

A Highly Selective and Sensitive Calcium(II)-Selective PVC Membrane Based on Dimethyl 1-(4-Nitrobenzoyl)-8-oxo-2,8-dihydro-1H-pyrazolo[5,1-a]isoindole-2,3-dicarboxylate as a Novel Ionophore

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Dimethyl 1-(4-nitrobenzoyl)-8-oxo-2,8-dihydro-1H-pyrazolo[5,1-a]isoindole-2,3-dicarboxylate has been used as an ionophore and *o*-nitrophenyloctyl ether as a plasticizer in order to develop a poly(vinyl chloride)-based membrane electrode for calcium ion detection. The sensors exhibit significantly enhanced response towards calcium(II) ions over the concentration range 8.0×10^{-7} – 1.0×10^{-1} M at pH 3.0–11 with a lower detection limit of 5.0×10^{-7} M. The sensors display Nernstian slope of 29.5 ± 0.5 mV per decade for Ca(II) ions. Effects of plasticizers, lipophilic salts and various foreign common ions are tested. It has a fast response time within 10 s over the entire concentration range and can be used for at least 2 months without any divergence in potentials. The proposed electrode revealed good selectivity and response for Ca^{2+} over a wide variety of other metal ions. The selectivity of the sensor is comparable with those reported for other such electrodes. The proposed sensor was successfully applied as an indicator electrode for the potentiometric titration of a Ca(II) solution, with EDTA.

Key Words: Calcium sensor, PVC membrane, Potentiometry, Dimethyl 1-(4-nitrobenzoyl)-8-oxo-2,8-dihydro-1H-pyrazolo[5,1-a]isoindole-2,3-dicarboxylate

Introduction

During the last decade, there has been a renewed resurgence in developing potentiometric membrane electrodes as devices for rapid, accurate, low cost and nondestructive analysis of different samples with small volume samples. Ion-selective sensors based on plasticized PVC membranes were successfully applied to the determination of many cations in various industrial, environmental and biochemical samples.^{1–3} Due to the urgent need for selective potentiometric determination of minute amounts calcium ion, in biological, environmental and industrial samples, many compounds have been employed as an ionophore in the construction of ISEs calcium ion.^{4–17} Most of these reported Ca(II) sensors have one, two, or in some cases all following problems: 1) relatively high detection limit, 2) narrow working concentration range, 3) serious interfering from Na^+ , K^+ , Sr^{2+} , Ba^{2+} , ... ions.

In this work, we wish to introduce a highly calcium(II)-selective sensor based on Dimethyl 1-(4-nitrobenzoyl)-8-oxo-2,8-dihydro-1H-pyrazolo[5,1-a]isoindole-2,3-dicar-

boxylate (DNOD), as a novel ionophore for the potentiometric determination of Ca(II) ion over a wide concentration range (Fig. 1).

Experimental Section

Reagents. Reagent grade 2-nitrophenyloctyl ether (NPOE), dibutyl phthalate (DBP), acetophenone (AP), sodium tetraphenyl borate (NaTPB), tetrahydrofuran (THF) and high relative molecular weight PVC were purchased from Merck and Aldrich, used as received. Ligand Dimethyl 1-(4-nitrobenzoyl)-8-oxo-2,8-dihydro-1H-pyrazolo[5,1-a]isoindole-2,3-dicarboxylate (DNOD) was synthesized and purified as described elsewhere.¹⁸ The nitrate and chloride salts of all cations used (all from Merck and Aldrich) were of the highest purity available and used without any further purification except for vacuum drying over P_2O_5 . Triply distilled de-ionized water was used throughout.

Emf measurements. The emf measurements with the polymeric membrane electrodes were carried out with the following cell assembly:

$\text{Ag-AgCl}|\text{internal solution, } 1.0 \times 10^{-3} \text{ M CaCl}_2|\text{PVC membrane}|\text{test solution}|\text{Hg-Hg}_2\text{Cl}_2, \text{KCl (saturated)}$

A Corning ion analyzer 250 pH/mV meter was used for the potential measurements at 25.0 ± 0.1 °C. Activities were calculated according to the Debye–Huckel procedure.¹⁹

Electrode preparation. The general procedure to prepare the PVC membrane was to mix thoroughly 32 mg of powdered PVC, 62 mg of plasticizer NPOE, 2 mg of additive NaTPB, and 4 mg of ionophore DNOD in 4 mL of

