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Dextrans in Aqueous Solution. Experimental Review on Intrinsic Viscosity Measurements and Temperature Effect

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Abstract The study of biopolymers as dextran in aqueous solution, is effectively determined by intrinsic viscosity [η] measurements at different temperatures. Molecular weight (M_v) and hydrodynamic properties can be calculated from there. The Mark-Houwink parameters indicate the dependence with temperature (T) in the range from 20 to 50ºC, ie with increasing T a increases and $k_{M\text{-}H}$ decreases. These hydrodynamic parameters show that these polysaccharides behave as a compact rigid sphere and contract by the increase of temperature (R_H decreases) for the M_w range from 8.8 to 200kDa.

Keywords: *intrinsic viscosity, dextrans, Mark-Houwink parameters, hydrodynamic, temperature*

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1. Introduction

Dextran consists of α-D glucose units with a majority of α (1→6) glucosidic linkages between them. A few percent of R (1→3) glucosidic linkages provides side chains which appear to be short. Dextran is a branched polysaccharide, composed of α-D-glucopyranosyl residues. The mostly used commercial product/ polysaccharide is dextran, and it is produced from bacterium *Leuconostoc mesenteroides*, with an overall degree of branching of about 5% [1-3]. Dextran is soluble in water, methyl sulphoxide, formamide, ethylene glycol, glycerol, 4-methylmorpholine-4-oxide, and hexamethyl phosphamide [4]. Dextrans and their derivatives find an interest in clinical applications, as well as excipients in tablets in the pharmaceutical industry [5].

The fast increasing of these polyglucosans for medical, industrial and research purposes motivated a survey of the types obtainable. The particular dextrans which were used initially for conversion into synthetic blood-volume expanders [6,7], human red blood cells aggregation for increasing the degree of polymerization and hence the molecular weight [8,9,10], hydrogels and microspheres [11], in drug transport system and its modifications as nanoparticles [12], in the removal through absorption of contaminant effluents such as heavy metals, organic molecules and inks [13], in the formation of biodegradable films [14,15].

A lot of research has been devoted to dextrans modification in order to describe special characteristics relevant to specific applications such as surfactants [16], as visible marker [17], polysaccharides-based nanoparticles, covalent crosslinking [18], ionic crosslinking, polyelectrolyte complex, and the self-assembly of hydrophobically modified polysaccharides, and hydrophilic modified polysaccharides [19].

Molecular weight, particle size and diffusion coefficient can be determined in many studies by Dynamic Light Scattering [20,21,22], Gel Permeation Chromatography [23], Analytical Ultracentrifuge [24, intrinsic viscosity [1,7,14], size exclusion chromatography / multiangle laser light scattering / differential viscometry, Flow Field-Flow Fractionation [25], and so on.

Determination of the intrinsic viscosity has been the most used measurement in the last 60 years. Viscosity of in water solution polysaccharides depends on intrinsic characteristics of the biopolymer (such as molecular weight, volume, size, shape, surface charge, deformation facility, esterification degree, and galacturonic content) and on ambient factors (such as pH, temperature, ionic strength, solvent, etc.). The most widely used method for the characterization of macromolecules is the capillary viscometry, as it is a simple and economic method. Although, in literature there is much information on hydrodynamic measurements from determinations viscosity; very few of them evaluate the situation at different temperatures. The importance of this type of study lies in the analysis of the polysaccharide behavior at industrial processes, the requirements to reduce energy, avoid flow problems and product quality control. Many works are aimed at determining molecular weights [1,7,26], hydrodynamic radius, among other parameters for characterizing the physics and chemistry properties of dextran in solution.

Table 1 shows some values of dextrans Mark-Houwink parameters, from literature consulted, where all data are based on the logarithmic plot of intrinsic viscosity $[\eta]$ and molecular weight M_w.

Table 1. Intrinsic viscosity, molecular weight, Mark-Houwink parameters dates of various studies released with dextrans at different temperatures

T (°C)	Solvent	M (Da)	$[\eta]$ (cm^3/g)	a	k_{M-H} (cm^3/g)	σ^2	Reference
25	Water	20000 - 100000	-	0.5000	0.0974	-	[27] [f]
20	Water	10000 -500000	-	0.4300	0.0443	-	[28] [f]
25	Formamide	2000 - 32000	-	0.4900	0.0165	-	[29] [f]
20	0.5M NaOH	500000 - 2000000	-	0.4780	0.0132	-	[30] [f]
30	0.1M $NaNO_3$ / 0.025M K_2HPO_4	97000 – 1750000	-	0.3440	0.0476	-	[31] [g]
	0.05M Na_2SO_4			0.2780	0.1130		
30	0.2M $NaNO_3$	40000 - 590000	-	0.3900	0.0485	0.8800	[32] [a]
25	0.4M $NaCH_3COOH$ / 0.4M CH_3COOH	9500 - 2000000	11.0 – 140.0	0.4800	0.0138	-	[33] [b]
25	Water	29500* - 191500*	17.8 - 48.2	0.5330	0.07337	0.9817	[34] [f]
31			17.3 - 45.9	0.5190	0.08268	0.9804	
34			17.1 - 44.8	0.5150	0.08474	0.9783	
40			16.6 - 42.9	0.5080	0.08600	0.9875	
43			16.3 - 41.6	0.5000	0.09462	0.9854	
25	Dimethyl- sulfoxide	29500* - 191500*	25.1 - 68.3	0.5330	0.1050	0.9996	[35] [e]
30			23.9 - 63.4	0.5250	0.1070	0.9995	
35			21.9 - 57.8	0.5190	0.2085	0.9991	
40			21.0 - 55.1	0.5170	0.1040	0.9994	
45			18.2 - 47.7	0.5140	0.0919	0.9991	
25	Ethylene-glycol	29500* - 191500*	17.8 - 50.9	0.5620	0.0551	0.9895	[36] [b]
30			15.4 - 50.9	0.5490	0.0548	0.9691	
35			13.6 - 37.6	0.5430	0.0511	0.9871	
40			12.6 - 34,7	0.5400	0.0486	0.9893	
45			11,7 - 31.8	0.5340	0.0485	0.9879	
20	Water - NaOH 0.5M	9000 - 506000	8.6 - 53.1	0.4363	0.1900	0.9662	[1] [a]
20	Water	40000 - 500000	21.0 - 50.0	0.3311	0.6066	0.9691	[37] [b]
25	Water	9000 -600000	12.0 - 60.0	0.3775	0.3685	0.9922	[3] [d]
25	phosphate- buffered saline pH 7.4	19500 - 500000	10.97 - 50.50	0.4500	0.1361	0.9863	[8] [c]
25	Water	12000 - 520000	11.8 - 51.6	0.3873	0.3197	0.9975	[16] [b]
25	Water	39000	20.0	-	-	-	[38] [b]
45			16.5				
65			15.3				
37	Water	42973 - 1988000	17.8 - 76.5	0.3888	0.2628	0.9887	[5] [b]
25	Water	1270 – 676000	2.8 - 70.8	0.5060	0.0901	0.9870	[39] [b]
30	0.05M Na_2SO_4	180 – 158000	1.2 – 35.0	0.5120	0.0832	0.9950	
	0.05M Na_2SO_4	226000 – 1360000	46.3 – 91.8	0.4250	0.2297	0.9170	
	0.05M Na_2SO_4	1907000 - 5900000	73.6 – 104.5	0.2730	1.4300	0.8260	

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From Table 1, It is worth noting that the value of σ^2 is above 0.95, being an acceptable value for viscosimetric measurement. The same way, many of these authors emphasize the non-linear or hyperbranched of dextran molecular weight range from 9 to 2000kDa [3,5,8,16, 37,38]. In the case of the work performed in references [34,35,36] they studied using the number average molecular weight, which rearranges the value of *a* and forces it to enter into unbranched or linear molecules, on the other hand, if molecular weights are used the value would be less than 0.5.

