

## Short Review Article



# Estimation of the Diffusion Coefficient and Hydrodynamic Radius (Stokes Radius) for Inorganic Ions in Solution Depending on Molar Conductivity as Electro-Analytical Technique-A Review

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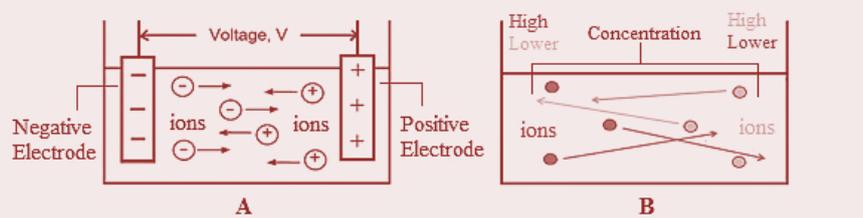
### Abstract:

Diffusion coefficient (D) and radiuses of inorganic charge ions (R) in different environments is of importance in scientific fields, explaining certain features of ions. D values were obtained using the Einstein-Smoluchowski equation depending on limiting molar conductivity ( $\lambda^{\circ}$ ) of inorganic charge ions. Inorganic ions have D values at the range of  $1-3 \times 10^{-9} \text{ m}^2 \cdot \text{s}^{-1}$ , except hydroxyl and hydrogen ion ( $5.2 \times 10^{-9}$  and  $9.1 \times 10^{-9} \text{ m}^2 \cdot \text{s}^{-1}$ , respectively). The hydrodynamic radius R for diffusing ions was calculated using the Stokes-Einstein equation based on D values. Inorganic ions have R, values at the range of  $1-3 \times 10^{-10} \text{ m}$ , except hydroxyl and hydrogen ion ( $R=0.47 \times 10^{-10}$  and  $0.27 \times 10^{-10} \text{ m}$ , respectively).

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**Keywords:** Diffusion coefficient; Hydrated radius; Molar conductance; Movement of ions

### Graphical Abstract:



Graphical abstract illustration the conductance of ions (A), and the diffusion of ions (B), in solution.

### Biography:



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**Maher Ibraheem Gamaj** Lecturer obtained B.Sc. in an electric engineer in 1983 and M.Sc. in 1985 from an electric engineer department, an engineer College, Belgrade University, Serbia. Currently Maher Ibraheem Gamaj serves as teaching member in Power Mechanical Techniques, Institute of Technology, Baghdad, Middle Technical University. Maher Ibraheem Gamaj has numerous scientific searches published in Iraqi and word scientific researches journals.

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## 1. Introduction

Diffusion is the motion result of atoms or molecules from a higher concentration area (chemical potential is higher) to a lower concentration area (chemical potential is lower). In chemical potential, diffusion is a gradient driven by diffusing atoms, molecules or ions. At the unit concentration gradient of materials in a mixture, the diffusion coefficient  $D$ , provides a number of moles of a given ions, atoms or molecules which passes through unit area per unit time. Conductance and diffusion are including motion of ions, so a joining between them is present [1]. Conductance and diffusion can be attributed to velocity property at infinite dilution, because, the interionic forces are disappear, which repels movement of ions in the solvent [2]. The movement of ions through the solvent molecules as an environment is very important. There are two sides of these movements. One of them is ionic motions with random in direction and speed basically. Secondly, movements have a collection side that is of particular impact when more ions are movement in certain sides than in others and product drift of ions. The ions drift has important results because an ion has a mass and bears a charge [3]. Electrolyte substances are constituents of ions, those anions and cations in dissolved state or liquid exist in dissociation form. They are capable to conduct the electric current, as the charge cations and anions carriers are free to motion between the cathode (-) and the anode (+) by diffusion [4]. Measurement of molar conductance of solutions is a classical electro-analytical practice that had application in different chemical and biochemical studies. For example, conductivity can be used to evaluate the solvent purity, follow kinetics of dissolution, determine relative solution ionic strengths (including functioning as a detector for ion chromatography), the attitude to partially soluble salts equilibrium, monitor of some enzymatic reactions course, determine critical concentrations of micelle, and to provide thermodynamic electrolyte solutions data [5]. Conductivity measurements have been used in many environmental and industrial applications as a fast and trustworthy method of measuring the ionic content in solutions [6]. Many techniques are available for the determination of diffusion coefficients of ions in aqueous solutions; one of them is the ionic conductivity method. Diffusion coefficient of different species in different media is an important property in scientific and practice research [7], like in petroleum engineering [8], biochemistry [9], and nanotechnology [10]. The radiuses of inorganic charge ions are important to use in explain a certain features of the ion, like bonding, shielding and numerous biological properties in solution [11-13]. In this review, we estimated the diffusion coefficient and

