samples was studied. Always one from the chosen parameters was variable (concentration, Mw, solvent, pH), while the temperature was always constant (25℃).

4.3.1 The effect of Mw and concentration

The effect of Mw and concentration on dynamic viscosity of hyaluronan solution was studied. The range of Mw of measured HA samples was 16 000 – 2 612 000 g/mol. For all those measurements 0.1M PBS, pH 7.00 was used as a solvent.

4.3.1.1 VLMW HA

Figure 7 shows the rheological flow behavior of 1% VLMW HA in range of molecular weight 16 000 – 275 600 g/mol in 0.1M PBS at pH = 7.00. Up to the 102 600 g/mol, hyaluronic acid exhibited essentially Newtonian characteristics throughout all the shear rate range analyzed.

Pseudoplastic behavior (shear thinning) was observed for higher molecular weight HA, from 133 000 g/mol. At shear rate lower than 1000 s^{-1}, the viscosity is almost constant decreasing slightly with the shear rate (Newtonian plateau). At shear rate greater than 1000 s^{-1} the viscosity decreases. At higher shear rate, sharply drops with the shear rate (thinning in an S-shaped fashion) and a second plateau should be expected.

The rheological behavior of these solutions is typical of entangled networks. In these networks, the rheological response is controlled by the rate of entanglement formation and disruption. At low shear rate, the two rates are comparable and the total number of active entanglement is almost constant. As the shear rate increases, the rate of disruption becomes predominant leading to the thinning. [20]

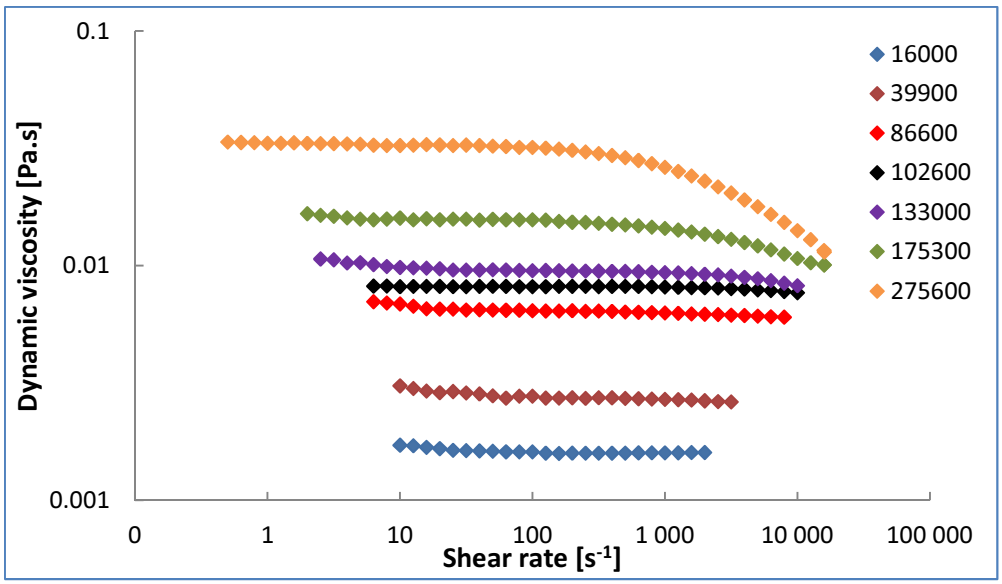

Fig. 7 The flow curves of 1% VLMW HA in range of Mw 16 000 – 275 600 g/mol in 0.1 M PBS, pH = 7.00, T=25℃

From the flow curves, the zero shear viscosities (η_0) were calculated using the relevant rheological model Such a practice was applied for all measurements (different solvents, pH and concentrations of HA).

To study the effect of concentration and Mw on zero shear viscosity of VLMW HA, seven different molecular weight (16 000 – 275 600 g/mol) and five different concentrations (1-5%,w/w) of HA were chosen. All these measurements were done in PBS, pH 7.00.

The zero shear viscosity of HA is highly dependent on its Mw and concentration (Fig. 8). With increasing both, concentration and Mw, the zero shear viscosity strongly increases. The increase of zero shear viscosity by increasing only concentration is dependent on Mw. So for example: by increasing the concentration 5 times for sample with Mw 16 000 g/mol, the zero shear viscosity increases about 4 times. But by increasing the concentration 5 times for sample with Mw 102 600 g/mol, the zero shear viscosity increases about 36 times and for sample with Mw 275 600 g/mol, the zero shear viscosity increases even more than 177 times. That explains the necessity of logarithmic scale in these graphs. The curves of two highest MW samples show folding dependence. The explanation may be in the interaction and entanglement of longer chains that causes the increase of viscosity, whereas the viscosity of shorter chains increases only as a result of increasing concentration.

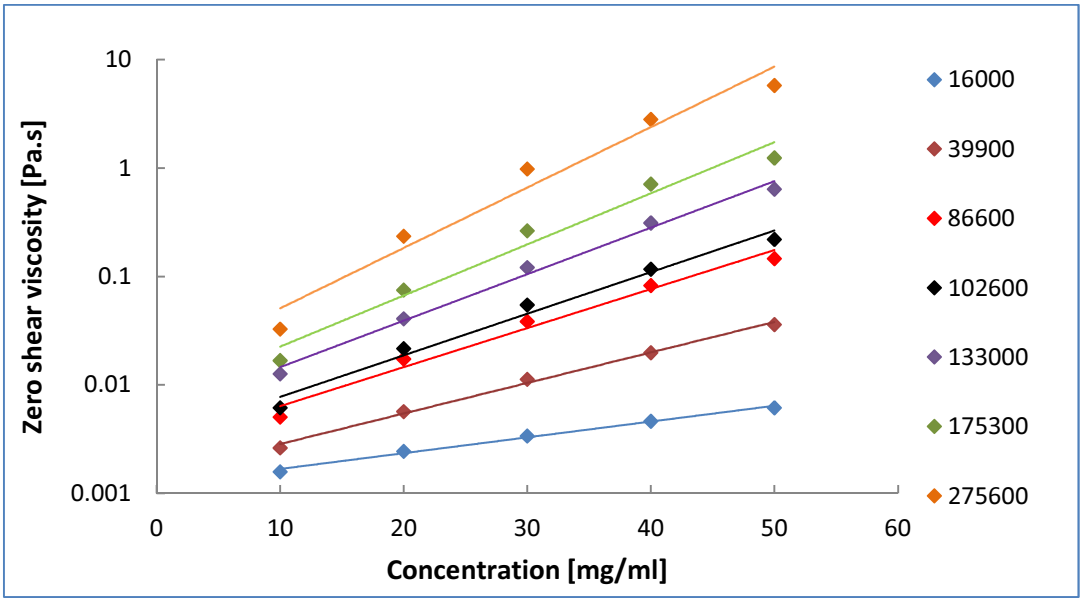

Fig. 8 The effect of Mw and concentration on zero shear viscosity of VLMW HA in 0.1 M PBS, pH = 7.00.

The specific viscosity versus Mw*c dependence of all measured samples in PBS, pH 7.00 is summarized in Fig. 9. Also the same curve of aqueous solutions is added to make a complete notion of this dependence.