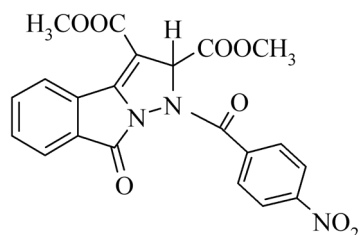


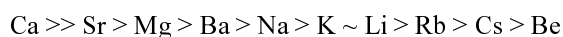
Figure 1. Structure of DNOD.

fresh THF. The resulting mixture was transferred into a glass dish of 2 cm diameter. The solvent was evaporated slowly until an oily concentrated mixture was obtained. A Pyrex tube (3-5 mm o.d.) was dipped into the mixture for about 5 s, so that a transparent membrane of about 0.3 mm thickness was formed. The tube was then pulled out from the mixture and kept at the room temperature for about 24 h. The tube was then filled with internal filling solution (1.0×10^{-3} M of CaCl_2). The electrode was finally conditioned by soaking in a 1.0×10^{-2} M CaCl_2 solution for 24 h.²⁰⁻²⁹ A silver/silver chloride wire was used as an internal reference electrode.

Results and Discussion

The existence of donating nitrogen and oxygen atoms in the structure of the ionophore, enables DNOD to act as a suitable ion carrier for some special alkali and alkaline earth metal ions, which can be used in PVC membranes.⁸⁻¹⁵

In preliminary experiments the ability of the DNOD for the formation of the relatively strong complex of Ca-DNOD rather than other alkali and alkaline earth cations was evaluated by conductometric technique in acetonitrile solution at 25 °C.^{30,31} The results showed that the following sequences for the stability of the resulted 1:1 complexes;



In next experiments to get a view about the tendency of DNOD toward chromium and some other metal ions, ab-initio quantum-mechanical calculations were carried out. The binding energy (E) was calculated with the enlarged basis sets using equation (1)

$$\Delta E(\text{A-B}) = E_{\text{complex}} - (E_{\text{Ligand}} - E_{\text{Cation}}) \quad (1)$$

The calculations were performed according to the second-order Møller-Plesset (MP2) perturbation theory,^{32,33} which takes into account, the electron correlation energy in addition to the Hartree-Fock (HF) energy. The use of such calculations is fully justified by the fact that the description of base stacking requires calculations with explicit inclusion of the electron correlation.³⁴ The interaction energy, at a given order of the Møller-Plesset (MP) perturbation expansion, is calculated as:

$$\Delta E_{MPn} = \Delta E_{HF} - \sum_{i=2}^n \Delta E_{Corr}(MPi) \quad (2)$$

Where ΔE_{HF} is the HF energy and $\Delta E_{Corr}(MPi)$ is the i^{th} order perturbative correction to the correlation energy. During our calculations, only the valence electrons were explicitly correlated, which correspond to the usual frozen core approximation. We also limited the perturbation

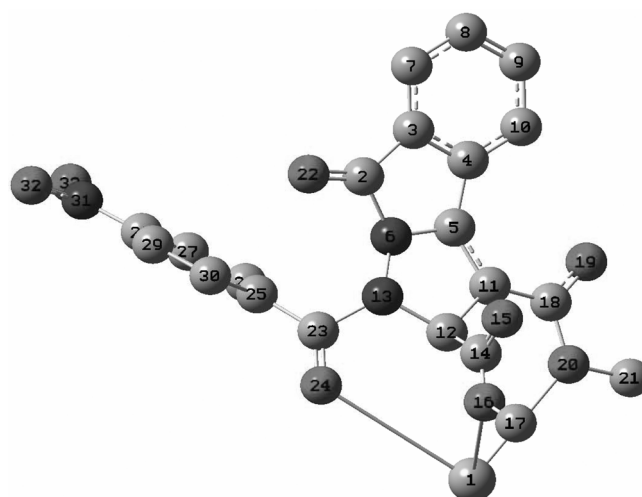


Figure 2. Optimal conformation of ligand after complexation with Ca^{2+} .

expansion (2) to the second order, which is expected to take into account the major contributions to the van der Waals energies (electrostatic, polarization, dispersion, electron transfer and exchange contributions).³⁵ The lan12mb basis-set was used for all atoms to optimize molecules. All the calculations were performed using the Gaussian 98 package.³⁶

Interaction energies for ionophore and some metal ions were calculated from equation

(1) and showed that the calculated interaction energies decreased in the order: of $\text{Ca} \gg \text{Sr} > \text{Mg} > \text{Ba} > \text{Na} > \text{K}' \sim \text{Li} > \text{Rb} > \text{Cs} > \text{Be}$. Thus, based on the above ab-initio calculation results, the ligand could be used as a suitable ionophore in the preparation of a chromium ion-selective membrane electrode.