If plotted for all molecular weights, the double logarithm of $[\eta]$ and M_w, the value of "*a*" obtained in all cases shows a value smaller than 0.5, which reports that dextran macromolecule has a degree of hyperbranched with increasing molecular weight and increases much for higher M_w (< 200kDa) which making the application of M-H method more difficult.

Although, intrinsic viscosity is a molecular parameter that can be interpreted in terms of molecular conformation, it does not offer as high resolution on molecular structure as other methods such as Light Scattering, Circular Dichroism, Sedimentation Velocity, Sedimentation Equilibrium, Size Exclusion Chromatography Coupled to Multi-Angle Laser Light Scattering (SEC-MALLS), High-performance Size Exclusion Chromatography (HPSEC), Gel Permeation Chromatography (GPC), NMR, X-rays, etc. Intrinsic viscosity determination offers a simple and useful method that requires low cost equipment and yields useful information on soluble macromolecules.

In this work, hydrodynamic properties are investigated in different dextran aqueous solutions with different molecular weights (8.8-2000kDa), in a temperature range from 20ºC to 50ºC. The Mark-Houwink parameters and the effect of temperature on them are specifically studied. In order to understand the behavior of this biopolymer in water and to support changes at the M-H parameters with temperature, the hydrodynamic parameters are analyzed (hydrodynamic radius, (R_H); Simha number, ($\nu_{(a/b)}$); Perrin parameter (P); Flory parameter (ϕ_0); and stiffness chain ($d\ln[\eta]/dT$)).

2. Theory

The solution viscosity (η) is related to the solvent viscosity (ηo), resulting in the relative viscosity,

$$\eta_\mathrm{r} = \frac{\eta}{\eta_0} = \frac{t\rho}{t_0\rho_0} \qquad (1)$$

where η (poise) is the viscosity, the ρ (g/cm^3) fluid density, and t the liquid draining time (s) subscript zero is referred to solvent, and without subscript is referred to the solution [40], and inherent viscosity is $\eta_i = \eta_r - 1$.

Huggins equation [41] gives the relation to the relative viscosity increase (η_i),

$$\frac{\eta_i}{c} = [\eta] + k_H [\eta]^2 c \qquad (2)$$

where c is the solute concentration (g/cm^3), $[\eta]$ is the intrinsic viscosity (cm^3/g), and k_H represents Huggins' constants (cm^3/g). The $[\eta]$ is connected to the dimensions of the biopolymer molecule isolated in a certain solvent.

The first term on the left-hand side of equation 2 (η_i/c) has a linear relation as a function of the concentration (c in g/cm^3), where is the intrinsic viscosity $[\eta]$ is given by ($c \to 0$) [42,43]. The intrinsic viscosity calculation requires several concentrations, and because of this inconvenient will not use the Huggins method in this paper. The intrinsic viscosity can be easily calculated by the Solomon-Ciuta single-point equation [44,45],

$$[\eta] = \frac{1}{c}\sqrt{2\eta_i - 2\ln\eta_r} \qquad (3)$$

By studying the molecular weights of various solutions of polymer, Solomon-Ciuta arrived at the formula which allowed the calculation of the intrinsic viscosity of polymer solutions by a single viscosity determination. The formula is verified for different systems of polymer-solvent and the values are in accord with those obtained by extrapolation.

The relation between M_w and the intrinsic viscosity is given by Mark-Houwink equation,

$$[\eta] = k_{MH} (M_w)^a \qquad (4)$$

The calculation of Mark-Houwink parameters is carried out by the graphic representation of the following equation:

$$\ln[\eta] = \ln k_{MH} + a \ln M_w \qquad (5)$$

where k_{MH} (cm^3/g) and a are Mark-Houwink constants, depending on the type of polymer, solvent, and temperature of intrinsic viscosity determinations [46]. The exponent a is a function of polymer geometry, and varies from 0.5 to 2 and exponent is dimensionless. These constants can be determined experimentally by measuring the intrinsic viscosity of several polymer samples for which the molecular weight has been determined by an independent method (i.e. osmotic pressure or light scattering). Using the polymer standards, a plot of the ln $[\eta]$ vs ln M_w usually gives a straight line. The slope is a value and intercept is equal to the ln k_{MH} value [47]. The Mark-Houwink exponent bears the signature of a three-dimensional configuration of a polymer chain in the solvent environment. For a values from 0-0.5 a rigid sphere is predicted in a ideal solvent, from 0.5-0.8 a random coil in good solvent, and from 0.8-2 a rigid or rod like shape is expected (stiff chain). The fact that the intrinsic viscosity of a given polymer sample is different according to the solvent used gives and insight about the general shape of polymer molecules in solution. A long-chain polymer molecule in solution takes on a somewhat kinked or curled shape, intermediate between a tightly curled mass (coil) and a rigid linear configuration. All possible degrees of curling can be displayed by any molecule, but there will be an average configuration which will depend on the solvent. In a good solvent, which shows a zero or negative heat of mixing with the polymer, the molecule is less-extended, and the intrinsic viscosity is high. The Mark-Houwink "a" constant is close to 0.75 (or higher) for these "good" solvents. In a "poor" solvent which shows a positive heat of mixing, segments of a polymer molecule attract each other in solution more strongly than attract the surrounding solvent molecules. The polymer molecule assumes a tighter configuration, and the solution has a lower intrinsic viscosity. The Mark-Houwink "a" constant is close to 0.5 in "poor" solvents. For a rigid or rod like polymer molecule that is greatly extended in solution, the Mark-Houwink "a" constant approaches to a value of 2.0 [48].The hydrodynamic radius (R_H), for a sphere ($\nu_{(a/b)}$ = 2.5) is given by the Einstein relation [49],

$$[\eta]M = \nu_{(\mathrm{a/b})} N_A \frac{3}{4}\pi (R_H)^3 \qquad (6)$$

For simplicity, macromolecules are treated as rigid molecules for a hydrodynamic study. It is worth noting that the size of macromolecules is much bigger than that of solvent (water) molecules [50].

Hydrodynamic properties, such as the intrinsic viscosity, $[\eta]$, and equilibrium solution properties such as the hydrodynamic radius R_H can be combined to construct dimensionless quantities that are universal since they are of being independent of the macromolecular particle size, while they depend more or less sensitively on its shape [51].