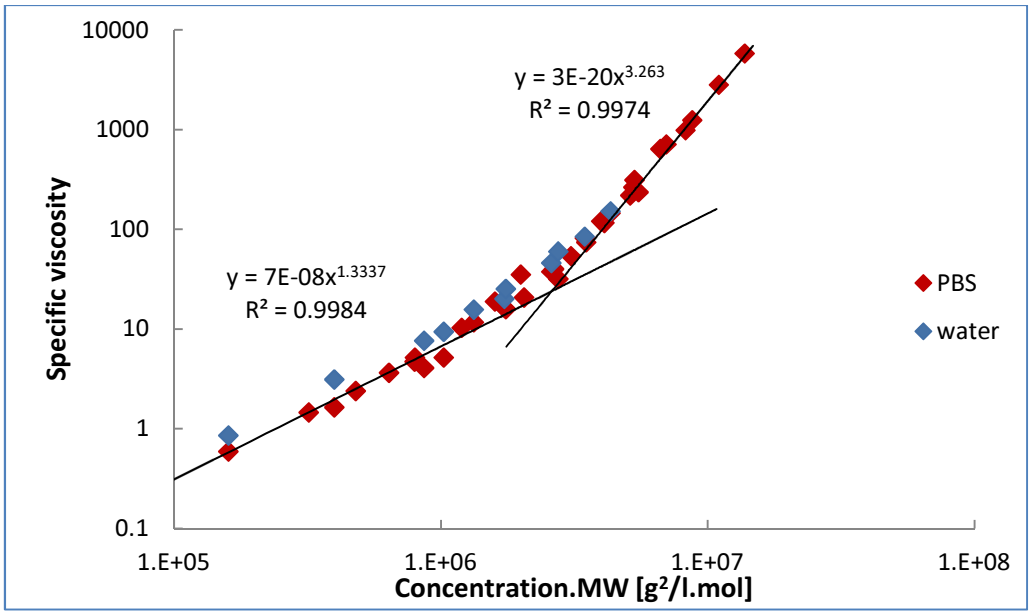

*Fig. 9 The dependence of specific viscosity on Mw*c of VLMW HA in 0.1 M PBS, pH = 7.00 and water.*

The data span two decades in Mw*c and crossovers from the dilute to the semidilute entangled regime, that are observed as changes in slope. In dilute solution, viscosity should be proportional to concentration ($\eta_{sp} \sim c$) for polyelectrolytes in the high salt limit (as well as neutral polymers in good solvent).[52] This study found $\eta_{sp} \sim c^*Mw$ 1.33 in dilute solution, in excellent agreement with the results in literature. For example Krause et al. who measured only one sample of HA with Mw $1.5*10^6$ g/mol in phosphate buffer saline mix (pH 7.4, 0.138 M NaCl, 0.0027 M KCl).[25] Their study found $\eta_{sp} \sim c$ 1.1. The overlap concentration was determined to be c^* = 0.59 mg/ml, and the entanglement concentration c_e which characterizes the end of the semidilute unentangled regime and the beginning of the entangled regime was determined to be c_e = 2.4 mg/ml.

Briefly, the specific viscosity η_{sp}, measured for homogeneous well-behaved HA solutions at very low or zero shear rate is a simple function of the concentration, c, and average molecular weight of the HA, described in terms of its intrinsic viscosity[53]

$$\eta_{sp} = c[\eta] + k'(c[\eta])^2 + \frac{(k')^2}{2!}(c[\eta])^3 + \cdots \qquad \text{(Eq.3)}$$

where the value of k´, the Huggins constant, is explicitly 0.4, based on its derivation from the Stokes–Einstein equation for the viscosity of a suspension of spheres. Presented measurements of the zero shear viscosity for HA in neutral salt solution as a function of concentration and molecular weight are in excellent agreement with the simple predictions of the four-term interaction equation (Eq. 18).

In dilute solution, when the product c[η] is less than about 1, the specific viscosity is apparently dependent on c[η] to a little more than the first power. The data are often expressed in the literature in terms of the molecular weight, M, rather than [η]. Cowman and Matsuoko in their review[54] recall that [η] is proportional to $M^{0.80}$ for the spherical HA

conformation, and can easily interconvert the variables. The actual range of exponents observed (probably strongly dependent on the exact range of c[η] used in the data fit) show that η_{sp} depends on $c^{0.8–1.6}$ $M^{1.0–1.5}$ in dilute solution, with exponents near 1.2 for c and 1.0 for M most commonly found. This corresponds to $c^{1.2}$ $\eta^{1.25}$ and shows that both the first and second power terms contribute in dilute solution.

In more concentrated solutions, when c[η] is greater than about 10, the specific viscosity has been found to depend on $c^{3.8–4.1}$ $M^{3.3–4}$ equivalent to $c^{3.8–4.1}$ $\eta^{4.1–5}$. The values are summarized from eight articles and together are reported in Cowman and Matsuoko work.[54]

4.3.2 HMW HA

Also the flow curves of different concentrations of HMW HA solutions were measured in 0.1M PBS solution, pH 7.00 (Fig. 10). The concentration range was 0.1 – 1% (w/w), except the highest concentration of HA with Mw 2 612 000 was only 0.75 %, because higher concentration was too viscous to prepare it.

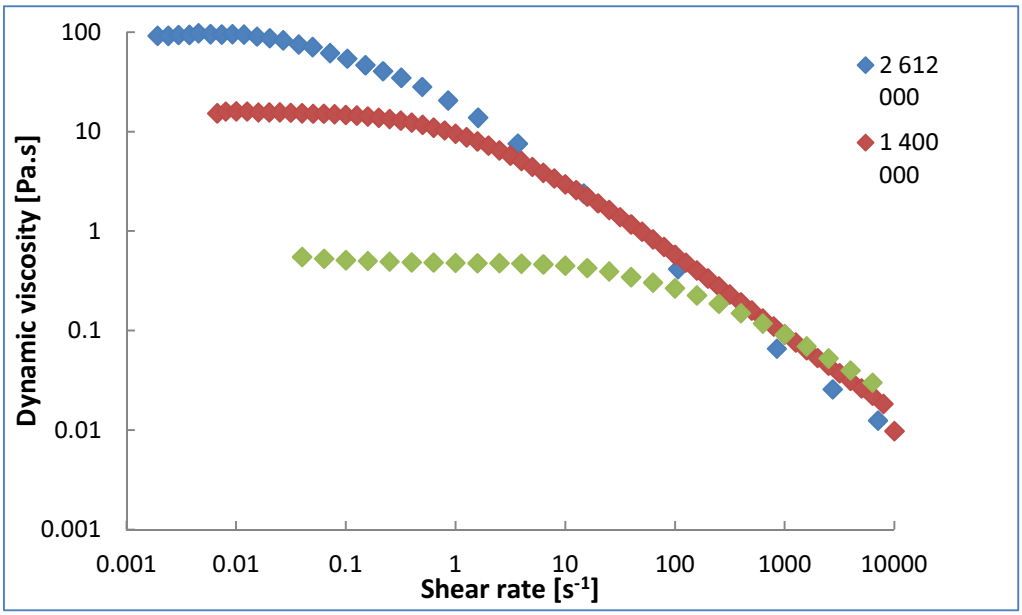

Fig. 10 The flow curves of HMW HA in range of Mw 750 000 – 2 612 000 g/mol in 0.1 M PBS, pH = 7.00.