The optimized structures Ca^{2+} complexes are shown in Figure 2 and some of their selected geometric parameters are summarized in Table 1 and 2. As it is seen from Figure 2, only three donating atoms of the ligand molecule will be in suitable proximity of the central metal ion for proper binding interactions. Of course, the contribution of a change in solvation – desolvation energies of the metal ions, in both

Table 2. Some of the optimized selected geometric parameters^b

	Atomic Charge (O) 16	Atomic Charge (O) 20	Atomic Charge (O) 24	Atomic Charge (N) 6	Atomic Charge (N) 13
Ligand Free	-0.716	-0.736	-0.518	-0.669	-0.507
Complex with Ca^{2+}	0.248	-0.266	-0.280	-0.058	-0.007

^aangles in degrees

Table 1. Selective geometric parameters for free ligand and its Ca^{2+} -complex^a

	< 13-23-24	< 14-16-17	< 18-20-21	16-Ca	20-Ca	24-Ca
Ligand Free	119.165	116.684	116.339	–	–	–
Complex with Ca^{2+}	113.231	127.797	128.563	2.652	2.648	2.547

^aDistances in Å, angles in degrees.

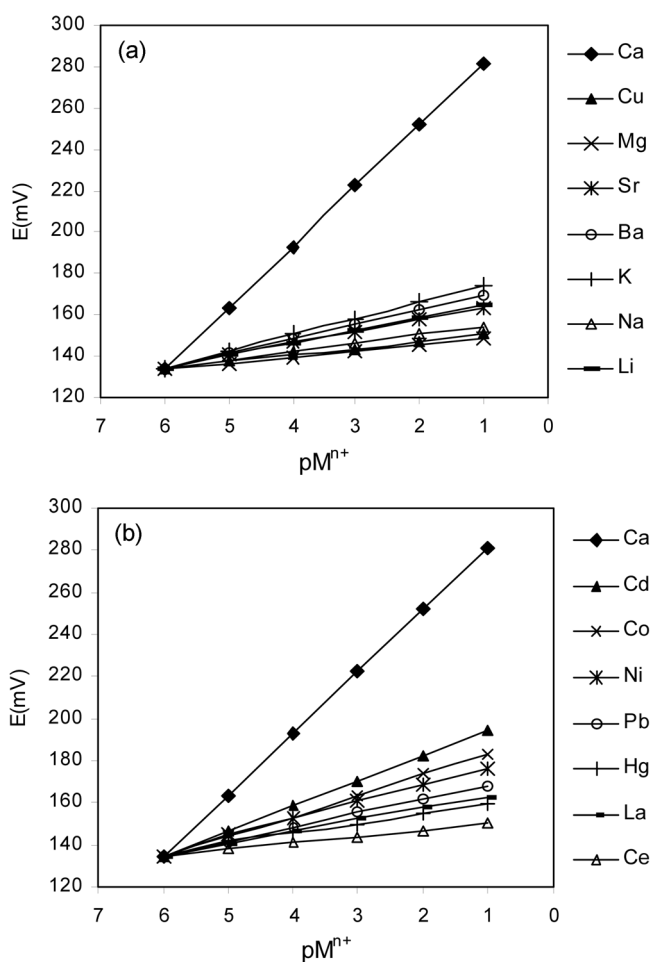


Figure 3. Potential responses of various ion-selective electrodes based on DNOD.

aqueous and membrane phases on the stability order of the different metal ions complexes with ligand cannot be ignored. The obtained results revealed that among the different alkaline and earth alkaline ions, Ca^{2+} possesses the energy changes for the ligand.

Thus, at first, DNOD was used as a neutral carrier to prepare PVC-based membrane electrodes for Calcium a variety of alkali, alkaline earth, transition and heavy metal

ions, including sodium, lithium, potassium, strontium, magnesium, barium, copper, nickel, cobalt, cadmium, lead, mercury, lanthanum, and cerium. The potential responses of the most sensitive ion-selective membrane electrodes based on DNOD are shown in Figure 3a and Figure 3b. As it is seen, among the different cations tested, Ca^{2+} with the most sensitive response seems to be suitably determined with the PVC membrane based on DNOD. This is most probably due to both, the selective behavior of the ionophore against calcium ion in comparison to other metal ions, and the rapid exchange kinetics of the resulting DNOD- Ca^{2+} complex.

