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Determination of Water and Solute Transport in Polyacrylamide Gels

Jesper Brahm,[*1] Robert Lessel,[2] Sisse Ditlev,[1] Richard Schmidt[2]*

Summary: Water exchange between five polyacrylamide gels (Bulkamid®, Aquamid®, Rectamid®, HV-PAAG, Acuvue) with a physiological salt solution was determined by means of tritium-labeled water. Urea and chloride exchange was also determined in Acuvue. The method was a modified version to measure rapid transport processes in red blood cells. The study shows that water and solutes easily exchange between the hydrogel under study and the surrounding medium, independent of the solid polymer content (2.5–40 wt%) and an over ten-fold variation of the cross-linking density.

Keywords: Aquamid®; exchange; hydrogels; PAAG; water

Introduction

Several polyacrylamide gels (PAAG) are used for different biomedical purposes, such as tissue fillers, contact lenses, and urethral and rectal bulking agents. In general, the products are hydrogels consisting of a minor amount of dissolved polymeric network in water. We raised the question whether such biomacromolecules, when introduced into the body, behave as purely foreign elements in relation to the surrounding tissues. We studied the ability of the following PAAGs to exchange water with the surrounding medium: Bulkamid®, an urethral bulking agent with a solid polymer content of 2.5 wt%. Aquamid®, a tissue filler and implant with a solid polymer content of 2.5 wt%, and a cross-linking density of ~0.5 × of Bulkamid®.

Rectamid®, an investigational bulking agent with a solid polymer content of 2.5 wt%, and a cross-linking density of ~2× of Bulkamid®, HV-PAAG, an investigational bulking agent with a solid polymer content of 3.4 wt%, and a cross-linking density of ~6× of Bulkamid®. Acuvue, soft contact lenses, cross-linked poly-2-hydroxyethyl methacrylate with a solid polymer content of 40 wt%. The exchange of chloride and urea was also determined with Acuvue.

Methods and Calculations

The exchange rate of water between the PAAGs and a physiological electrolyte medium was determined by means of a modified version of the filtering method developed to determine solute exchange rates in red blood cells.[1] In short, we prepared solid polyacrylamide by gently freeze-drying a swollen polyacrylamide hydrogel of approx 0.4 ml. We hydrated the sample to the original volume with a medium with ^3H_2O and methylene blue in order to color the lump to make it visible in the efflux medium. The radioactive labeled lump was next suspended in approximately 40 ml of the well-stirred efflux medium that is a physiological electrolyte medium (150 mM NaCl, 2 mM KH_2PO_4, pH 7.2) at 25 °C. Usually five samples of the suspending medium were serially taken at determined times. The samples contained increasing amounts of the radioactive isotope under

1 Department of Cellular and Molecular Medicine, The Panum Institute, University of Copenhagen, DK-2200 Copenhagen N, Denmark
E-mail: j.brahm@dadlnet.dk
2 Chempilots A/S, Rugmarken 24-26, DK-3520 Farum, Denmark

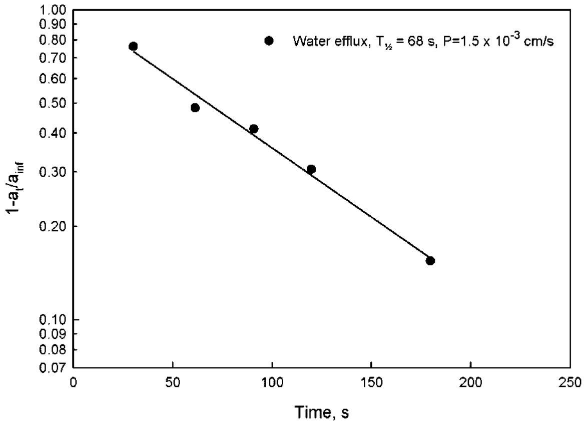

Figure 1.
The rate of ^3H_2O efflux from a Bulkamid® lump into an isotope-free medium. The ordinate expresses the fraction of tracer that remains in the gel lump at a given time.

study that disappeared from the lump (and appeared in the efflux medium) with time. For Acuvue additional experiments were carried out with $^{36}Cl^-$ and ^{14}C-urea.