Whereas the viscosity of HMW sample is too high that it is impossible to measure 1% HA in PBS solution, by decreasing the Mw less than twice, the zero shear viscosity of 1% solution is about 15 Pa.s and by another decrease (approximately 3,5x) the viscosity of 1% aqueous solution is only about 0,5 Pa.s. On the other hand, a critical shear γ^*, which is the shear rate when the curve pass from the linear region to the shear–thinning region, increases with the decreasing molecular weight and concentration of HA.

As mentioned above, the viscosity is strongly dependent on concentration and molecular weight of HA. At any molecular weight of HA, the viscosity increases by ~ 10^3 for a 10-fold

increase in concentration and at concentration of 10 mg/ml the viscosity varies from 1 to 100 Pa.s as the molecular weight is increased (Fig. 11).

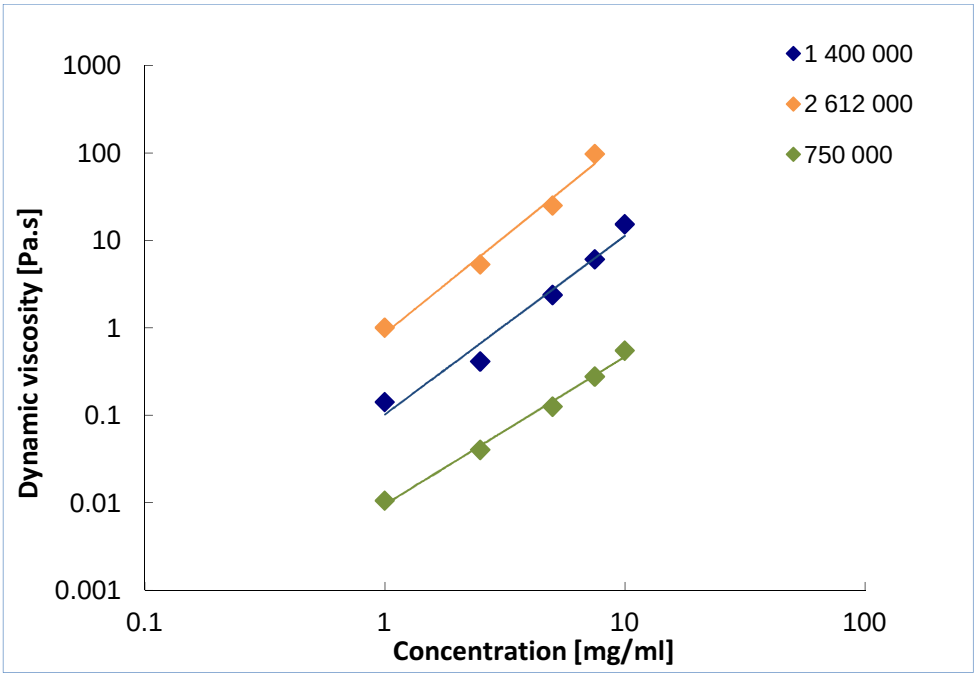

Fig. 11 The log-log plot of zero shear viscosity, η_0, as a function of solution concentration for HA at three molecular weights, 0.1M PBS, pH 7.

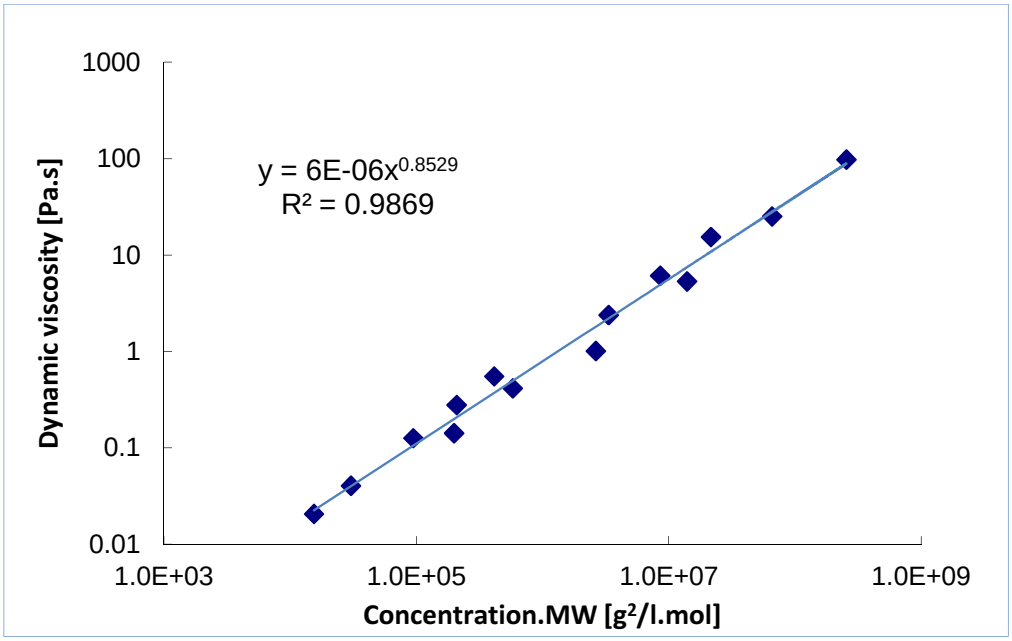

Fig. 12 The log of zero shear viscosity plotted versus the log of the (concentration · molecular weight) for HMW HA, 0.1M PBS, pH 7.

For these data (Fig. 12), η_0 correlates very well with HA (concentration · molecular weight) and the HA solution η_0 can be predicted from the relationship: $\eta_0 = 6 \cdot 10^{-6} (c \cdot Mw)^{0.853}$. This equation also matches the previous results, which are known from the literature.[54] Cowman

and Matsuoka wrote down a review informing about the research on hyaluronan structure to the year 2005. For the high molecular weight region, results of a parameter from Mark-Howing equation were reported from 0.73 to 0.92.[54] This equation is valid only for limited range of molecular weights. It is requisite to make a new curve for smaller or higher values of molecular weights, because this dependence is not strictly linear and the deviations in lower and upper parts of the curve may be inconsiderable.

4.3.3 The effect of solvent

Three different types of solvent, demineralised water, physiological solution and phosphate buffer solution, were used at the pH 7.00 and the concentration of HA was always 1% (w/w). The viscosity of HA in water is always higher than in PB or PBS, which is caused by the conformation of chains in a given solvent (Fig. 13). While in water, HA chains are more extended and that is why the viscosity is higher, in presence of ions HA forms more rigid entanglements.[36] The structure of chains in PB and PBS is more compact and there is no big difference in viscosity between them.