Typical examples are the classical size-independent combinations like the Flory parameter, which that combine the intrinsic viscosity, $[\eta]$, and the gyration radius, R_g:

$$\varphi_0 = \frac{[\eta] M_w}{6^{3/2} R_g^3} \qquad (7)$$

These quantities have been proposed along the years, by different eminent scientists, after whom they are named. As a consequence of the diversity in their origin, the set of classical universal size independent quantities suffers from shortcomings. For a sphere and a random coil ϕ_0 the values are 9.23x10^{23} mol^{-1} and 2.60x 10^{23}mol^{-1}, respectively. Thus, it is accepted that, for every flexible-chain polymer in a Θ (ideal) solvent, there is a universal value of ϕ0 = 2.1-2.5x1023mol-1 [52]. The intrinsic viscosity classical theory of random coils at Θ conditions [η]0 predicts the quotient a0 = d ln[η]0/d ln M to decrease from unity to 0.5 as the chain length increases. The proportionality between [η]0 and M0.5 is obtained as a limiting law for the no draining regime. For a given polymer-solvent pair, the theta condition is satisfied at a certain temperature, called the theta (Θ) temperature or theta point. A solvent at this temperature is called a theta solvent [53].

For rigid macromolecules, it is also conventional to combine a solution property with the volume of the particle itself, or with a quantity directly derived from it [54,55,56]. Thus, it is a common practice to express the frictional coefficient of rigid structures as

$$P \equiv \frac{f}{f_0} = \frac{f}{6\pi\eta_0 \left(3V/4\pi\right)^{1/3}} \tag{8}$$

Where f_0 is the frictional coefficient of a sphere having the same hydrodynamic (hydrated or solvated) volume V as the particle. The term f/f_0 is sometimes denoted as P, Perrin constant. A similar combination involves the intrinsic viscosity and specific volume:

$$\nu_{(a/b)} = \frac{[\eta]}{V_s} \tag{9}$$

$\nu_{(a/b)}$ is called Einstein viscosity increment, and V_s is specific volume (cm^3/g). For ellipsoids, as studied by Simha, $\nu_{(a/b)}$ is a function of axial ratio.

3. Experimental Section

3.1. Samples

Seven dextrans, provided by Sigma, with molecular weight of 8.8, 40, 71.9, 110, 200, 580 and 2000 kDa. The solutions were prepared in bidestilated water at 1, 0.75, 0.5, 0.25 % wt.

3.2. Viscosity

Measurements were made with a Ubbelohde C type "suspended level" viscometer [57] (IVA, Argentina); with a diameter capillary of 0.81mm and water draining time of 35.89s at 20°C, with viscometer constant of 0.027883 mm^2/s [58]. The range of temperatures used was 25-50 (±0.1) ºC and it was regulated by thermostatic bath Haake C. The viscosity measurements required Hagenbach-Couette correction time (t_g 37.31s).

3.3. Density

The solution was measured using an Anton Paar DMA35N densitometer.

3.4. Gel Permeation Chromatography

The measurements of dextrans molecular weight were determined by size exclusion HPLC (Gilson, France) with Refraction Index detector using a Polysep-GFC-P5000 column (7.80×30 mm). The column was eluted with bidestilled water a flow rate of 0.8 ml/min, injection 5µL, back pressure 200psi. Dextran standards with sequence molecular weight from 8.8, 40, 71.9, 110, 200, 580 and 2000 kDa were utilized for the plot of calibration curve.

4. Results and Discussion

Table 2 shows that comparing the intrinsic viscosity data obtained from the Huggins method and the Solomon-Ciuta single-point method, a similar values are obtained and the *%RE* is lower for low M_w and it increases for higher M_w. Use of the single point method is correct because it is based in the Huggins method (HM); owing the HM requiring many viscosity and density measurements (at least four) for each M_w, but Solomon Ciuta method with a single measure is sufficient. The analysis of errors using the Solomon-Ciuta method is compared with HM [59].

In order to confirm the molecular weight the gel permeation chromatography (GPC) for standard dextrans is used in a range of molecular weights from 8.8 to 2000kDa and these correspond to the following equation,

$$\ln t_r = -00717 \ln M_w + 3.2892 \tag{10}$$

where t_r is the column retention time in minutes (σ^2 of 0.9792).

Table 2. Comparison of intrinsic viscosity released by Huggins and Salomon-Ciuta methods for 8.8 and 2000kDa M_w at different temperatures

	c (g/cm^3) →	0.01	0.0075	0.005	0.0025	Huggins	Solomon-Ciuta	
M_w (Da)	T (ºC)	η_i/c (cm^3/s)	η_i/c	η_i/c	η_i/c	$[\eta]$ (cm^3/g)	$[\eta]$ (cm^3/g)	%RE
8800	20	8.36	8.33	8.26	8.17	8.12	8.15	0.37
	25	8.20	8.15	8.12	8.04	7.99	8.05	0.75
	30	7.66	7.62	7.57	7.54	7.49	7.63	1.87
	35	7.49	7.45	7.42	7.37	7.23	7.27	0.55
	37	7.24	7.20	7.16	7.13	7.09	7.21	1.69
	40	6.32	6.38	6.43	6.48	6.54	6.74	2.06
	45	5.69	5.87	5.98	6.21	6.35	6.41	0.94
	50	5.11	5.22	5.26	5.31	5.38	5.44	1.12
2000000	20	72.02	68.01	65.43	62.30	59.02	61.18	3.67
	25	69.63	66.08	62.75	60.59	57.15	59.46	4.04
	30	68.36	65.60	62.51	59.28	56.35	58.53	3.88
	35	63.41	60.69	58.31	54.64	52.09	54.90	5.39
	37	60.96	58.42	55.38	53.20	50.41	53.07	5.28
	40	59.13	57.31	54.39	51.56	49.18	51.69	5.11
	45	55.60	53.69	51.57	48.77	46.75	49.11	5.05
	50	51.23	48.54	46.84	44.57	43.38	45.62	5.17

The Solomon-Ciuta single-point method is used for calculating dextran intrinsic viscosity and the error relative is calculated, and *%RE* respect to Huggins method is >4.18% for 2000kDa, and >2.06% for 8.8kDa (Table 2). These values indicate for dextrans in dilute aqueous solution, both methods give very similar results of the intrinsic viscosity and the respective M_w. Table 3 shows the intrinsic viscosity for the rest of the dextrans obtained by using the single-point method, measured at different temperatures.