the hydrated radius by Einstein-Smoluchowski equation and Stokes-Einstein equation respectively for inorganic charge ions in water solution depending on molar conductivity.

## 2. Electrical Mobility and Conductivity

Electrical mobility is the capability of charged particles to motion through an environment relative to an electric field that is pulling the charged ions. The split-up of ions resulting to their mobility in (gas phase) is termed to ion mobility spectrometry, in (liquid phase) it is termed to electrophoresis. When a charged species in a liquid or gas is acted upon uniform electric field, it will be speeded until it reaches a constant drift velocity according to Ohm's law formula that can be explained in terms of drift velocity [14] as Equation 1:

$$v_d = \mu E \quad (1)$$

Where,  $v_d$  is drift velocity, ( $m \cdot s^{-1}$ ),  $E$  is magnitude of the applied electric field, ( $V \cdot m^{-1}$ ),  $\mu$  is mobility, ( $m^2 \cdot V^{-1} \cdot s^{-1}$ ).

In physics the average of velocity achieved by charged species is a drift velocity, like ions, in a solution accustom to an electric field. In other words, the electrical mobility of the ion is well-defined as the ratio of the drift velocity to the amount of the electric field Equation 2:

$$\mu = v_d / E \quad (2)$$

Conductivity can be measured by applying an alternating electrical current to two electrodes immersed in a solution and measuring the resulting voltage. Kohlrausch's law states that the equivalent conductivity of a material at infinite dilution is equal to the anions conductance plus cations conductance. If electrolyte dissolved in water, the conductivity of the solution is the sum of anions and cations conductance, so Kohlrausch's law can be expressed as Equation 3 [15]:

$$\Lambda_m^0 = v_+ \lambda_+^0 + v_- \lambda_-^0 \quad (3)$$

Where,  $\Lambda_m^0$  is the limiting molar conductivity, ( $S \cdot m^2 \cdot mol^{-1}$ ),  $v$ : is the number of ions  $i$  in the formula unit of the electrolyte,  $\lambda^0$  is the limiting molar conductivity of ion, i., ( $S \cdot m^2 \cdot mol^{-1}$ ).

In solution the limiting molar conductivity of ion species can be represented by Equation 4 [16]:

$$\mu = \lambda / zF \quad (4)$$

Where,  $\lambda$  is molar limiting conductivity of ion, ( $S \cdot m^2 \cdot mol^{-1}$ ),  $z$  is the charge number of ion,  $\mu$  is mobility of ion, ( $m^2 \cdot V^{-1} \cdot s^{-1}$ ),  $F$  Faraday's constant, ( $Coulomb \cdot mol^{-1}$ ).

As the values of mobility by different expression (Equation 2 and Equation 4) are equal, the units after deriving is the same as shown in Equation 5:

$$\mu = \frac{\lambda}{zF} = \frac{S \cdot m^2}{C} = \frac{C \cdot s^{-1} \cdot m^2}{V \cdot C} = \frac{m^2}{V \cdot s} \quad (5)$$

Where  $m$  is meter,  $V$  is volt,  $s$  is second,  $S$  is Siemens,  $C$  Coulomb.