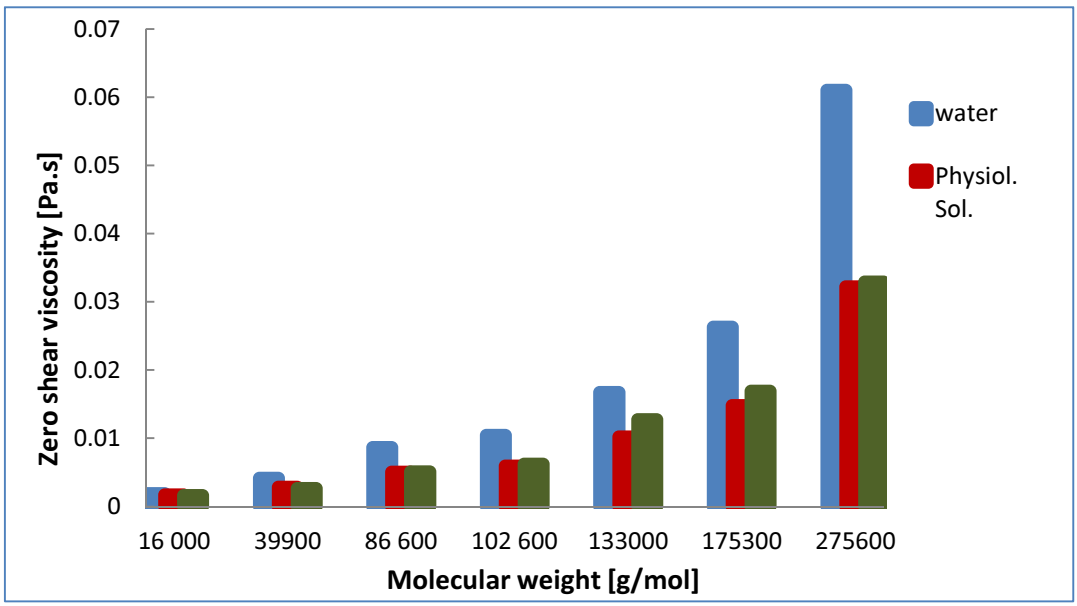

Fig. 13 The effect of solvent on zero shear viscosity of 1% (w/w) VLMW HA.

4.3.4 The effect of pH

Phosphate buffer solution of pH 5.00, 6.00, 7.00 and 8.00 was chosen to study the effect of pH on zero shear viscosity of 1% (w/w) VLMW HA (Fig. 14). Because the values of zero shear viscosities are comparable for each sample, molecular weight of HA is not degraded and also the conformation does not change in this range of pH. It's known that HA degradation is significant when the pH is very low (less than 3) or on the other hand very high (higher than 10). The effect of pH would be probably more evident for HA with higher molecular weight, but in case of VLMW HA is insignificant.

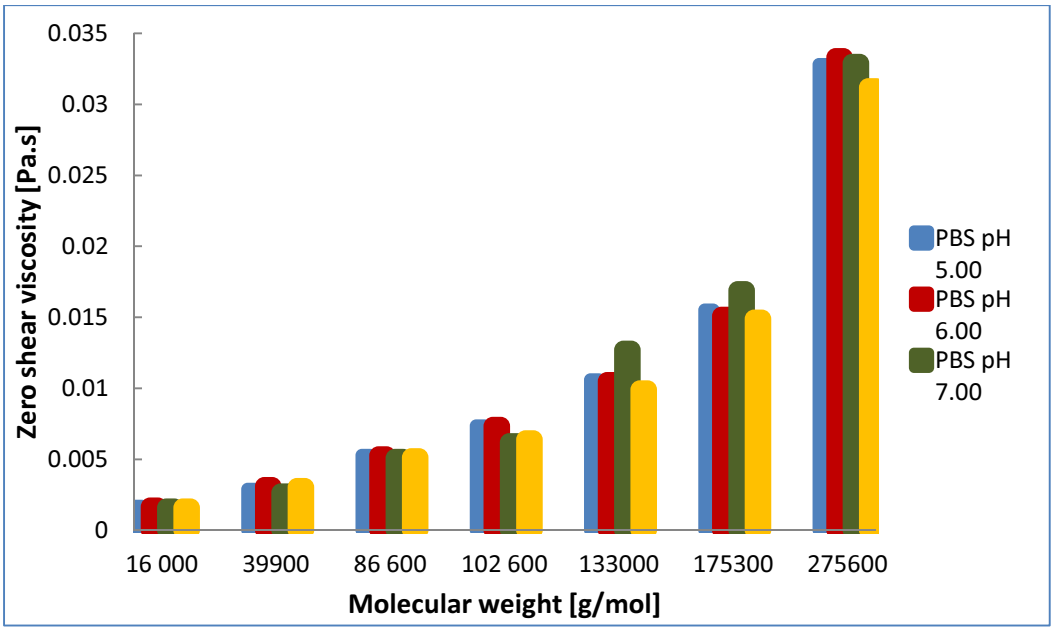

Fig. 14 The effect of pH on zero shear viscosity of 1% (w/w)VLMW HA.

A surprising pH-dependent transition, near neutral pH, was reported by Barrett and Harrington[55] Using potassium phosphate buffers in the pH range 6.0–8.5 at an ionic strength of 0.1, these authors observed a dramatic drop in zero shear intrinsic viscosity as pH was decreased from 7.5 to 7.0. It should be noted that the concentration range used to extrapolate the reduced viscosity to zero concentration was quite high, opening the possibility that a small change in bulk viscosity due to aggregation could result in an erroneous estimation of the intrinsic viscosity. The phenomenon was reexamined by Balazs et al.,[52] but no change in intrinsic viscosity between pH 6 and 8 in potassium phosphate under the same conditions was observed. That is also coincident with results presented in this work.

4.4 The temperature curves

The temperature dependence of liquid viscosity is the phenomenon by which liquid viscosity tends to decrease (or, alternatively, its fluidity tends to increase) as its temperature increases.

To evaluate the temperature curves, Arrhenius model has been used. The model is based on the assumption that the fluid flow obeys the Arrhenius equation for molecular kinetics:

$$\mu(T) = \mu_0 \exp\left(\frac{\eta}{RT}\right) \qquad \text{(eq. 4)}$$

where T is temperature

μ_0 is a coefficient

η is the viscosity

R is the universal gas constant.

The effect of increasing temperature on dynamic viscosity of HA was studied according to evaluated method. It means shear rate was 100 s^{-1} and the temperature ramp was always 4℃/min. 1% sample concentration and two types of s olvent, demineralised water and PBS pH 7.00, were used for these measurements. It is evident that with increasing temperature the viscosity decreases. This phenomenon is due to the changes of chain conformation and at higher temperatures (more than 60℃), the degrad ation process of HA starts.

An interesting phenomenon is observed when comparing the decrease of viscosity in demineralised water and in PBS, pH 7.00 (Fig. 15). While in case of PBS the decrease of viscosity is nearly linear (in log scale) during the whole range of temperatures, in case of water a little increase of viscosity at higher temperatures can be observed. Because the double gap concentric cylinders were used for all these measurements, the effect of chosen geometry is impossible. The surface that solution occupies in this type of geometry is very small and so the effect of different evaporation of PBS and water is also improbable. Maybe in water at temperatures higher than 60℃ some orga nized structure, which is the cause of viscosity increase, is formed. With another increase of temperature, the viscosity would probably decrease again. However, it is impossible to verify, because of near boiling point of water.