Table 3. Intrinsic viscosity for dextrans released at different temperatures

T (ºC) →	20	25	30	35	37	40	45	50
M (Da)	[η] (cm^3/g)	[η]	[η]	[η]	[η]	[η]	[η]	[η]
40000	15.23	14.99	14.33	13.65	13.48	12.69	12.14	10.68
71900	19.37	19.17	18.21	17.31	17.23	16.11	15.65	13.63
110000	24.05	23.60	22.47	21.35	20.65	19.84	19.00	16.91
200000	30.40	29.75	28.47	26.93	26.29	25.15	24.54	21.64
580000	48.22	46.79	46.12	45.13	42.71	40.76	38.59	36.91

The M-H equation is empirical and valid for monodisperse polymers, and it is applied to biomacromolecules (complex, hyperbranched, crosslink), taking the precaution of comparing the value of M_v with the polydispersity index ($q_{M\text{-}H}$). The molecular weight of dextran samples can be obtained by a variety of methods including light scattering, HPLC/SEC, sedimentation, osmometry and end-group analysis. Various average molecular weights (M_v, M_n, M_w, and M_z) instead of M_v were substituted in M-H equation. The value of M_v is different from M_n, M_w, and M_z in a polydisperse polymer sample [38,60,61,62]. Determination of constants, $k_{M\text{-}H}$ and *a*, from the intrinsic viscosity data, requires a series of monodisperse polymer samples with known molecular weight or a series of polydisperse polymer samples with known viscosity average molecular weights, M_v. In general, M_v is not experimentally accessible, whereas other average molecular weights are accessible. The equation 4 can be rearranged and resulted in a modified M-H equation as follows:

$$[\eta]=k_{M-H}\left(\frac{M_v}{M_w}\right)^a M_w^a \qquad (11)$$

where

$$q_{M-H}=\left(\frac{M_v}{M_w}\right)^a \qquad (12)$$

where the value $q_{M\text{-}H}$ is the polydispersity correction factor, and it is a statistical function of the molecular weight distribution. It is a measure of the width of molecular weight distributions (MWD) as well as probability of molecular weight distribution curve (GPC). The value of $q_{M\text{-}H}$ varies from one sample to another one, because it is a function of *a* and the average molecular weights (M_v, M_w). Alternatively, the value of $q_{M\text{-}H}$ can be calculated using numerical methods and other-average molecular weights (M_n, M_w, M_z) according to where *c* and *d* are empirical polynomial functions of the exponent *a*.

$$q_{M-H}=\left(\frac{M_w}{M_n}\right)^c\left(\frac{M_z}{M_w}\right)^d \qquad (13)$$

The $q_{M\text{-}H}$ values given by equation 13, these vary from 0.9993 to 0.9841 for the range between 8.8 to 200kDa in a temperature range of 20 to 40°C. This low polydispersity realizes that the Mark-Houwink equation is forced at a given M_w regardless of the hyperbranched nature of the dextran molecule. In this sense, the largest deviations were obtained for the highest molecular weight (580-2000kDa with values from 0.8467 to 0.7346).

Furthermore, the influence of temperature on the intrinsic viscosity is given by the chain flexibility parameter (dln[η]/d*T*), which gives information about the conformation of the macromolecule chain in solution [62]. As intrinsic viscosity of dextrans decreases with an increase in solution temperature; chain flexibility enhances with an increase in temperature (see Table 4) showing that the intrinsic viscosity of dextran (with different molecular weights M_w from 8.8 to 200kDa) decreases linearly with an temperature increase in solution, but change to high molecular weight to hyperbranched macromolecule.

For a limited temperature range, the viscosity of a polymer solution varies generally following a relation similar to that of usual liquids (Ărrhenius plot), where the polymer concentration is not very high and that temperature remains far enough from glass transition [38], and for system PEA–organic solvents see reference [63].

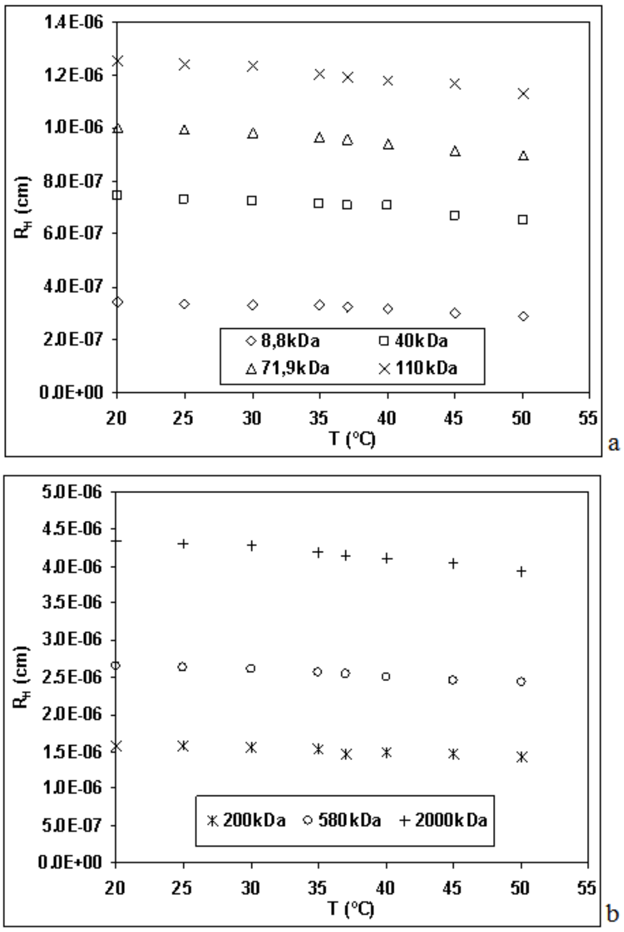

Figure 1. R_H vs. *T*. a)- M_w from 8.8 – 110 kDa ; b)- M_w form 200 – 2000 kDa

Table 4. **Stiffeness chain parameter obtained for dextrans**

M (Da)	dln[η]/dT (K^{-1})
8800	1098.9
40000	1071.3
71900	1059.4
110000	1053.2
200000	1029.2
580000	1118.8
2000000	1189.3

At the same temperature, the hydrodynamic radius and the intrinsic viscosity are higher for different molecular weights, while these properties decrease with an increase of temperature at the same molecular weight (Figure 1). Studies carried out at different ionic strength you can see them in the references [64,65] and works with different solvents in the references [66,67].