**Table 1.** Molar Ionic conductivity,  $\lambda^\circ/S \text{ cm}^2 \text{ mol}^{-1}$ , in water at 298 K [18].

Ion	$\lambda^\circ$	D	Ion	$\lambda^\circ$	D	Ion	$\lambda^\circ$	D
K <sup>+</sup>	073.5	1.957	IO <sup>3-</sup>	040.5	1.078	Na <sup>+</sup>	050.1	1.334
I <sup>-</sup>	076.8	2.045	H <sub>2</sub> PO <sub>4</sub> <sup>-</sup>	036.0	0.959	Ni <sup>2+</sup>	099.2	0.661
H <sup>+</sup>	349.6	9.311	NO <sub>2</sub> <sup>-</sup>	071.8	1.912	Co <sup>2+</sup>	110.0	0.732
Cl <sup>-</sup>	076.4	2.032	CO <sub>3</sub> <sup>2-</sup>	138.6	0.923	HPO <sub>4</sub> <sup>2-</sup>	114.0	0.759

**Table 2.** Molar Ionic conductivity,  $\lambda^\circ/S \text{ cm}^2 \text{ mol}^{-1}$  and Ions mobility,  $\mu/10^{-8} \text{ m}^2 \text{ s}^{-1} \text{ V}^{-1}$ , in water at 298 K [19].

Ion	$\lambda^\circ$	$\mu$	Ion	$\lambda^\circ$	$\mu$	Ion	$\lambda^\circ$	$\mu$
H <sup>+</sup>	34.96	36.23	NH <sub>4</sub> <sup>+</sup>	07.35	07.62	Mg <sup>2+</sup>	10.60	05.50
Li <sup>+</sup>	03.87	04.01	OH <sup>-</sup>	19.91	20.64	Ca <sup>2+</sup>	11.90	06.17
Na <sup>+</sup>	05.01	05.19	F <sup>-</sup>	05.54	05.74	Sr <sup>2+</sup>	11.89	06.16
K <sup>+</sup>	07.35	07.62	Cl <sup>-</sup>	07.64	07.92	CO <sub>3</sub> <sup>2-</sup>	13.86	07.18
Rb <sup>+</sup>	07.78	08.06	Br <sup>-</sup>	07.81	08.09	NO <sub>3</sub> <sup>-</sup>	07.15	07.41
Cs <sup>+</sup>	07.72	08.00	I <sup>-</sup>	07.68	07.96	SO <sub>4</sub> <sup>2-</sup>	16.00	08.29

### 3. MIP-Based Sensors for Determination

The relation between diffusion coefficient D, and the mobility of ion  $\mu$ , described by Einstein–Smoluchowski equation (6) [17].

$$D = K_B T \mu / q \quad (6)$$

Where D: is the diffusion coefficient, ( $\text{m}^2 \cdot \text{s}^{-1}$ ),  $\mu$ : is mobility of ion, ( $\text{m}^2 \cdot \text{V}^{-1} \cdot \text{s}^{-1}$ ),  $K_B$ : is Boltzmann constant, ( $\text{J} \cdot \text{K}^{-1}$ ), T: is the absolute temperature, (K), q: is the elementary charge, (Coulomb).

Conductivity of the solution is a function of the movement rate of ions in the potential field, which, in turn, is a function to the transfer speed of individual ions, the interactions between individual ions, the concentrations of the ions, and the charges. Petr Vanysek [18] evaluated the molar conductivity at infinitive dilution,  $\Lambda^\circ$ , in aqueous solution for some important ions at 298 K, by used Debye–Hückel–Onsager relation:

$$\Lambda = \Lambda^\circ - (A + B\Lambda^\circ)\sqrt{C} \quad (7)$$

Where  $\Lambda^\circ$ : is the limiting molar conductivity, ( $\text{S} \cdot \text{m}^2 \cdot \text{mol}^{-1}$ ),  $\Lambda$ : is the molar conductivity, ( $\text{S} \cdot \text{m}^2 \cdot \text{mol}^{-1}$ ), C is the solution concentration, ( $\text{mol} \cdot \text{dm}^{-3}$ ),  $A \equiv 60.20$  and  $B \equiv 0.229$ .

He also calculated the diffusion coefficient D of these ions by equation 8, (Table 1):

$$D = R T \lambda / z F^2 \quad (8)$$

Where T is the temperature, (K), R is the gas constant, ( $\text{J} \cdot \text{K}^{-1} \cdot \text{mol}^{-1}$ ), F is Faraday constant, ( $\text{C} \cdot \text{mol}^{-1}$ ), and z is the ion charge. Atkins [19], used equation 9 to calculate the ions mobility. He concluded that ion with highly charged has a high mobility.

$$\mu = ez / 6 \pi \eta a \quad (9)$$

Where  $\mu$  is the mobility of ion, ( $\text{m}^2 \cdot \text{V}^{-1} \cdot \text{s}^{-1}$ ), ez is the moving ion charge,  $\eta$  is the solution viscosity, ( $\text{kg} \cdot \text{m}^{-1} \cdot \text{s}^{-1}$ ), a is the ion radius, (m). The results for limited molar conductivity  $\lambda^\circ$ , and mobility  $\mu$ , are shown in Table 2.