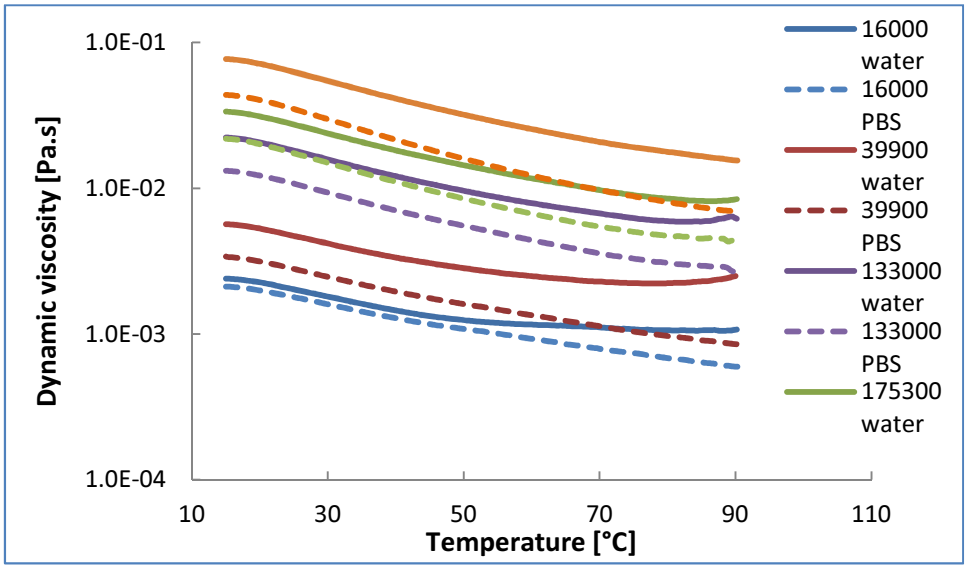

Fig. 15 The comparison of temperature ramp curves of 1% VLMW HA with different molecular weight in phosphate buffer solution, pH = 7.00 and demineralised water. Shear rate 100s^{-1}, temperature ramp 4℃/min.

4.5 Other physical chemical methods

To confirm the hyaluronan quality and eliminate the presence of any impurities which can affect the results, other physical methods, such as NMR, UV VIS and dynamic scattering were used. All of those methods were supporting for rheological measurements, that is why are presented in this separate chapter.

4.5.1 NMR

By measuring 1D NMR spectra, the purity of all measured HA samples was proved. Only in few cases (Mw 102 600, 86 600 and 39 900 g/mol), traces of IPA were found.

4.5.2 UV-VIS spectra

Typical UV VIS spectra for hyaluronan were obtained by measuring 1% HA solutions in PBS, pH 7.00 (Fig. 16). The peaks at 220 nm correspond with the pure hyaluronan and the second smaller peaks belong to impurities, which increase during the degradation process throughout the produce. With exception of 200409-E2 sample (Mw 175 300 g/mol), intensity of impurities peak increases with decreasing Mw of hyaluronan.

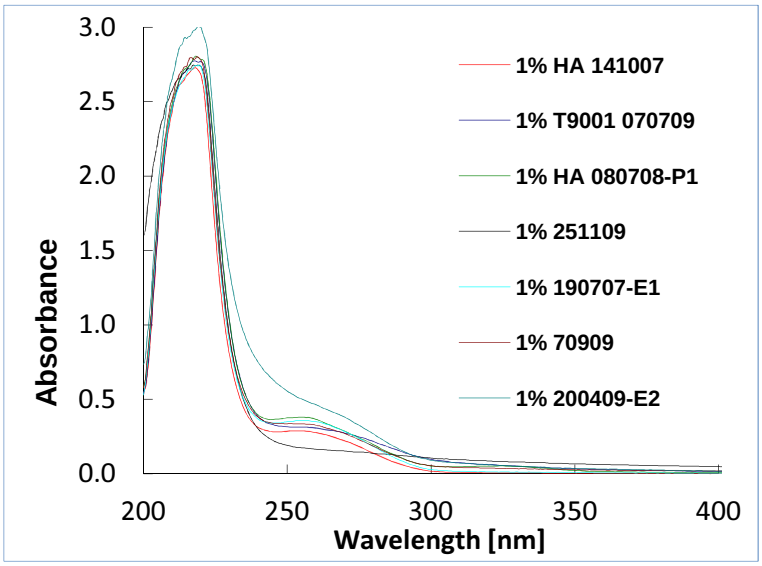

Fig.16 UV-VIS spectra of 1% very low molecular weight HA

4.5.3 The size of particles in VLMW HA solutions

Using the zeta sizer, the size of the HA particles present in 0.1 M PBS, pH 7.00, was measured. Although each sample was measured at least for three times (more often for five times), the results were rather different. The chains of HA in solution are still moving and changing its conformation, the equilibrium is dynamic, and that could caused problems with verification of the results.

The sample 200409-E2 (Mw 175 300 g/mol) has higher content of impurities (peak about 4000 nm) which scattered, because of their size, more light than molecules of HA. This result agrees with the information from measuring UV VIS spectra.

4.6 The time stability of hyaluronan

As was mentioned in the beginning of Experimental part, the dissolution of any polysaccharide and especially of hyaluronic acid depends on many factors, such as

temperature, speed of rotation, concentration of final solution, Mw of the polysaccharide, the way of adding the powder sample, the size of solution surface and a few others.

The aim of present part of the work is to characterize the dissolution and storage stability of hyaluronan, using some of the physical – chemistry methods. To be specific, the dynamic viscosity, particle size, surface tension and the conductivity of the samples were measured during a few days of mechanical stirring. Also the effect of filtration and ultrasound on the HA aggregates was studied.

4.6.1 Hyaluronan in water

Using Zetasizer Nano ZS, the size of the particles present in the solution may be studied. In case of hyaluronan in demineralised water with addition 0.05% NaN_3 (Figs. 17 and 18) some small, middle and very big particles have been observed. The particles about 400 nm may be classified as hyaluronan aggregates, particles about 60 nm are chains of hyaluronan and the small particles about 4 nm may be probably assigned to molecules of sodium azide. The idea was that during the time of mixing the amount of middle particles will increase, whereas the very big particles (aggregates of HA) will dissolve and the peaks will decrease. Nothing like this theory can be seen on Figs. 17-18.

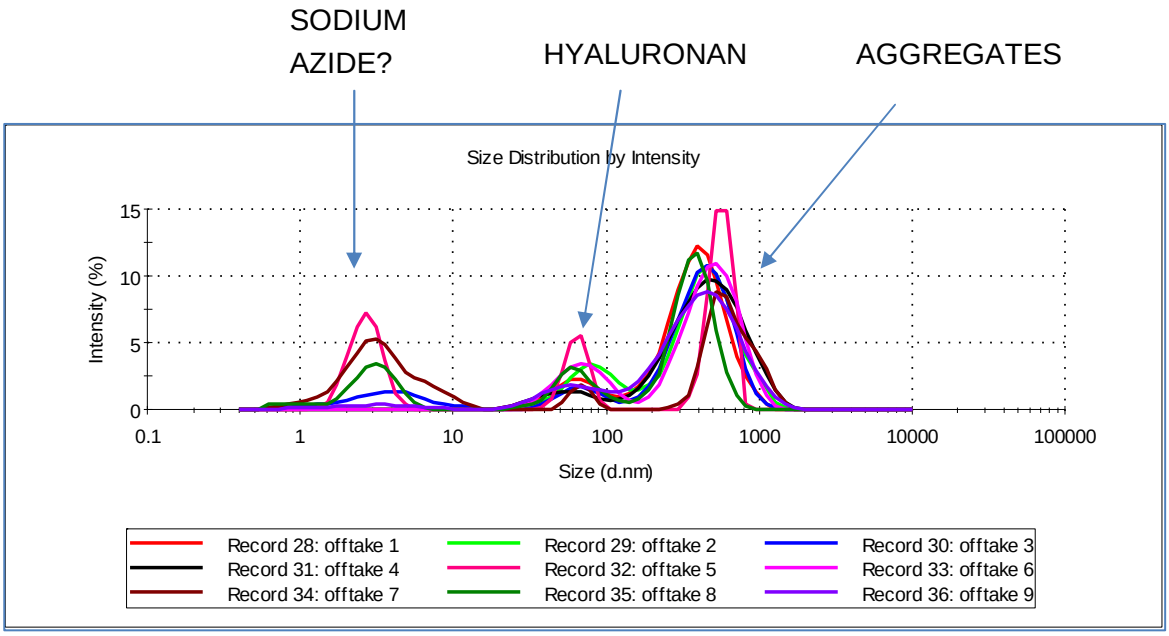

Fig.17 Filtered solutions of HA 250205-D1 in demineralised water with addition of 0.05% NaN_3. The numbers in the graph legend are numbers of the sampling (red 1st, green 2nd, blue, 3rd sampling …).

