

EFFECT OF IONIC STRENGTH AND POROSITY ON ION DIFFUSION IN AGAROSE GELS

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INTRODUCTION

Understanding ion diffusion phenomena in biological tissues is important for the study of signal transduction in tissue and cells. However, knowledge on ion diffusion in biological tissues is limited in literature [1-3]. In this paper, we report a new approach to investigating ion diffusion in non-charged porous materials using an electrical conductivity method. The objective of this study is to understand the effect of ionic strength and porosity on ion diffusion in hydrogels. Ion diffusivity is related to electrical conductivity and tissue water content or porosity [4,5]. By measuring electrical conductivity of various gel concentrations in different bathing solutions, one can determine ion diffusivity as a function of gel porosity and ionic strength. Our results show that this new method can be used for determining ion diffusivity in gels and biological tissues.

MATERIALS AND METHODS

Specimen preparation

Agarose gel specimens (low-melting temperature SeaPlaque® agarose, BioWhittaker Molecular Applications, Rockland, ME) were used in this study. The agarose powder was dissolved in 0.05M KCl or 0.1M KCl in concentrations ranging from 2% to 12%. The different mixtures were heated using a water bath at 78 °C until the powder was completely dissolved in the solution and no bubbles were present. The solutions were poured into 3 mm glass molds and were allowed to gel at room temperature (22 °C). Using a corneal trephine (d = 5 mm), cylindrical specimens (n = 6) were punched out from the gels. The volume fraction of water (ϕ^w) of the specimens was calculated using the following equation:

$$\phi^w = 1 - \frac{m_{gel} / \rho_{gel}}{V} \quad (1)$$

where m_{gel} is the mass of the agarose, ρ_{gel} is the density of agar, found in the literature to be 1.4 g/mL [6], and V is the volume of the gel.

Conductivity measurement

A conductivity apparatus developed in our lab was used to measure the resistance (R) values of the agarose gel specimens using the four-wire method [7]. The conductivity values of the gels were calculated using equation,

$$\chi_{gel} = \frac{h}{RA} \quad (2)$$

where h and A are the height and cross-sectional areas of the specimens respectively. The conductivity of the bathing solutions (χ_0) at 22.5 °C was measured to be 6.3 mS/cm for the 0.05M KCl and 12.24 mS/cm for the 0.1M KCl. All conductivity measurements were taken at room temperature (22 ±1 °C).

Theory

Potassium and chloride ion diffusion coefficients (D^\pm) are related to the specific electrical conductivity (χ_{gel}), ion concentrations (C^\pm) and volume fraction of water by the following equation [4,5]:

$$\chi_{gel} = \frac{F_c^2}{RT} \phi^w (C^+ D^+ + C^- D^-) \quad (3)$$

where F_c is the Faraday constant, R is the gas constant, and T is the absolute temperature. In this case, the positive and negative ion concentrations are the same since the agarose gels used in this study are non-charged. The diffusion coefficients can also be assumed to be the same [8]. Since $C^+ = C^- = C$ and $D^+ = D^- = D$, and taking into account the conductivity of the bathing solution, the normalized ion diffusion coefficient in gel (D/D_0) can be obtained by the following equation:

$$\frac{D}{D_0} = \frac{\chi_{gel}}{\chi_0 \phi^w} \quad (4)$$

where D_0 the ion diffusion coefficient in solution and χ_0 is the electrical conductivity of the bathing solution. The ion diffusion coefficient in gel is related to the volume fraction of gel (ϕ^s), the pore size (ξ) of gel and radius of the ion (a), given by [9, 10]:

$$\frac{D}{D_0} = e^{-\alpha \Phi^{0.5}} \quad (5)$$

where

$$\Phi = \frac{a}{\xi} \phi^s \quad (6)$$

and α is the parameter. The radii of the potassium and chloride ions were calculated using the Stokes-Einstein equation. Since the radii of the ions used in this experiment were close in magnitude (1.37×10^{-10} m for K^+ and 1.421×10^{-10} m for Cl^-), the average value of 1.40×10^{-10} m was used for a in Equation 6. Finally, the pore size of the gel (ξ) is the square root of the Darcy permeability given by [11]:

$$\xi = 0.058 \left(\frac{\phi^w}{\phi^s} \right)^{1.618} \quad (\text{nm}). \quad (7)$$

RESULTS

The normalized ion diffusivity in gel (D/D_0) is plotted versus volume fraction of water (Fig. 1). The calculated ion diffusivity was curve-fitted to the theoretical model proposed (Equations 5-7), yielding a value for α of 5.22 ± 0.21 (mean \pm SD) ($R^2=0.98$). Also included in the plot for comparison is the Mackie and Meares model which describes the diffusion of electrolytes in a resin membrane and is represented by the equation below [12]:

$$\frac{D}{D_0} = \left[\frac{1-\phi^s}{1+\phi^s} \right]^2. \quad (8)$$

DISCUSSION AND CONCLUSIONS

From the experimental results it can be inferred that varying the concentration of the bathing solution does not influence ion diffusion phenomena. However, the pore size of the gel, which decreases with decreasing water content, plays a significant role in ion diffusion. The theoretical model presented in this study and the model proposed by Mackie and Meares [12] effectively predict the behavior of ion diffusion in gels at high water concentration. Our results are similar to the findings on ion diffusion in charged gels by Lanir and coworkers [13]. Our method can be used for determining ion diffusivity in gels and tissues.

ACKNOWLEDGEMENT

This project was supported by a grant from the NIH (AR46860).

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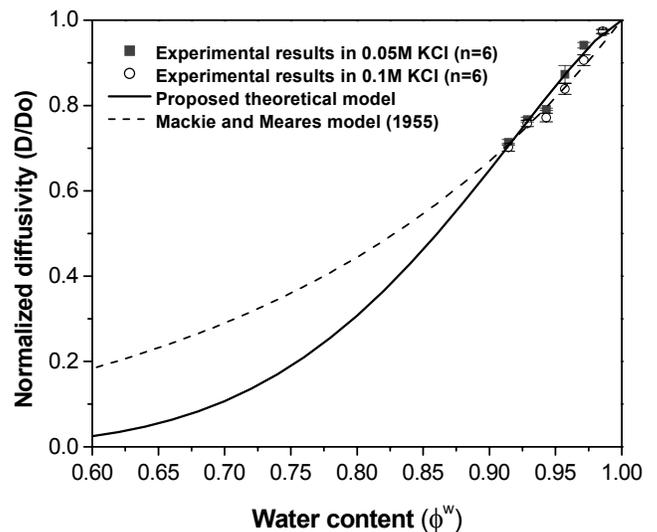


Figure 1. Experimental results with proposed theoretical model ($\alpha=5.22 \pm 0.21$ (mean \pm SD), $R^2=0.98$) and comparison with Mackie and Meares model.