The molar conductance, the mobility (by used Equation 4) and the diffusion coefficient (by used Equation 6) of different inorganic ions are listed in Table 3 and 4.

**Table 3.** The molar conductance  $\lambda^\circ/(\times 10^{-4} \text{ S m}^2 \text{ mole}^{-1})$ , the mobility  $\mu/(\times 10^{-8} \text{ m}^2 \text{ s}^{-1} \text{ V}^{-1})$ , and the diffusion coefficient D/ $(\times 10^{-9} \text{ m}^2 \text{ s}^{-1})$  of different inorganic cations.

Ion	$\lambda^\circ$	$\mu$	D
H <sup>+</sup>	349.6	35.549	9.132
Li <sup>+</sup>	038.7	04.011	1.030
Na <sup>+</sup>	050.1	05.193	1.333
K <sup>+</sup>	073.5	07.638	1.893
Rb <sup>+</sup>	077.8	08.063	2.071
Cs <sup>+</sup>	077.2	08.001	2.055
Ag <sup>+</sup>	061.9	06.416	1.647
Be <sup>2+</sup>	090.0	04.664	1.198
Mg <sup>2+</sup>	106.0	05.493	1.411
Ca <sup>2+</sup>	119.0	06.167	1.584
Sr <sup>2+</sup>	118.9	06.162	1.582
Ba <sup>2+</sup>	127.2	06.592	1.693
Mn <sup>2+</sup>	107.0	05.545	1.424
Fe <sup>2+</sup>	108.0	05.597	1.437
Co <sup>2+</sup>	110.0	05.234	1.345
Ni <sup>2+</sup>	099.2	04.457	1.145
Cu <sup>2+</sup>	107.2	05.555	1.427
Zn <sup>2+</sup>	105.6	05.472	1.405
Cd <sup>2+</sup>	108.0	05.597	1.437
Hg <sup>2+</sup>	137.2	07.110	1.826
Pb <sup>2+</sup>	142.0	07.359	1.890
UO <sub>2</sub> <sup>2+</sup>	064.0	03.317	0.852
Ra <sup>2+</sup>	133.6	06.923	1.778
Sr <sup>2+</sup>	118.8	06.156	1.581
Al <sup>3+</sup>	183.0	06.322	1.624
La <sup>3+</sup>	209.1	07.224	1.855
Fe <sup>3+</sup>	204.0	07.048	1.810
Co <sup>3+</sup>	102.0	03.524	0.905
Cr <sup>3+</sup>	201.0	06.944	1.783

\* The values of the molar conductivity of the ions, at 298 K based on Reference, [ 5, 18 and 20] .



**Table 4.** The molar conductance  $\lambda^\circ$  ( $\times 10^{-4}$  S m<sup>2</sup> mole<sup>-1</sup>), the mobility  $\mu$  ( $\times 10^{-8}$  m<sup>2</sup> s<sup>-1</sup> V<sup>-1</sup>), and the diffusion coefficient  $D$  ( $\times 10^{-9}$  m<sup>2</sup> s<sup>-1</sup>) of different inorganic anions.