Comparing these two plots (Figs. 17 and 18), means filtrated and non-filtrated solutions, the difference between the peaks of aggregates may be observed. The particles bigger than 1000 nm were filtered out using the filter with size of pores 0.22 μm.

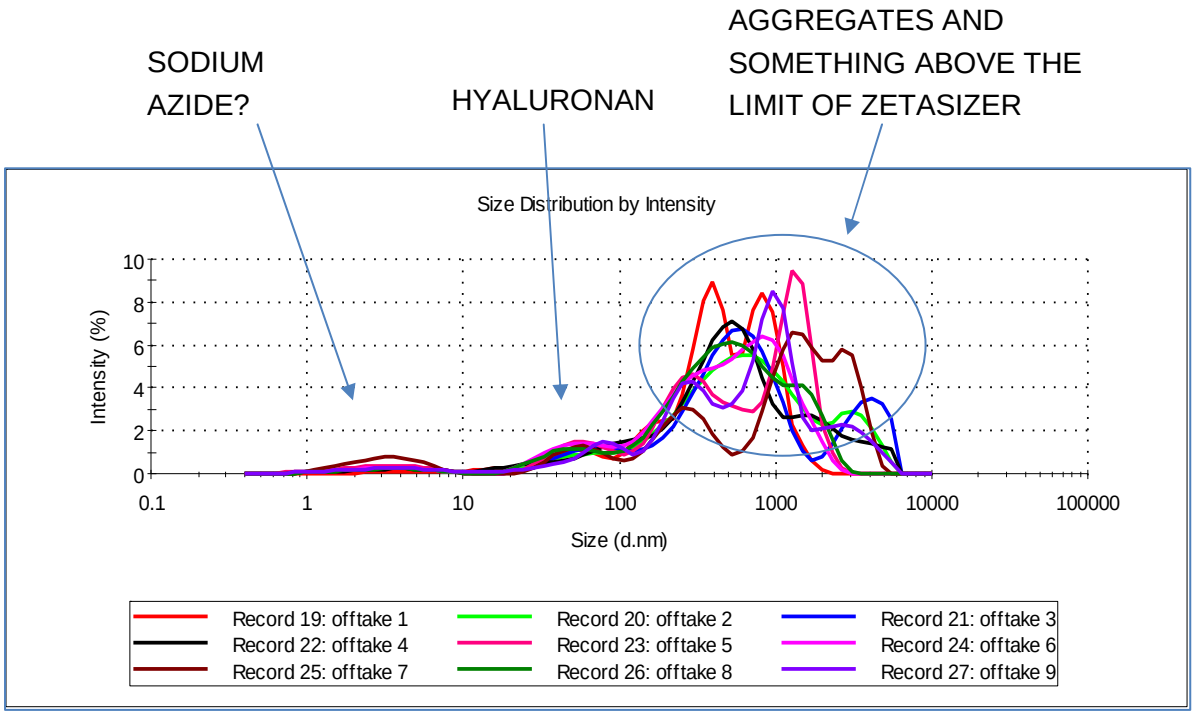

Fig.18 Non-filtered solutions of HA 250205-D1 in demineralised water with addition of 0.05% NaN_3

The conductivity and surface tension of all samples were also measured. Changes of surface tension during three days testing time period are negligible, the values vary between 29 and 32 mN/m. The conductivity of solution slowly decreases (except one error point) during the time period.

4.6.2 Hyaluronan in phosphate buffer

Dissolving hyaluronan in 0.1M phosphate buffer and 0.05% NaN_3, the small particles about 5 nm have disappeared (Figs 19 and 20). After the filtration of solutions throw the 0.22 μm filters, only one peak about 60 nm of single hyaluronan chains was observed (Fig. 19). In this case (phosphate buffer solvent), the increase of the peak height may be seen with the increasing time of mixing for filtrated samples. With the elongating time of mixing, the hyaluronan aggregates have dissolved and after the sampling 6 (9 h of mixing, 16 h in fridge, 7 h of mixing – Tab.4) the peak have shown its maximum. So nearly two days are necessary for good dissolution of 1% HA, which corresponds with the result mentioned in Chap.4.1.

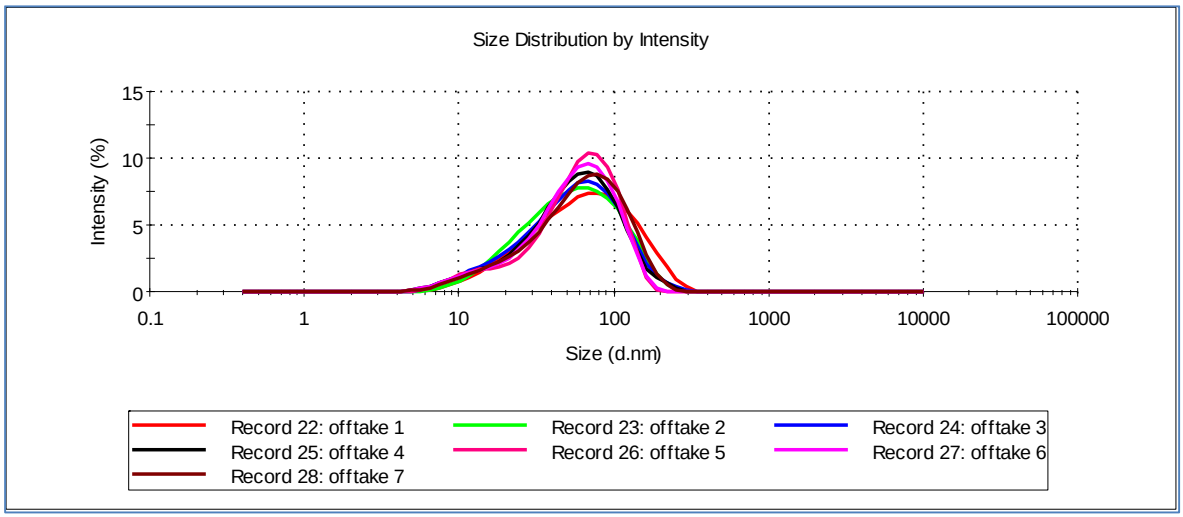

Fig. 19 Filtered solutions of HA 250205-D1 (Mw 750 000 g/mol) in phosphate buffer with addition of 0.05% NaN_3. The numbers in the graph legend are numbers of the samplings (red 1st, green 2nd, blue, 3rd…offtake).