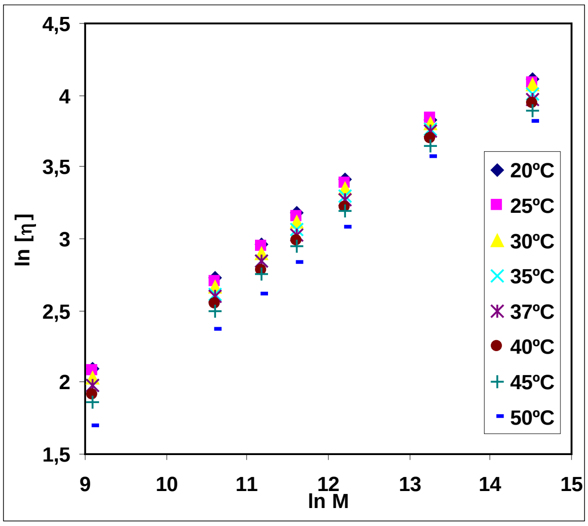

Figure 2. ln [η] in function of ln M_w

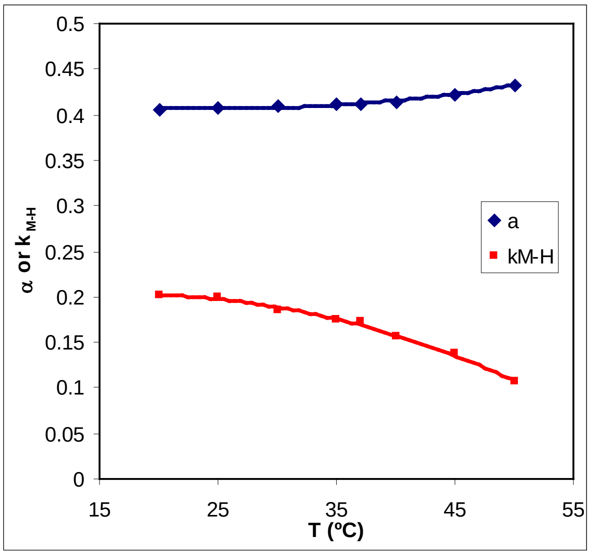

Figure 3. Effect of temperature on Marck-Houwink parameters

Figure 2 shows the classical method for calculating Mark-Houwink parameters, where a linear relation between the intrinsic viscosity and the molecular weight is established for each temperature. Figure 3 shows that the parameters vary with temperature, evidencing a clear functionality of them. These studies on Mark-Houwink parameters are usually carried out at a given temperature, obtaining a consistent result but in a very limited temperature range [68].

Table 5 shows the data of Mark-Houwink parameters determined in figure 4 from linear regressions with σ^2 values higher than 0.9797. The calculated dextran molecular weights are corroborated by those tabulated data by the manufacturer with a relative error lower than 10%, being the exception dextrans 580 and 2000kDa with the highest relative error. There is a deviation from linearity after 580kDa [69,70]. The Dextrans intrinsic viscosity is determined as a function of the molecular weight in water and NaOH 0.5 M see reference [1]. They concluded that a power law behavior seems to be approached only in the small molecular weight region. The reason for a nonlinear Mark-Houwink relationship is confirmed by the intrinsic viscosity which in contrast with scaling prediction shows no power law behavior. The flattening of the curves at higher molecular weight is in agreement with an increased branching density. The dextran was chosen as another branched polysaccharide which, like the others was suspected to show hyperbranched behavior. This conjecture found to be correct. All branched polysaccharide types could be described approximately by the hyperbranching theory. In contrast to linear chains, power law behavior is observed only asymptotically at large M_v. In fact, short chains do contain minor branching points. The effect of branching is best recognized from the molecular weight dependencies of [η].

Table 5. The ***a*** **and** $k_{M\text{-}H}$ **parameters and their standard deviation (**σ^2**) calculated from plot 4**

T ºC	a	k$_{\text{M-H}}$	σ^2
20	0.4161	0.1871	0.9892
25	0.4213	0.1743	0.9917
30	0.4244	0.1606	0.9857
35	0.4255	0.1510	0.9906
37	0.4268	0.1477	0.9896
40	0.4272	0.1378	0.9797
45	0.4339	0.1165	0.9569
50	0.4411	0.0934	0.9491

Dextran theta temperature between 43.14 and 44.44ºC for all the range of molecular weights explains the deviation at 45 and 50ºC [36,37].

A simple way of universalizing the measurements is shown in figure 4 where there is a curve at each temperature for every molecular weight. This universalization of the parameter´s leads to a higher error ratio in the calculation of the respective molecular weights. The values of Mark-Houwink parameters universalized for the range of working temperatures are the following: 0.4267 for $a*$, and 0.1455 cm^3/g for $k*_{M\text{-}H}$, with σ^2 of 0.9399. Conducting a comparative analysis of the data shown in Table 1 can observer that parameter data Mark-Houwink "*a*", obtained by these authors are very similar to that obtained in this work, which affirms its validity.

In the range of working temperatures and molecular weights of dextrans, similar intrinsic viscosity results obtained by other researchers and published here are slight, as shown in tables 1 and 3. At 20°C data "*a*" value obtained in this work is intermediate to those given by references [1,37] while the value of k_{M-H} is lower. At 25°C both values of *a* and k_{M-H} are within the range reported by [3,8,16]. The above data are not useful because it can not be compared with those obtained in this work. This situation is mainly the result of using dextans, solvent, additives, etc. of different origins. Similar results are obtained in references [35,36,37], using a system of dextran / ethylene glycol, and dextran/dimethylsulfoxide, respectively. Therefore, the trend of "*a*" and k_{M-H} decreases with *T*, where the presence of ethylene glycol or dimethylsulfoxide strongly changes the interactions of this solvent with the macromolecule. Ultimately they concluded that the temperature increment found to be an effective force in disturbing these interactions, mainly between polymer-polymer and polymer-solvent molecules for the used system.

Table 6. Comparative analysis (*%RE = 100 {M_w – M_v}/ M_w*) between molecular weights provided by manufacturer (M_w), and M_v calculated with Mark-Houwink parameters in this work

T (ºC) →	25		30		35		40	
Manufacturer	this work		this work		this work		this work	
M_w (Da)	M_v	%RE	M_v	%RE	M_v	%RE	M_v	%RE
8800	8930.23	1.43	8931.82	1.50	9001.33	2.29	9007.68	2.36
40000	39061.59	2.34	39436.79	1.41	39564.96	1.09	39616.44	0.96
71900	70032.49	2.60	69359.14	3.53	69145.71	3.83	69257.09	3.67
110000	114712.88	4.28	113818.99	3.47	113205.68	2.91	112767.17	2.51
200000	198763.89	0.62	198793.54	0.60	195369.34	2.31	196462.18	1.77
580000	582297.82	0.40	619504.79	6.81	657406.58	13.34	608332.22	4.88

A similar article of dextran/water [35] clearly demonstrating the dependence of Mark-Houwink parameters with temperature. The correct way to interpret what Mark-Houwink parameters is determined graphically ln [η] versus ln M_w, where M_w is the molecular weight provided by manufacturer, and calculate the percentage relative error (*%RE*) respect to M_w. The *a* value is higher than calculated in this work, because these calculations were performed with number average molecular weight (M_n) which rearranges the value of *a* and forces him to enter into unbranched or linear molecules ($a > 0.5$), on the other hand, if molecular weights (M_w) ware used to value would be less than 0.5.

The value of k_{M-H} in this work decreases with increasing temperature in contrast to published by reference [34] where k_{M-H} increases. The explanation for the anomalous values of *a* and k_{M-H} is because the mixture solute-solvent is highly compatible due a great compaction of biopolymer, from undisturbed state in the absence of interactions, where free energy of mixing less than zero, and emphasize the nature non-linear or hyperbranched of dextran for M_w high to 200kDa.

Working with the molecular weights given by the manufacturer and compare them with the molecular weights, calculated from the Mark-Houwink parameters in this work; can be seen that the *%RE* obtained, see Table 6.