Ion	$\lambda^\circ$	$\mu$	D
OH <sup>-</sup>	199.1	20.210	5.192
F <sup>-</sup>	055.4	05.742	1.474
Cl <sup>-</sup>	076.4	07.670	1.970
Br <sup>-</sup>	078.1	08.095	2.079
I <sup>-</sup>	076.8	08.410	2.160
IO <sub>3</sub> <sup>-</sup>	040.5	04.052	1.041
IO <sub>4</sub> <sup>-</sup>	054.5	05.649	1.451
NO <sub>2</sub> <sup>-</sup>	071.8	07.193	1.848
NO <sub>3</sub> <sup>-</sup>	071.5	07.410	1.903
N <sub>3</sub> <sup>-</sup>	069.0	07.151	1.836
ClO <sub>3</sub> <sup>-</sup>	064.6	06.695	1.719
ClO <sub>4</sub> <sup>-</sup>	067.3	06.975	1.791
CN <sup>-</sup>	078.0	08.084	2.076
SCN <sup>-</sup>	066.0	06.840	1.756
IO <sub>4</sub> <sup>-</sup>	054.5	05.649	1.451
HCO <sub>3</sub> <sup>-</sup>	044.5	04.353	1.118
H <sub>2</sub> PO <sub>4</sub> <sup>-</sup>	036.0	05.700	1.464
HS <sup>-</sup>	065.0	06.737	1.730
HSO <sub>4</sub> <sup>-</sup>	050.0	05.182	1.331
HCOO <sup>-</sup>	054.6	05.659	1.453
CH <sub>3</sub> COO <sup>-</sup>	040.9	04.239	1.089
MnO <sub>4</sub> <sup>-</sup>	061.3	06.353	1.631
CO <sub>3</sub> <sup>2-</sup>	138.6	07.364	1.892
SO <sub>4</sub> <sup>2-</sup>	160.0	08.291	2.130
SO <sub>3</sub> <sup>2-</sup>	144.0	7.4623	1.916
CrO <sub>4</sub> <sup>2-</sup>	170.0	08.810	2.262
PO <sub>4</sub> <sup>3-</sup>	278.4	09.618	2.470

\* The values of the molar conductivity of the ions, at 298 K based on Ref. [ 5, 18 and 20].

The resulted data from Einstein-Smoluchowski equation (6) that detailed in Table 3 and Table 4, showed that D for inorganic ions have values between  $1-3 \times 10^{-9}$  m<sup>2</sup>.s<sup>-1</sup>, except hydroxyl and hydrogen ion ( $5.2 \times 10^{-9}$  and  $9.1 \times 10^{-9}$  m<sup>2</sup>.s<sup>-1</sup> respectively).

#### 4. Hydrodynamic Radius

The hydration of ions is great importance in physical and biological chemistry. Hydration of an ion depends on the electrostatic interaction of water molecules to ions. In this process, water molecules bind to ions by ion-dipole bonds of mainly electrostatic character.

**Table 5.** Stokes radius of some ions

Ion	Li <sup>+</sup>	Na <sup>+</sup>	K <sup>+</sup>	Cs <sup>+</sup>	F <sup>-</sup>	Cl <sup>-</sup>	Br <sup>-</sup>	I <sup>-</sup>	Mg <sup>2+</sup>	SO <sub>4</sub> <sup>2-</sup>
R <sub>Stokes</sub> [11, 12]	1.91	1.88	1.14	1.15	1.77	1.33	1.22	1.35	-	-
R <sub>Stokes</sub> [13]	-	(1.84)	-	-	-	(1.21)	-	-	(3.41)	(2.31)

Hydrodynamic radius, R of an ion is the radius of a hard sphere that diffuses at the same speed as that ion or solute in solution. L.A. Bulavin *et al.* [21], R. Heyrovská [22] and A. A. Hussain *et al.* [23] presented in Table 5, the ions Stokes radius that determined by equation 10.

$$R = KT/6\pi\eta D \quad (10)$$

Where R is the radius of ion, (m), K is Boltzmann constant, (J.K<sup>-1</sup>), T is the absolute temperature, (K),  $\pi$  is constant ratio,  $\eta$  is the dynamic viscosity, (Kg.m<sup>-1</sup>.s<sup>-1</sup>), D is the diffusion coefficient, (m<sup>2</sup>.s<sup>-1</sup>).

P.C.F. Pau *et al.* [24], calculated the Stokes radius of ions in solution depending on relation 11, and the R values listed in Table 6.