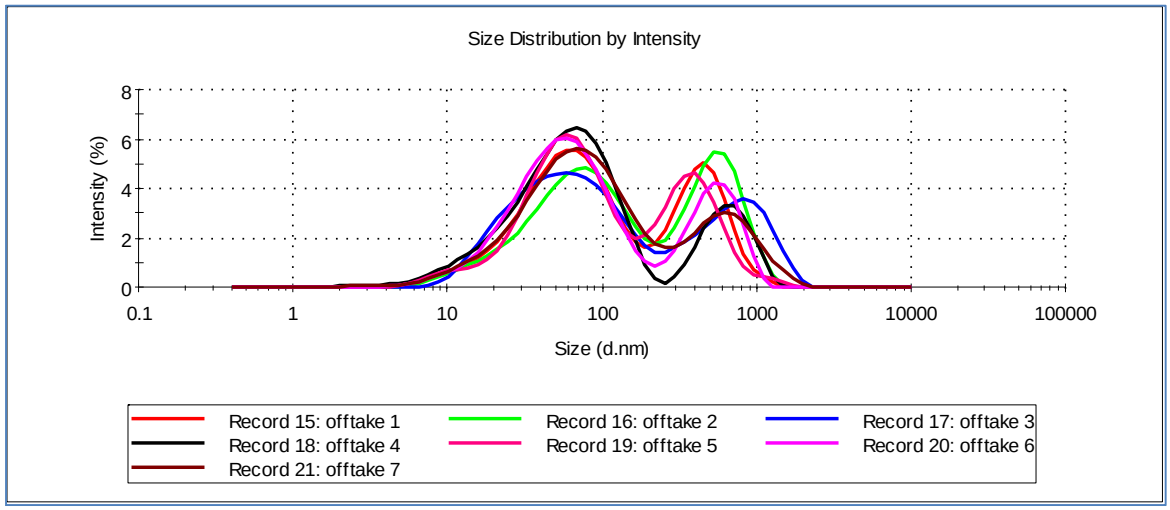

Fig.20 Non-filtered solutions of HA 250205-D1 (Mw 750 000 g/mol) in phosphate buffer with addition of 0.05% NaN_3. The numbers in the graph legend are numbers of the offtake (red 1st, green 2nd, blue, 3rd… offtake).

4.6.3 Aggregates

The stability of the HA aggregates has been studied using ultrasound waves as a source of force disturbing them. The aqueous and phosphate buffer solutions of HA were prepared as mentioned in chapter “Methods” and were stirred for two hours at room temperature. Than the solutions were put into an ultrasound bath, power about 72 W was used and the samples were taken after 10, 20 and 30 minutes.

The peak of big particles (bigger than 1000 nm) has progressively decreased with the time of ultrasound incidence (Fig. 21), whereas the peaks of smaller particles have increased.

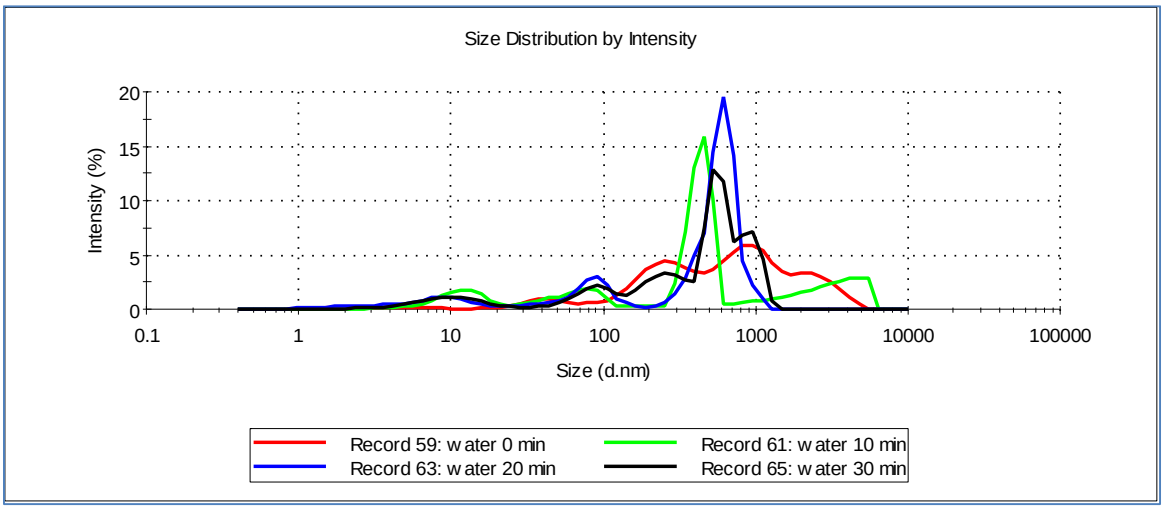

Fig.21 Size of the HA particles in non-filtrated aqueous solutions of HA 250205-D1 (Mw 750 000 g/mol) after 0, 10, 20 and 30 minutes of ultrasound.

There is no evidence of any changes of HA in phosphate solution after the ultrasound (Fig. 22). From the plots, it is clearly seen that the system of HA in water is much more complicated than that in phosphate buffer. In both cases, 30 minutes of ultrasound with such a power is not enough to destroy all aggregates in solution. Maybe it would be better to use higher power or longer time, but it may cause degradation of the single chain of HA.

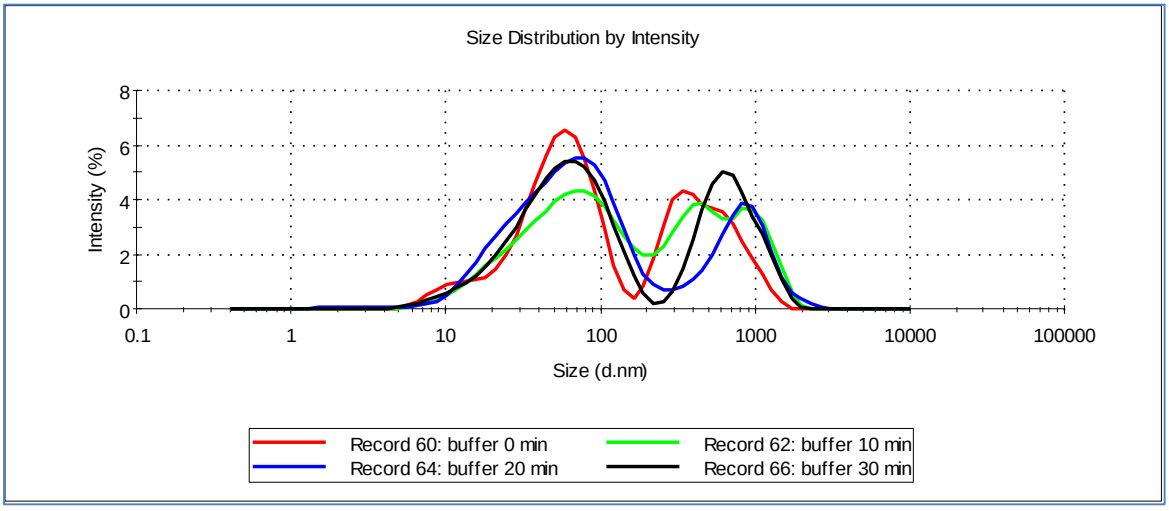

Fig.22 Size of the HA particles in non-filtrated solutions of HA 250205-D1 (Mw 750 000 g/mol) in 0.1M phosphate buffer after 0, 10, 20 and 30 minutes of ultrasound.