We may consider the system as a closed two compartment system in which the radioactivity in the efflux medium increases with time according to:

$$\ln\left(1 - \frac{a_t^{*(o)}}{a_{\text{inf}}^{*(o)}}\right) = -k^* \times t \qquad (1)$$

where $a_t^{*(o)}$ and $a_{\text{inf}}^{*(o)}$ are respectively the isotope concentration in the efflux medium at time time t and at equilibrium (infinity). In a semilogarithmic plot that depicts Equation (1), the slope of the line is equal to the numerical value of the rate coefficient, k^*, which is related to the halftime $T_{\frac{1}{2}}$ (s) of the efflux by:

$$T_{\frac{1}{2}} = \frac{\ln 2}{k*} \qquad (2)$$

A comparison of the tracer efflux in this system with e.g. biological cell systems requires that we transform the rate coefficient into a permeability coefficient P (cm/s). P takes into account the ratio of the donor volume that is accessible to the solute (V_w, cm^3) and the surface area of the

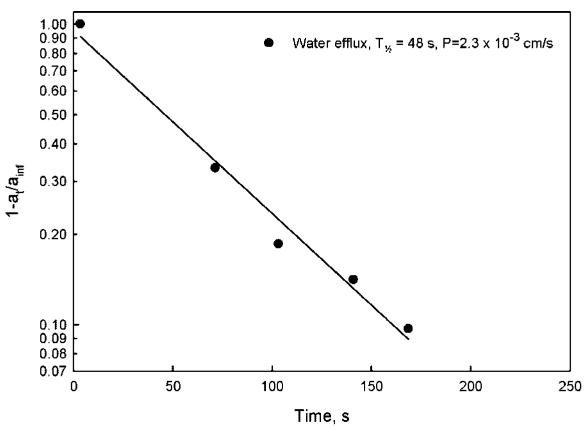

Figure 2.
The rate of ^3H_2O efflux from a Rectamid® lump into an isotope-free medium.

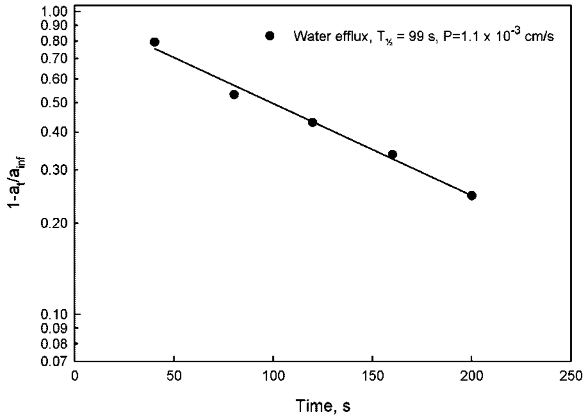

Figure 3.
The rate of ^3H_2O efflux from an Aquamid® lump into an isotope-free medium.

volume that likewise is accessible to the transport (A, cm^2):[2]

$$P = k \times \frac{V_w}{A} \tag{3}$$

Results

Figures 1–5 show the efflux of tritiated water from lumps of the hydrogels under study. Figure 5 also show the efflux of ^{14}C-labelled urea from a double labeling experiment with Acuvue. Figure 6 depicts the efflux rate of radioactive labeled chloride from Acuvue. All efflux curves show linearity in the semilogarithmic plots, and supports the suggestion that the exchange process follows first order kinetics.

We found that the water permeability of the PAAGs was $1.1–2.6 \times 10^{-3}$ cm/s (Table 1). These permeabilities are very similar to the water permeability coefficients in biological membranes, e.g. human red blood cells.[3] The preliminary results here with Aquamid® are in agreement with the results of our more detailed study of the gel.[4]

For Acuvue P_{Cl} was 1.5×10^{-3} cm/s, and P_{urea} was 1×10^{-3} cm/s that are close to values obtained in red blood cells that have special transport systems for the solutes in the membrane.[5–6]

