Extraction and Carrier Facilitated Membrane Transport Studies of Some Biologically Important Metal Ions (Na^+ , K^+ and Ca^{2+}) using Redox Switched Ionophore

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ABSTRACT

Membrane transport study is one of the important applications of supramolecular chemistry. Supramolecular chemistry has evolved from efforts to mimic the non-covalent interactions and the phenomenon of molecular recognition in biological system. Redox switched ionophore 1-lanthraquinonyloxy pentane (P_1) has been synthesized and used as carrier for transport and extraction studies of some biologically important metal ions (Na^+ , K^+ and Ca^{2+}) through chloroform bulk liquid membrane system. The sequence of metal ions extracted in oxidised state and reduced state by ionophore was $\text{Na}^+ > \text{K}^+$ and $\text{Ca}^{2+} > \text{K}^+$ respectively. The order of metal ions transported by ionophore is found to be $\text{K}^+ > \text{Na}^+ > \text{Ca}^{2+}$ and $\text{Ca}^{2+} > \text{K}^+ > \text{Na}^+$ respectively. The extraction results reveal that ionophore is selective for Na^+ in oxidised state and for Ca^{2+} in reduced state. The carrier ability of ionophore to transport metal ions is higher for K^+ in oxidised state and for Ca^{2+} in reduced state.

INTRODUCTION

Alkali and alkaline earth metal ions (Na^+ , K^+ , Ca^{2+} and Mg^{2+}) play a vital role in biological systems as charge carrier in nerve impulse and help in maintaining membrane potential across cell membranes /1/. The liquid membrane systems have much importance as models for transport of some biologically important alkali and alkaline earth metal ions across bio-membranes and are helpful in understanding complex behaviour in biochemical transport processes. Bulk liquid membranes are often used to simulate biological membrane functions /2/. Research concerning selective transport of metal ions through liquid membrane using glymes, polyethylene glycols and non-cyclic synthetic receptors as carriers has been reported /3,4/.

Awasthy et. al have used anthraquinone-derived redox-switched ionophores for extraction and transport studies of main group metals /5/. The anthraquinone moiety has proven to be the most versatile and useful

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redox-active group in biological and chemical system /6,7,14/. Crown ether derivatives containing an anthraquinone moiety were studied for cation binding and redox coupling /7,13/.

Keeping these studies in view we have synthesized a redox-switched ionophore based on anthraquinone-derived podands as reported earlier /8/. For the first time we have used an anthraquinone moiety containing a hydrophobic side-arm for the extraction and transport studies of (Na^+ , K^+ , Ca^{2+}) across a chloroform bulk liquid membrane system. Isolation studies of the metal salt with ionophore have also been reported.

MATERIALS AND METHODS

Metal picrates and salts were prepared as reported earlier /8/. The reagents used in synthesis are 1-chloroanthraquinone, sodium hydride (Merck), pentanol (Fluka). The solvents: CHCl_3 , CH_2Cl_2 and THF (Qualigens) were used as obtained. Systronics flame photometer was used for the estimation of metal ions.

Synthesis of ionophore

A solution of pentanol (1.56 ml) in THF (10 mL) was added to vigorously stirred suspension of NaH (60% in 0.24 gm) and the mixture was refluxed for 30 minutes as shown in Scheme 1. Then a solution of 1-chloroanthraquinone (2.42 gm) in THF was added to it and this mixture refluxed at 80°C for 10 h with stirring. The reaction was carried out under N_2 atmosphere. The reaction mixture was concentrated and the residue was mixed with CH_2Cl_2 and then washed with water and then with brine. The organic phase was separated and dried over (MgSO_4), filtered and concentrated. Column chromatography (silica gel, 2% $\text{MeOH}/\text{CH}_2\text{Cl}_2$) was followed by recrystallization with CH_2Cl_2 / hexane / ethanol and characterized by m.p., TLC, IR spectral analysis.

m. p : 138°C , Yield: 3.76 gm (75.6 %).

IR (KBr)(v cm^{-1}) : 2924 ($\text{CH}_3\text{-CH}_2\text{-}$), 1680 (-C=O), 1272 ($\text{Ar-O-CH}_2\text{-}$), 854 (Ar-H).