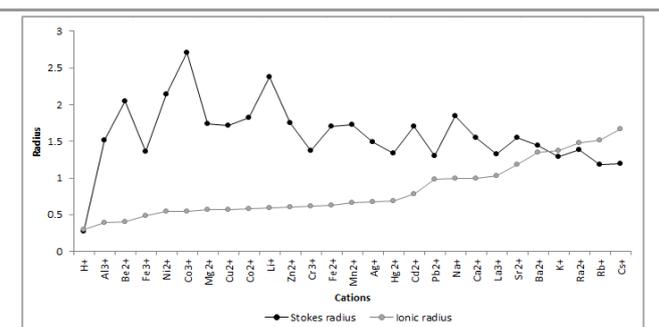
$$a_\gamma = ZeF/300\gamma\pi\eta\Lambda_o \quad (11)$$

Where  $\gamma$  is factor equal 6, Ze is the ion charge,  $\eta$  is the solvent viscosity, (kg.m<sup>-1</sup>.s<sup>-1</sup>), F is Faradays constant. As shown from Table 6, the least Stokes radius relates to an I<sup>-</sup> anion, whereas the largest one is detected for a small Li<sup>+</sup> cation.

Yan-Zhen Wei *et al.* [25], used limiting conductivity in solution to estimate the ions Stokes radius by equation 12. Results are presented in Table 7.

$$r = N_o e^2 / 6\pi\Lambda_o \eta \quad (12)$$

Where N<sub>o</sub> is Avogadro number, (mol<sup>-1</sup>), e is the electron charge, (C),  $\eta$  is the solvent viscosity, (kg.m<sup>-1</sup>.s<sup>-1</sup>),  $\Lambda_o$  is the limiting molar conductivity, (S.m<sup>2</sup>.mol<sup>-1</sup>). The ionic radius of an ion is estimated by calculating relative to another ion in an ionic bond at a crystal lattice.

**Figure 1.** Ionic and Stokes radius, ( $\times 10^{-10}$  m) of cations [26].

**Table 6.** Stokes radius of some ions.

Ion	Li <sup>+</sup>	Na <sup>+</sup>	K <sup>+</sup>	Rb <sup>+</sup>	Cs <sup>+</sup>	F <sup>-</sup>	Cl <sup>-</sup>	Br <sup>-</sup>	I <sup>-</sup>
<b>R<sub>Stokes</sub></b>	2.39	1.84	1.25	1.18	1.19	1.66	1.21	1.18	1.20

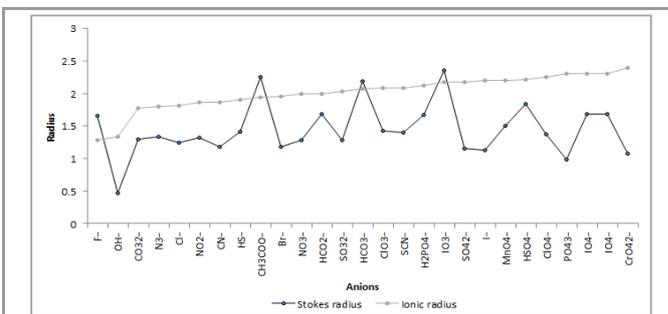
**Table 7.** The calculated hydrodynamic radius R of inorganic cations and ionic radius R ( $\times 10^{-10}$  m) reported from Reference [26].

Ion	R Calculated	R* Ionic radius
H <sup>+</sup>	0.268	0.30
Li <sup>+</sup>	2.380	0.59-0.92
Na <sup>+</sup>	1.840	0.99-1.39
K <sup>+</sup>	1.295	1.37-1.64
Rb <sup>+</sup>	1.184	1.52-1.83
Cs <sup>+</sup>	1.193	1.67-1.88
Ag <sup>+</sup>	1.489	0.67-1.28
Be <sup>2+</sup>	2.046	0.40-0.96
Mg <sup>2+</sup>	1.737	0.57-0.89
Ca <sup>2+</sup>	1.548	1.00-1.34
Sr <sup>2+</sup>	1.550	1.18-1.44
Ba <sup>2+</sup>	1.448	1.35-1.61
Mn <sup>2+</sup>	1.722	0.66-0.96
Fe <sup>2+</sup>	1.706	0.63-0.92
Co <sup>2+</sup>	1.823	0.58-0.90
Ni <sup>2+</sup>	2.141	0.55-0.69
Cu <sup>2+</sup>	1.718	0.57-0.73
Zn <sup>2+</sup>	1.745	0.60-0.90
Cd <sup>2+</sup>	1.706	0.78-1.31
Hg <sup>2+</sup>	1.343	0.69-1.14
Pb <sup>2+</sup>	1.297	0.98-1.49
Ra <sup>2+</sup>	1.379	1.48-1.70
Al <sup>3+</sup>	1.510	0.39-0.54
La <sup>3+</sup>	1.322	1.03-1.36
Fe <sup>3+</sup>	1.355	0.49-0.78
Co <sup>3+</sup>	2.709	0.55-0.61
Cr <sup>3+</sup>	1.375	0.62
Co <sup>2+</sup>	1.823	0.58-0.90