The parameters of Mark-Houwink for polymers can vary with the polymer solution and temperature. This is because the macromolecule hydrodynamic radius changes the solution type and temperature via change in their chain flexibility. In a good solvent, a temperature increase results in an intrinsic viscosity decrease and in a less-extended conformation (R_H<), because the entropy value increases with an increase in temperature and it is unfavorable for an extended conformation. In the case of a poor solvent, a temperature increase causes an increase in entropy and intrinsic viscosity and is favorable for the extended conformation. Mark-Houwink values confirm that for these conditions dextrans behave as rigid spheres with a tendency at compaction as temperature increases.

Analyzing the values of the hydrodynamic properties of dextran in aqueous solution, it can be seen in Table 7, that all vary with the temperature. The values of ϕ_0 decreases from 2.5429 to 2.3326 x 10^{23}mol^{-1} demonstrating a relative flexibility of particles. The value of *P* increases from 1.0272 to 1.2694 (spherical shape with tendency to spheroid for high M_w). The $v_{(a/b)}$ value is 2.5 which confirms that dextran in aqueous solution is a biopolymer with a spherical conformation for an M_w range from 8.8 to 200kDa, and with tendency to compaction with increasing temperature (R_H decreases).

Table 7. Hydrodynamic parameters of dextrans at different temperatures

Dextran, M_w (Da)	*T* (ºC)	ϕ_0 x 10^{-23} (mol^{-1})	P
	20	3.0413	1.0272
	25	3.0040	1.0266
	30	2.8473	1.0232
8800	35	2.7129	1.0223
	37	2.6905	1.0220
	40	2.5152	1.0215
	45	2.3920	1.0200
	50	2.0300	1.0193
	20	2.6657	1.1147
	25	2.6237	1.1125
	30	2.5082	1.1090
40000	35	2.3892	1.1072
	37	2.3594	1.1067
	40	2.2212	1.1047
	45	2.1249	1.0873
	50	1.8693	1.0858
	20	2.5288	1.1695
	25	2.5027	1.1655
	30	2.3773	1.1649
71900	35	2.2598	1.1633
	37	2.2494	1.1615
	40	2.1032	1.1486
	45	2.0431	1.1385
	50	1.7794	1.1359
	20	2.5384	1.2356
	25	2.4909	1.2291
	30	2.3716	1.2285
110000	35	2.2535	1.2207
	37	2.1796	1.2160
	40	2.0941	1.2060
	45	2.0054	1.1982
	50	1.7848	1.1842
	20	2.3796	1.2694
	25	2.3287	1.2664
	30	2.2285	1.2605
200000	35	2.1080	1.2553
	37	2.0579	1.2509
	40	1.9687	1.2349
	45	1.9209	1.2179
	50	1.6939	1.2076

5. Conclusions

The Mark-Houwink parameters is calculated molecular weights range from 8.8 to 200kDa. The numerical value of a indicates that dextrans acquire the shape of a rigid sphere in aqueous solution; and $k_{M\text{-}H}$ demonstrates that under water the value decreases with temperature [71,72]. The great deviation at 2000kDa occurs due to the large hyperbranched structure of the macromolecule, generating a change in its conformation and, therefore, a change in the way it flows [73]. The values of Mark-Houwink parameters could be universalized with certain precautions, being an indication for the calculation of molecular weight in the temperature range of 20-40ºC.

The lack of data on the uniformity of intrinsic viscosity measurements in the system water/dextran, highlights the significant influence of the solvent and temperature [74]. The molecular weight and Simha number do not change in this temperature range (M_w from 8.8-200kDa), P slightly change, showing modifications in the hydrodynamic properties of the biopolymer in aqueous solution as $[\eta]$ and R_H.

The temperature increment can induce a macromolecule compaction (decreases in R_H and $[\eta]$), generating by this way, a greater difficult to flowing due at requires an increase of energy consumption (E_{avf}<). This phenomenon is observed in the case of hyperbranched biopolymers evidencing an increase of a with temperature.

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References

[1] Ioan, C.E.; Aberle, T; Burchard, W. (2000). Structure Properties of Dextran. 2. Dilute Solution. Macromolecules, 33, 5730-5739.

[2] Kim, D.; Robyt, J. F.; So-Young Lee; Jin-Ha Lee; Young-Min Kim. (2003). Dextran molecular size and degree of branching as a function of sucrose concentration, pH, and temperature of reaction of *Leuconostoc mesenteroides* B-512FMCM dextransucrase. Carbohydrate Research, 338, 1183-1189.

[3] De Belder, A.N. (2003). Dextran. Amersham Biosciences, AA Edition, www.amershambiosciences.com.

[4] De Belder, A. N. (2001). Dextran Fractions. Data File Dextran. Amersham Biosciences, AA Edition, www.amershambiosciences.com.

[5] Castellanos Gil, E. E.; Iraizoz Colarte, A.; El Ghzaoui, A.; Durand, D.; Delarbre, J.L.; Bataille, B. (2008). A sugar cane native dextran as an innovative functional excipient for the development of pharmaceutical tablets. European Journal of Pharmaceutics and Biopharmaceutics, 68, 319-329.

[6] Jeanes, A.; Haynes, W.C.; C. Wilham, A.; Rankin, J.C; Melvin, E.H.; Austin, M. J.; Cluskey, J. E.; Fisher, B.E.; Tsuchiya, H.M.; Rist, C.E. (1954). Characterization and Classification of Dextrans from Ninety-six Strains of Bacteria. Journal of American Chemical Society, 76 (20), 5041-5052.

[7] Arond L.H.; Fran, H.P. (1954). Molecular weight, molecular weight distribution and molecular size of a native dextran. Journal of Physical Chemistry, 58(11), 953-957.

[8] Armstrong, J. K.; Wenby, R. B.; Meiselman, H. J.; Fisher, T. C. (2004). The Hydrodynamic Radii of Macromolecules and Their Effect on Red Blood Cell Aggregation. Biophysical Journal, 87, 4259-4270.

[9] Pribush, A.; Zilberman-Kravits, D.; Meyerstein, N. (2007). The mechanism of the dextran-induced red blood cell Aggregation. European Biophysical Journal, 36, 85-94.

[10] Barshtein, G.; Tamir, I.; Yedgar, S. (1998). Red blood cell rouleaux formation in dextran solution: dependence on polymer conformation. European. Biophysical Journal, 27, 177-181.

[11] Stenekes, R.J.H.; Talsma, H.; Hennink, W.E. (2001). Formation of dextran hydrogels by crystallization. Biomaterials, 22, 1891-1898.

[12] Liu Zonghua; Yanpeng Jiao; Yifei Wang; Changren Zhou; Ziyong Zhang (2008). Polysaccharides-based nanoparticles as drug delivery systems. Advanced Drug Delivery Reviews, 60, 1650-1662.

[13] Crini, G. (2005). Recent developments in polysaccharide-based materials used as adsorbents in wastewater treatment. Progress in Polymer Science, 30, 38-70.