Scheme 1

Extraction Studies:

In the extraction studies /8/, 10mL of 1.0×10^{-3} M aqueous solutions of metal salts (Na^+ , K^+ and Ca^{2+}) and 10 mL of 1.0×10^{-3} M of ionophore (P_1) in chloroform were vigorously stirred in a 50 mL beaker for 4 h

on a magnetic stirrer. The amount of metal ion in the aqueous phase was initially determined. After 4 h, the depleted aqueous phase was estimated using flame photometry.

Transport Studies:

Transport studies were performed in a "U" tube glass cell also known as "Pressman cell" at room temperature /9/. The of ionophore (P_1), 1.0×10^{-3} M in 15 mL of chloroform, was placed in the bottom of the "U" tube, serving as the membrane. The aqueous solution, 10 mL of 1.0×10^{-3} M of metal salt, was placed in one limb of the "U" tube serving as the source phase, and 10 mL of double-distilled water, placed in the other limb of the U- tube, served as the receiving phase. The membrane phase was constantly stirred using a magnetic stirrer for 24 h. The samples were withdrawn from both phases and analyzed for the amount of metal ions transported.

RESULTS AND DISCUSSION

Blank experiments of extraction and transport studies for each metal salt, in which the membrane was devoid of carrier, were performed. No leakage of cation from source phase into organic phase was observed. All measurements were performed in duplicate to check reproducibility.

In order to find out the optimum concentration of metal ion for transport and extraction studies, we have varied the concentration of metal ions from 1.0×10^{-1} M to 1.0×10^{-3} M, keeping the concentration of ionophore constant (1.0×10^{-3} M) in both oxidised and reduced states. For optimization of the ionophore, its concentration was varied from 1.0×10^{-1} M to 1.0×10^{-3} M, keeping the concentration of metal ions constant (1.0×10^{-3} M). The optimised concentration for metal ions and ionophore was reported as 1.0×10^{-3} M respectively.

As is evident from **Table 1**, the sequence of metal ion extracted with ionophore (P_1) in oxidised and reduced states was $\text{Na}^+ > \text{K}^+$ and $\text{Ca}^{2+} > \text{K}^+$ respectively. The ionophore has been found selective towards Na^+ and Ca^{2+} . The selectivity ratio for $\text{Na}^+ : \text{K}^+$ is 2.31:1 and for $\text{Ca}^{2+} : \text{K}^+$ is found to be 12.5: 1 respectively. This selectivity is due to the small size with high charge density of Na^+ , which is responsible for its self encapsulation and formation of stable complex /10,11/. The IR frequency of the ionophore (P_1) in **Table 2**, shows peaks at $2924\text{--}2850 \text{ cm}^{-1}$ ($\text{CH}_3\text{--CH}_2\text{--}$), $1680\text{--}1600 \text{ cm}^{-1}$ (--C=O) and $1272\text{--}1200 \text{ cm}^{-1}$ (Ar--O--CH_2). **Table 3**, shows a comparative study of IR frequency of ionophore and its metal complexes, which reveals a shift for the quinonyl carbonyl and the side arm at 1680 cm^{-1} (--C=O) to 1674 cm^{-1} , 1676 cm^{-1} , 2910 cm^{-1} and 2915 cm^{-1} for NaOnp and KDnp respectively. The data of isolated complexes shows the participation of the donor oxygen sites of quinonyl carbonyl, and the side arm of the ionophore during complexation enhances metal binding property /10,12/. The extent of shifting of IR frequency in NaOnp ionophore complex is greater as compared to KDnp ionophore complex, indicating greater extent of interaction of ionophore with NaOnp.

Table 1

Amount of metal cations extracted with redox-switched ionophore (P_1) in chloroform
into organic phase after 4 h

Metal salt concentration = 1.0×10^{-3} M

Ionophore concentration = 1.0×10^{-3} M in (15mL) chloroform.