By measuring the flow curves, it was showed that the ultrasound has no effect on the viscosity of HA.

5 CONCLUSION

Presented work is focused on rheology of hyaluronan solutions. It studies hyaluronan dissolved in different solvents, effect of pH, temperature, time of storage. Nearly 600 samples were measured to have enough of high-quality data, their distribution is shown in Fig. 23.

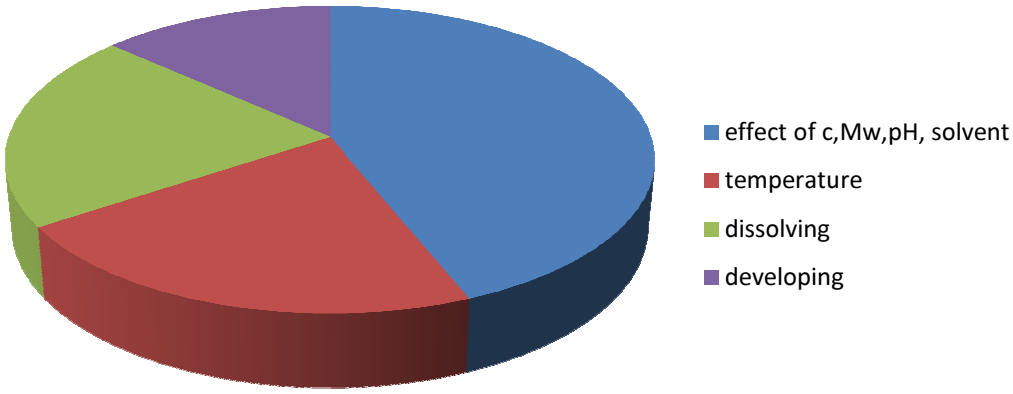

Fig. 23 Distribution of all rheological measurements between particular chapters

The biggest benefit of this work is particularly in very detailed study of hyaluronan behavior using so many different samples. The part dealing with hyaluronan dissolution and solvents temperature dependence show completely new results that can not be find in any literature. The part dedicated to hyaluronan flow curves describes mainly VLMW HA behavior in great detail, the results are in great agreement with data known from the literature. Although the known outcomes are in this work extended of the results of pH and solvent dependences.

Equally important are the detected conclusions in terms of practical point of view. This was first complete study of rhelogical properties of bacterial hyaluronan produced by the Contipro Holding a.s. that needed to examine their products for simplified RaD department work and to have detailed information for costumers.

To be concrete, at first, the dissolution of HA powder was studied to get the good solution. It was concluded, the best method of dissolution of HA is to mix it at least for two days.

In next step, the usable rheological methods were developed to get the best picture of HA behavior in solution. More than 240 flow curves and 130 temperature ramps were measured using the rotational rheometer to obtain such a complete review on physical properties of VLMW HA solutions. Seven different molecular weight samples were chosen and five concentration of each sample in six different solvents were measured. The values of zero shear viscosity were compared depending on molecular weight, concentration, used solvent

or pH of measured samples. At low molecular weights and concentrations, VLMW HA behaves as Newtonian solution, and the pseudoplasticity, common characteristic of polysaccharides, is observed at higher molecular weights and concentrations. This study found $\eta_{sp} \sim c^*Mw$ 1.33 in dilute solution and $\eta_{sp} \sim c^*Mw$ 3.26 in concentrated solution, which is in excellent agreement with the results in literature.

It was achieved that in water the HA chains are in a form of random coil, whereas in presence of ions (in PB or PBS), VLMW HA chains formed more rigid conformation. There was no effect of pH (in range 5-8) on conformation of VLMW HA.

Also HMW HA samples were measured. For HMW HA data η_0 correlates very well with HA (concentration · molecular weight) and the HA solution η_0 can be predicted from the relationship: $\eta_0 = 6 \cdot 10^{-6} (c \cdot Mw)^{0.853}$.

The kinematic viscosity was also determined and it was concluded that the difference between zero shear viscosity and kinematic viscosity is negligible for all samples.

The second part is focused on temperature dependence of HA viscosity. The effect of increasing temperature on viscosity of HA solution was measured. According to expectation, the viscosity decreases during the increasing temperature, but there were dissimilarities between VLMW HA in PBS and water at higher temperatures.

Interesting results showed the thermal curves of HMW HA. To stabilize HA solutions NaCl was added, but no effect of stabilization was observed. Whereas the viscosity of hayluronan solution in presence of NaCl molecules decreased equally, solutions of HA without the presence of NaCl showed significant peaks between 50-70℃.

The purity of used VLMW HA samples was verified by the spectral (1D NMR and UV-VIS) methods. ^{1}H and ^{13}C spectra showed, in addition to characteristic hyaluronan peaks, traces of residual IPA in three cases. Also some impurities in UV-VIS spectra were visible and their peak intensity increases with decreasing molecular weight.

The third part of the work is focused on the dissolution of hyaluronan in water and in phosphate buffer and to characterize the aggregates if there are any. Trials with two hyaluronan batches were performed and the dissolution has been studied using rheology, particle size measurements, measuring of conductivity and finally surface tension. It was achieved that nearly two days of mixing and filtration through 0.22 μm filters are necessary for good dissolution of 1% HA with Mw about 10^6 g/mol.

6 LIST OF ABBREVIATIONS AND SYMBOLS

a	radius of the plate [cm]
a_1	radius of inner cylinder [cm]
a_2	radius of outer cylinder [cm]
c	concentration [kg/m^3]
C*	overlap (critical) concentration [kg/m^3]
CP	cone and plate geometry
DCC	double concentric cylinder geometry
EM	electron microscopy
Eur. Ph.	European Pharmacopoeia
F	Farady constant
FRAP	fluorescence recovery after photobleaching
G'	dynamic modulus [Pa]
G''	dynamic modulus [Pa]
H	cylinder height [cm]
HA	hyaluronan
LS	light scattering
K	consistency coefficient
NMR	Nuclear magnetic resonance
PB	physiological buffer
PBS	phosphate buffer solution
R	gas constant
R_H	hydrodynamic radius [nm]
SLS	static light scattering

T	torque on the inner cylinder [Nm]
T_C	critical temperature [K]
TMAFM	taping mode atomic force microscopy
u_B	electric mobility of species B
VLMW	very low molecular weight
z_B	charge number of the ionic species B
Γ	surface concentration [mol·m^{-2}]
γ	surface tension [N·m]
$\dot{\gamma}$	shear rate [s^{-1}]
η	dynamic viscosity [Pa.s]
[η]	intrinsic viscosity
η_{rel}	relative viscosity
η_{red}	reduced viscosity [ml/g]
η_s	solvent viscosity [Pa.s]
η_{sp}	specific viscosity
η’	viscous component of the complex viscosity [Pa.s]
η’’	elastic component of the complex viscosity [Pa.s]
λ	ionic conductivity [S·m^{-1}]
v	kinematic viscosity [cm^2/s]
ρ	density [kg/m^3]
σ	shear stress [Pa]
ω	rotational rate of outer cylinder [rad/s]
Φ	the angle between the cone and plate [rad]

7 LITERATURE

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