[14] Pavlov, G.M.; Grishchenko, A.E.; Rjumtsev, E.I.; Yevlampieva N.P. (1999). Optical properties of dextran in solution and in films. Carbohydrate Polymers, 38, 267-271.

[15] Leiva, Angel; Muñoz, Natalia; Urzúa, Marcela; Gargallo, Ligia; Radic, Deodato (2010). Monolayers and Thin Films of Dextran Hydrophobically Modified. J. Braz. Chem. Soc., 21, 1, 78-86.

[16] Rotureau, E.; Dellacherie, E.; Durand, A. (2006). Viscosity of aqueous solutions of polysaccharides and hydrophobically modified polysaccharides: Application of Fedors equation. European Polymer Journal, 42, 1086-1092.

[17] Viet, D.; Beck-Candanedo, S.; Gray D. G. (2008). Synthesis and characterization of blue dextrans. Carbohydrate Polymers, 74, 372-378.

[18] Hennink, W.E.; De Jong, S.J.; Bos, G.W.; Veldhuis, T.F.J.; van Nostrum, C.F. (2004). Biodegradable dextran hydrogels crosslinked by stereocomplex formation for the controlled release of pharmaceutical proteins. International Journal of Pharmaceutics, 277, 99-104.

[19] Coviello, T.; Matricardi, P.; Marianecci, C.; Alhaique, F. (2007). Polysaccharide hydrogels for modified release formulations. Journal of Controlled Release, 119, 5-24.

[20] Kloster, C.; Bica, C.; Lartigue, C.; Rochas, C.; Samios, D.; Geissler E. (1998). Dynamics of a Polymer Solution in a Rigid Matriz. Macromolecules, 31, 7712-7716.

[21] Kloster, C.; Bica C.; Rochas C.; Samios, D.; Geissler, E. (2000). Dynamics of a Polymer Solution in a Rigid Matrix. 2. Macromolecules, 33, 6372-6377.

[22] Nordmeier, Eckliard (1993). Static and Dynamic Light-Scattering Solution Behavior of Pullulan and Dextran in Comparison. Journal of Physical Chemistry, 97, 5110-5185.

[23] Karmarkar, S.; Garber, R.: Kluza, J.; Koberda, M. (2006). Gel permeation chromatography of dextrans in parenteral solutions: Calibration procedure development and method validation. Journal of Pharmaceutical and Biomedical Analysis, 41, 1260-1267.

[24] Harding, Stephen E. (2005). Challenges for the modern analytical ultracentrifuge analysis of polysaccharides. Carbohydrate Research, 340, 811-826.

[25] Kirkland, J. J.; Dilks, C. H.; Rementer, S. W. (1992). Molecular Weight Distributions of Water-Soluble Polymers by Flow Field-Flow Fractionation. Analytical Chemistry, 64, 1295-1303.

[26] Antoniou, E.; Buitrago, C. F.; Tsianou, M.; Alexandridis, P. (2010). Solvent effects on polysaccharide conformation. Carbohydrate Polymers, 79, 380-390.

[27] Senti, F. R.; Hellman, N. N.; Ludwig, G.; Babcock, E.; Tobin, R.; Class, C. A., (1955). Viscosity, sedimentation, and light-scattering properties of fraction of an acidhydrolyzed dextran. Journal of Polymer Science, 17, 527-546.

[28] Granath, K. A. (1958). Solution properties of branched dextran. Journal of Colloid Science, 31, 308-328.

[29] Gekko, K. (1971). Physicochemical studies of oligodextran. II. Intrinsic viscosity molecular weight relationship. Die Makromolekulare Chemie, 148(1), 229-238.

[30] Bose, A.; Rollings, J. E.; Caruthers, J. M.; Okos, M. R.; Tsao, T. G. (1982). Polyelectrolytes as secondary calibration standards for aqueous SEC. Journal of Applied Polymer Science, 27, 795-810.

[31] Bahary, W.S.; Hogan, M.P. Determination of branching in biopolymers by size exclusion chromatography with light scattering (Malls), viscosity, and refractive index detection. Int. GPC Symp. Proc. 1994, 95-0355.

[32] Bahary, W. S.; Hogan, M. P.; Jilani, M.; Aronson, M. P. (1995). Chromatographic characterization of polymers: Hyphenated and multidimensional techniques. Advances in chemistry series Washington, DC: American Chemical Society., pp. 151-166.

[33] Eremeeva, T. E.; Bykova, T. O. (1998). SEC of mono-carboxymethyl cellulose (CMC) in a wide range of pH, Mark–Houwink constants. Carbohydrate Polymers, 36, 319-326.

[34] Guner, Ali (1999). Unperturbed dimensions and theta temperature of dextran in aqueous solutions. Journal of Applied Polymer Science, 72, 871-876.

[35] Catiker, E.; Guner, A. (2000). Unperturbed dimensions and the theta temperature of dextran in ethylene glycol solutions. European Polymer Journal, 36, 2143-2146.

[36] Guner, A.; Kibarer, G. (2001). The important role of thermodynamic interaction parameter in the determination of theta temperature, dextran/water system. European Polymer Journal, 37, 619-622.

[37] Tirtaatmadja, V.; Dunstan, D. E.; Boger, D. V. (2001). Rheology of dextran solutions. Journal Non-Newtonian Fluid Mech., 97, 295-301.

[38] Durand, A. (2007). Aqueous solutions of amphiphilic polysaccharides: Concentration and temperature effect on viscosity. European Polymer Journal, 43, 1744-1753.

[39] Kasaai, Mohammad R. (2012). Dilute solution properties and degree of chain branching for dextran. Carbohydrate Polymers 88 373-381.

[40] López Martínez, M. C.; Díaz Baños, F. G.; Ortega Retuerta, A.; García de la Torre, J. (2003). Multiple Linear Least-Squares Fits with a Common Intercept: Determination of the Intrinsic Viscosity of Macromolecules in Solution. Journal of Chemical Education, 80(9), 1036-1038.

[41] Huggins, Maurice L. (1942). The Viscosity of Dilute Solutions of Long-Chain Molecules. IV. Dependence on Concentration. Journal of American Chemical Society, 64(11), 2716-2718.

[42] Curvale, R.; Masuelli, M.; Perez Padilla, A. (2008). Intrinsic viscosity of bovine serum albumin conformers. International Journal of Biological Macromolecules, 42, 133-137.

[43] Masuelli, Martin Alberto (2013). Advances in Physical Chemistry, Vol. 2013, Article ID 360239, pp. 8.

[44] Solomon, O. F. ; Ciută I. Z. (1962). Détermination de la viscosité intrinsèque de solutions de polymères par une simple détermination de la viscosité. Journal of Applied Polymer Science, 6, 683-686.

[45] Gillespie, T.; Hulme, M. A. (1969). On single point determination of intrinsic viscosity. Journal of Applied Polymer Science, 13, 2031-2032.

[46] Takara, Andres; Acosta, Adolfo; Masuelli, Martin A. (2013). Hydrodynamic Properties of Tragacanthin. Study of temperature influence. Journal Argentine Chemical Society 100 (2013) 25-34.