S. No.	Metal salt	Oxidized form (ppm)	Reduced form (ppm)	Selectivity ratio	
				Oxidized form	Reduced form
1	CaDnp	-	-	-	-
2	CaOnp	1.3	5.0	-	12.5:1**
3	KDnp	2.6	-	-	-
4	KOnp	1.3	-	-	-
5	KPic	-	0.4	-	-
6	NaDnp	6.0	-	2.31:1*	-
7	NaOnp	1.0	-	-	-

* $\text{Na}^+ : \text{K}^+$

** $\text{Ca}^{2+} : \text{K}^+$

Table 2

IR spectroscopic data of ionophore (P_1) and its complexes

Complexes	Characteristic IR Frequencies of ionophore($\nu \text{ cm}^{-1}$)	Characteristic IR Frequencies of complexes ($\nu \text{ cm}^{-1}$)
NaOnP	2924 ($\text{CH}_3\text{-CH}_2\text{-}$) 1680 (-C=O) 1272 (Ar-O-CH_2)	2910 ($\text{CH}_3\text{-CH}_2\text{-}$) 1674 (-C=O) 1266 (Ar-O-CH_2)
KDnp	2924 ($\text{CH}_3\text{-CH}_2\text{-}$) 1680 (-C=O) 1272 (Ar-O-CH_2)	2915 ($\text{CH}_3\text{-CH}_2\text{-}$) 1676 (-C=O) 1269 (Ar-O-CH_2)

Table 3Properties of isolated complexes of metal salt with redox switched ionophore (P_1).

Metal salt	Solvent	m. p. ($^{\circ}\text{C}$)	Stoichiometry
NaOnp	Methanol	232	2:1
KDnp	Benzene	228	1:1

Table 4Amount of metal cations transported with redox switched ionophore (P_1) in chloroform into aqueous phase after 24 hMetal salt concentration = 1.0×10^{-3} MIonophore concentration = 1.0×10^{-3} M in (15mL) chloroform.

S. No.	Metal salt	Oxidized form (ppm)	Reduced form (ppm)	Selectivity ratio	
				Oxidized form	Reduced form
1	CaDnp	0.1	20.0	-	7.4:1**
2	CaOnp	-	15.8	-	-
3	KDnp	-	2.7	-	-
4	KOnp	1.2	0.4	1.2:1*	-
5	KPic	1.0	0.2	-	-
6	NaDnp	-	-	-	-
8	NaOnp	1.0	-	-	-

* $\text{K}^+ : \text{Na}^+$ ** $\text{Ca}^{2+} : \text{K}^+$

The results of transport studies are tabulated in Table 4. The trend of metal ion transported with ionophore (P_1) in oxidised and reduced state is found to be $\text{K}^+ > \text{Na}^+ > \text{Ca}^{2+}$ and $\text{Ca}^{2+} > \text{K}^+ > \text{Na}^+$ respectively. It is observed that the ionophore is selective for K^+ and for Ca^{2+} . The selectivity ratio for $\text{K}^+ : \text{Na}^+$ is 1.2: 1 and for $\text{Ca}^{2+} : \text{K}^+$ is found to be 7.4: 1 respectively. The hydrophobic side-arm of the ionophore (P_1) permits easy passage of metal-ionophore complex from the organic phase to the aqueous receiving phase and results in the effective release of metal ions to the receiving phase. The anthraquinone-derived ionophores containing simple glymes, glycols, single-and double-armed podands are found to possess more extraction ability in comparison to ionophores containing a hydrophobic side arm /10,12,14/. In contrast, ionophore (P_1) possesses better transportability, due to increased hydrophobicity of the side-arm. The side-arm with no donor sites is responsible for less extraction. The possibility of intramolecular hydrogen bonding between hydroxy-quinone hydrogen of the anthraquinone and oxygen of the side-arm is higher in reduced state, which enhances its selectivity.

CONCLUSION

From the above discussion, it can be concluded that the ionophore (P_1) shows good transport efficiency for Ca^{2+} and behaves as a selective extractant for Na^+ . This work emphasizes the ability of the synthesized ionophore to recognize biologically important metal ions, and acts as better carrier in chloroform bulk liquid membrane system. This work paves the way for the designing of ionophores having a side-arm without donor sites, with variable chain lengths and highly hydrophobic, to facilitate transport across organic membranes. This ionophore can be used in situ in oxidized and reduced forms and represents a biomodel for explaining the mechanism of counter-ion transport of Na^+ in oxidised and Ca^{2+} in reduced states across membranes.

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