This radius is not a stable property of a known ion, but different with electron spin state, number of coordination and other factors, Shannon [26] details different values of ions radius followed to the last two factors.

The ionic radius values are used to comparative with hydrodynamic radius (Stokes radius) of numerous ions. In this review Stokes–Einstein equation (Equation 10) is used to estimate R for diffusing ions. Calculating of R based on the viscosity of water at 298 K,  $\eta = 0.891 \times 10^{-3} \text{ kg}\cdot\text{m}^{-1}\cdot\text{s}^{-1}$  [27].

The obtained data can be represented in Table 7, Table 8, Figure 1 and Figure 2 (after rearrangement relative to ionic radius).

**Figure 2.** Schematic diagram for fabrication of a MIP-based PVC membrane sensor [8,26].**Table 8.** The calculated hydrodynamic radius R of inorganic anions and ionic radius R ( $\times 10^{-10}$  m) reported from Reference [8, 26].

Ion	R Calculated	R Ionic radius	Ref.
OH <sup>-</sup>	0.472	1.33	18
F <sup>-</sup>	1.663	1.29	26
Cl <sup>-</sup>	1.245	1.81	26
Br <sup>-</sup>	1.179	1.96	26
I <sup>-</sup>	1.135	2.20	26
IO <sub>3</sub> <sup>-</sup>	2.355	2.18	18
IO <sub>4</sub> <sup>-</sup>	1.690	2.31	18
NO <sub>2</sub> <sup>-</sup>	1.327	1.87	18
NO <sub>3</sub> <sup>-</sup>	1.288	2.00	18
N <sub>3</sub> <sup>-</sup>	1.335	1.80	18
ClO <sub>3</sub> <sup>-</sup>	1.426	2.08	18
ClO <sub>4</sub> <sup>-</sup>	1.369	2.25	18
CN <sup>-</sup>	1.181	1.87	18
SCN <sup>-</sup>	1.396	2.09	18
IO <sub>4</sub> <sup>-</sup>	1.690	2.31	18
HCO <sub>3</sub> <sup>-</sup>	2.193	2.07	18
H <sub>2</sub> PO <sub>4</sub> <sup>-</sup>	1.675	2.13	18
HS <sup>-</sup>	1.417	1.91	18
HSO <sub>4</sub> <sup>-</sup>	1.842	2.21	18
HCO <sub>2</sub> <sup>-</sup>	1.687	2.00	18
CH <sub>3</sub> COO <sup>-</sup>	2.251	1.94	18
MnO <sub>4</sub> <sup>-</sup>	1.503	2.20	18
CO <sub>3</sub> <sup>2-</sup>	1.296	1.78	18
SO <sub>4</sub> <sup>2-</sup>	1.151	2.18	18
SO <sub>3</sub> <sup>2-</sup>	1.280	2.04	18
CrO <sub>4</sub> <sup>2-</sup>	1.084	2.40	18
PO <sub>4</sub> <sup>3-</sup>	0.993	2.30	18

The strength of hydrogen-bond in the water molecules may vary with different ions. Ion hydration in solutions is governed by the electrostatic interaction to