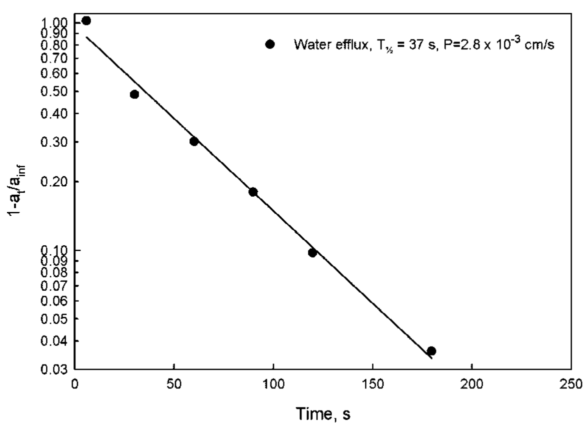

Figure 4.
The rate of ^3H_2O efflux from a HV-PAAG lump into an isotope-free medium.

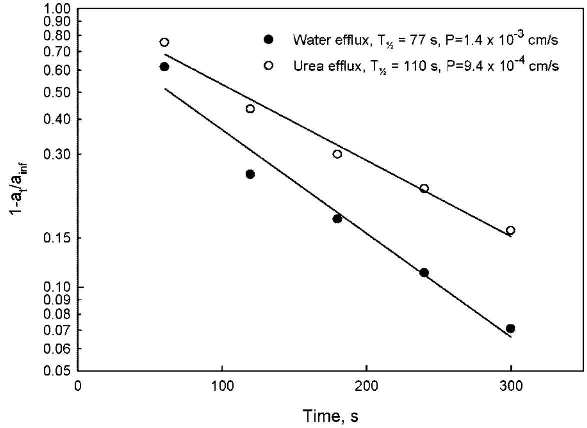

Figure 5.
The rates of ^3H_2O and ^{14}C-urea efflux from an Acuvue lump into an isotope-free medium, determined in a double labeling experiment.

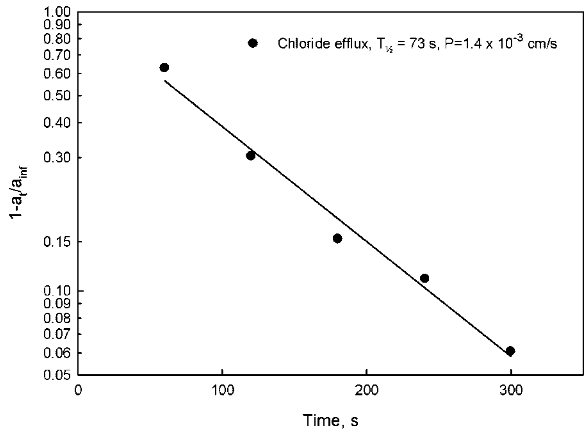

Figure 6.
The rate of $^{36}Cl^-$ efflux from an Acuvue lump into an isotope-free medium.

Table 1.
Summary of permeabilities of the hydrogels to water, and to urea and chloride (Acuvue). The values are averaged from four experiments. SD is included. The values are compared with values obtained in human red blood cells determined previously.

	P_{water} cm/s × 10^3	P_{urea} cm/s × 10^3	$P_{chloride}$ cm/s × 10^3
Bulkamid®	1.1 ± 0.4		
Rectamid®	2.6 ± 1.1		
Aquamid®	1.1 ± 0.2		
HV-PAAG	1.2 ± 0.8		
Acuvue	1.6 ± 0.4	1.1 ± 0.4	1.5 ± 0.5
Human Red blood cells	2.41[3]	0.262[6]	0.153[5]

Conclusion

Our results support the hypothesis that the PAAGs easily exchange water with the tissues. The water exchange appears not dependent on the solid polymer content, as P_{water} varies but little from Acuvue with a solid polymer content of 40 wt% to the other hydrogels with a solid polymer content of ca. 2.5 wt%. The cross-linking density of the hydrogels varies over tenfold, neither with an effect on P_{water}. The results of chloride and urea with the Acuvue further support that small ions and nonelectrolytes diffuse as easily as water between the polymer and the tissue, in accordance with the results with Aquamid®.[4]

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