[47] Harding, Stephen E. (1997). The Intrinsic Viscosity of Biological Macromolecules. Progress in Measurement, Interpretation and Application to Structure in Dilute Solution. Progress in Biophysical Molecules Biological, 68, 207-262.

[48] Harding, S. E.; Varum, K.; Stoke B.; Smidsrod, O. (1991). Molecular weight determination of polysaccharides. Advances in Carbohydrate Analysis, 1, 63-144.

[49] Smith, David R.; Raymonda, John W. (1972). Polymer molecular weight distribution. An undergraduate physical chemistry experiment. Journal of Chemical Education, 49(8), 577-579.

[50] He, L.; Niemeyer, B. (2003). A novel correlation for protein diffusion coefficients based on molecular weight on radius of gyration. Biotechnology Progress, 19, 544-548.

[51] Ortega, A.; García de la Torre, J. (2007). Equivalent Radii and Ratios of Radii from Solution Properties as Indicators of Macromolecular Conformation, Shape, and Flexibility. Biomacromolecules 8, 2464-2475.

[52] Garcia de la Torre, J.; Carrasco, B. (1999). Universal size-independent quantities for the conformational characterization of rigid and flexible macromolecules. Progr. Colloid Polym. Sci. 113, 81-86.

[53] Bohdanecky, Miloslav (1996). Mark-Houwink-Kuhn-Sakurada Exponent at the Θ Condition. Its Invariancy with Respect to the Cross-Sectional Dimensions of Polymer Chains. Macromolecules, 29, 2265-2268.

[54] Morris, G.A.; Patel, T.R.; Picout, D.R.; Ross-Murphy, S.B.; Ortega, A.; Garcia de la Torre, J.; Harding, S.E. (2008). Global hydrodynamic analysis of the molecular flexibility of galactomannans. Carbohydrate Polymers 72, 356-360.

[55] Palmuti Braga Vettoria, Mary Helen; Martins Franchetti, Sandra Mara; Contiero, Jonas (2012). Structural characterization of a new dextran with a low degree of branching produced by Leuconostoc mesenteroides FT045B dextransucrase. Carbohydrate Polymers 88 1440-1444.

[56] Harding, S. E., & Simpkin, N. J. (1990). On the molecular weight distribution of dextran T-500. Gums and stabilisers for the Food Industry, 5, 447-450.

[57] Ubbelohde, Leo. (1937). The Principle of the Suspended Level: Applications to the Measurement of Viscosity and Other Properties of Liquids. Ind. Eng. Chem. Anal. Ed., 9(2), 85-90.

[58] Viswanath, D.S.; Prasad, D.H.L.; Dutt, N.V.K.; Rani, K.Y.; Ghosh, T.K. (2007). Viscosity of Liquids. Theory, Estimation, Experiment, and Data. Chapter 2.1.4 Suspended level viscometers for transparent liquid, Ubbelohde Viscometer page 28-31. Springer Editions.

[59] Pamiés, R.; Hernández Cifre, J. G.; López Martínez, M.C.; García de la Torre, J. (2008). Determination of intrinsic viscosities of macromolecules and nanoparticles. Comparison of single-point and dilution procedures. Colloid and Polymer Science, 286, 1223-1231.

[60] Elias, Hans-Georg (1975). Polymolecularity and polydispersity in Molecular weight determinations. Pure Appl. Chem. 43-1, 115-147.

[61] Kasaai, M. R.; Arul, J.; Charlet, G. (2000). Intrinsic viscosity-molecular weight relationship for chitosan. Journal of Polymer Science Part B: Polymer Physics, 38, 2591-2598.

[62] Kasaai, Mohammad R. (2007). Calculation of Mark–Houwink–Sakurada (MHS) equation viscometric constants for chitosan in any solvent–temperatura system using experimental reported viscometric constants data. Carbohydrate Polymers, 68, 477-488.

[63] Cecopieri-Gómez, Martha L.; Palacios-Alquisira, Joaquín (2005). Interaction Parameter (χ); Expansion Factor (ε); Steric Hindrance Factor (σ); and Shielding Function F(ξ); for the System PEA–Organic Solvents by Intrinsic Viscosity Measurements. J. Braz. Chem. Soc., 16, 3A, 426-433.

[64] Ghimici, Luminita; Nichifor, Marieta; Wolf, Bernhard (2009). Ionic Polymers Based on Dextran: Hydrodynamic Properties in Aqueous Solution and Solvent Mixtures. J. Phys. Chem. B 113, 8020-8025.

[65] Ghimici, Luminita; Nichifora, Marieta; Eich, Andreas; Wolf, Bernhard A. (2012). Intrinsic viscosities of polyelectrolytes in the absence and in the presence of extra salt: Consequences of the stepwise conversion of dextran into a polycation. Carbohydrate Polymers 87, 405-410.

[66] Covis, Rudy; Ladaviere, Catherine ; Desbrieres, Jacques ; Marie, Emmanuelle ; Durand, Alain. (2013). Synthesis of water-soluble and water-insoluble amphiphilic derivatives of dextran in organic medium. Carbohydrate Polymers 95 360-365.

[67] Mainaa, Ndegwa Henry; Pitkänen, Leena; Heikkinen, Sami; Tuomainen; Päivi; Virkki, Liisa; Tenkanen, Maija (2014). Challenges in analysis of high-molar mass dextrans: Comparison of HPSEC, AsFlFFF and DOSY NMR spectroscopy. Carbohydrate Polymers 99, 199-207.

[68] Beer, M.U.; Wood, P.J.; Weisz, J. (1999). A simple and rapid method for evaluation of Mark–Houwink–Saturada constants of linear random coil polysaccharides using molecular weight and intrinsic viscosity determined by high performance size exclusión chromatography: application to guar galactomannan. Carbohydrate Polymers, 39, 377-380.

[69] Walkenhorst, S.; Olivier, R. (2002). Determination of polymer structure by Gel Permeation Chromatography. Materiaux 1-5. Viscotek GmbH, Europe.

[70] Walkenhorst, S.; Olivier, R. (2003). Dextran Triple Detector Application Note 1, Viscotek GmbH, USA.

[71] Chen Rong Huei; Wei Yu Chen; Shang Ta Wang; Chu Hsi Hsu; Min Lang Tsai (2009). Changes in the Mark-Houwink hydrodynamic volume of chitosan molecules in solutions of different organic acids, at different temperatures and ionic strengths. Carbohydrate Polymers, 78, 902-907.

[72] Chen Rong Huei; Min Lang Tsai (1998). Effect of temperature on the intrinsic viscosity and conformation of chitosan in dilute HCl solution. International Journal of Biological Macromolecules, 23, 135-141.

[73] Kuge Takashi; Kimie Kobayashi; Shinichi Kitamura; Hiroshi Tanahashi. (1987). Degrees of long-chain branching in dextrans. Carbohydrate Research, 160, 205-214.

[74] Masuelli, Martin A. Hydrodynamic properties of whole arabic gum. American Journal of Food Science and Technology 2013, 1(3), 60-66.