water molecules. Charge density of the ion is very effect on this interaction, so ions with small size attract more water molecules. Ion with an interior hydration sphere is six H<sub>2</sub>O molecules and the second hydration sphere is twelve water molecules. Like an arrangement M<sup>Z+</sup>(H<sub>2</sub>O)<sub>6</sub>(H<sub>2</sub>O)<sub>12</sub> found in Mg<sup>2+</sup> [28], Al<sup>3+</sup>, Zn<sup>2+</sup>, Be<sup>2+</sup> ions, while Na<sup>+</sup> and Li<sup>+</sup> ions clusters with Na<sup>+</sup>(H<sub>2</sub>O)<sub>4</sub>(H<sub>2</sub>O)<sub>9</sub>(H<sub>2</sub>O)<sub>5</sub>, Li<sup>+</sup>(H<sub>2</sub>O)<sub>4</sub>(H<sub>2</sub>O)<sub>9</sub>(H<sub>2</sub>O)<sub>5</sub> [29] arrangements. Anions form a hydration shell with water molecules by hydrogen-bonded water. Some of these ions arrangement in clusters like, SO<sub>4</sub><sup>2-</sup>(H<sub>2</sub>O)<sub>16</sub>, HSO<sub>4</sub><sup>-</sup>(H<sub>2</sub>O)<sub>16</sub> [30], PO<sub>4</sub><sup>3-</sup>(H<sub>2</sub>O)<sub>15</sub> [31]. So the big charge density of Li<sup>+</sup> (2.380), Be<sup>2+</sup> (2.380) and F<sup>-</sup> (1.663) ions appears at high hydrodynamic radius (Stokes radius) relative to alkali metal ions and halogens group, and because that the smaller ions drag a greater number of water molecules (stronger hydration) with it as it moves through the solution relative to larger ions with weaker hydration like K<sup>+</sup>, Rb<sup>+</sup>, Cs<sup>+</sup>, Ca<sup>2+</sup>, Sr<sup>2+</sup>, Ba<sup>2+</sup> and Cl<sup>-</sup>. The results (Figure 1 and 2) are closing to be less than ionic radius in some cations and most anions (Stokes radius of most anions closet to have the radius of water molecule (1.34×10<sup>-10</sup> m)) and this may be attributed to "Several phenomena occur in aqueous solutions under a potential field since ions in solution are surrounded by a sphere of oppositely charged ions and water, when a potential field is imposed on a solution, the migration of the central ion distorts the co-sphere of water and oppositely charged ions, and the co-sphere itself seeks to move in the opposite direction" [32]. The results of hydrodynamic radius R, for diffusing inorganic ions had values between 1×10<sup>-10</sup>–3×10<sup>-10</sup> m, except hydroxyl and hydrogen ion (0.47×10<sup>-10</sup> and 0.27×10<sup>-10</sup> m, respectively), with using Stokes–Einstein relation.

## 5. Conclusion

The strength of hydrogen-bond in the water molecules might vary with different ions, which governed by the electrostatic interaction to water molecules. Ions form a hydration shell with water molecules by hydrogen-bonded water. So the big charge density of Li<sup>+</sup>, Be<sup>2+</sup>, Na<sup>+</sup> and F<sup>-</sup> ions appears at high hydrodynamic radius (2.380, 2.380, 1.840 and 1.663 ×10<sup>-10</sup> m) relative to alkali metal ions and halogens group, and because that the smaller ions drag a greater number of water molecules (stronger hydration) with it as it moves through the solution relative to larger ions with weaker hydration like K<sup>+</sup>, Rb<sup>+</sup>, Cs<sup>+</sup>, Ca<sup>2+</sup>, Sr<sup>2+</sup>, Ba<sup>2+</sup> and Cl<sup>-</sup> (hydrodynamic radius 1.295, 1.184, 1.193, 1.548, 1.550, 1.448 and 1.245×10<sup>-10</sup> m respectively). The results are closing to be less than ionic radius in some cations (K<sup>+</sup>, Ra<sup>2+</sup>, Rb<sup>+</sup> and Cs<sup>+</sup>) and most anions except F<sup>-</sup>, CH<sub>3</sub>COO<sup>-</sup>, HCO<sub>3</sub><sup>-</sup> and IO<sub>3</sub><sup>-</sup> (Stokes radius of

most anions closet to have the radius of water molecule, 1.34×10<sup>-10</sup> m). The obtained results for hydrodynamic radius of inorganic charge ions had values between 1×10<sup>-10</sup>–3×10<sup>-10</sup> m, except hydroxyl and hydrogen ion (0.47×10<sup>-10</sup> and 0.27×10<sup>-10</sup> m, respectively).

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## Disclosure statement

No potential conflict of interest was reported by the authors.

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