Some important features of the PVC membranes, such as the properties of the plasticizer, the plasticizer/PVC ratio, the nature and amount of ionophore, and especially, the nature and amount of the additives used, are reported to significantly influence the sensitivity and selectivity of the ion-selective electrodes.³⁷⁻⁴⁰ Thus, different aspects of the preparation of a Ca^{2+} -selective membrane based on DNOD were optimized and the results are given in Table 3. Since the nature of plasticizer influences the dielectric constant of the membrane phase, the mobility of the ionophore molecules, and the state of ligand,^{19-21,37-40} it was expected to play a key role in determining the selectivity, working concentration range, and response time of the membrane electrode. Among the three different solvent mediators was tested, we found that, in construction of the calcium membrane sensor, NPOE acts superior with respect to DBP and AP. The data in Table 3 revealed that the membrane prepared with a plasticizer/PVC ratio about 2.0 was suitable, and displayed the best performance. As can be seen from Table 3, the optimum amount of ionophore (DNOD) was 4% (No. 7).

The presence of lipophilic, negatively charged additives in the PVC-base membrane sensors, improves the potentiometric behavior of certain cation-selective sensors by reducing their ohmic resistance, and improving the response behavior and selectivity, and in some cases, by catalyzing the exchange kinetics at the sample-membrane interface.⁴¹⁻⁴³

The data given in Table 3 revealed that, the presence of 2% sodium tetraphenyl borate as a suitable lipophilic additive considerably improves the sensitivity of the calcium sensor (No. 7 with a slope of 29.5 mV per decade). However, the membrane 7 with a PVC: NPOE: DNOD: NaTPB

Table 3. Optimization of membrane ingredients

No.	Composition (wt.%)				Linear range (M)	Slope (mV/decade)
	PVC	Plasticizer	Ligand	NaTPB		
2	32	NPOE,66	2	0	$1.0 \times 10^{-1} - 5.0 \times 10^{-3}$	6.7 ± 0.3
3	32	NPOE,65	3	0	$1.0 \times 10^{-1} - 1.0 \times 10^{-4}$	12.9 ± 0.6
4	32	NPOE,64	4	0	$1.0 \times 10^{-1} - 1.0 \times 10^{-4}$	16.7 ± 0.5
5	32	NPOE,63	5	0	$1.0 \times 10^{-1} - 1.0 \times 10^{-4}$	14.8 ± 0.4
6	32	NPOE,63	4	1	$1.0 \times 10^{-1} - 3.0 \times 10^{-5}$	23.3 ± 0.3
7	32	NPOE,62	4	2	$1.0 \times 10^{-1} - 8.0 \times 10^{-7}$	29.5 ± 0.5
8	32	NPOE,61	4	3	$1.0 \times 10^{-1} - 1.0 \times 10^{-6}$	28.1 ± 0.2
9	32	AP,62	4	2	$6.0 \times 10^{-1} - 1.0 \times 10^{-6}$	22.6 ± 0.7
10	32	DBP,62	4	2	$9.0 \times 10^{-1} - 8.0 \times 10^{-5}$	17.4 ± 0.6

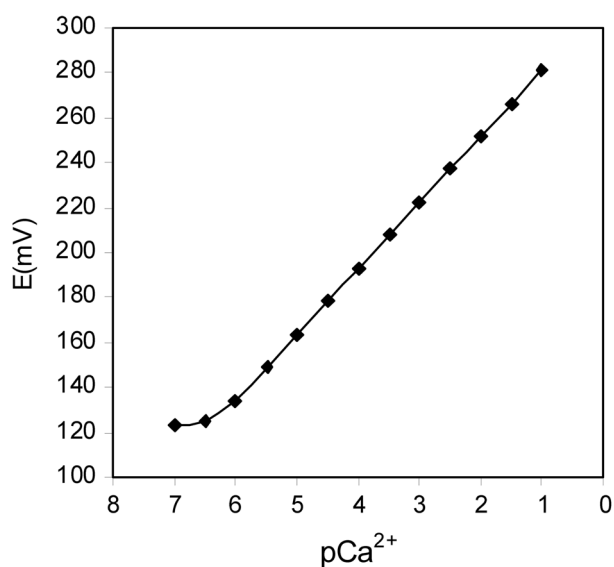


Figure 4. Calibration curve of the calcium electrode based on DNOD.

percent ratio of 32 : 62 : 4 : 2 showed a Nernstian behavior over a wide concentration range (8.0×10^{-7} to 1.0×10^{-1} M). The concentration of the internal solution (CaCl_2) of the membrane electrode was changed from 1.0×10^{-3} to 1.0×10^{-5} M and the potential response of the calcium ion-selective electrode was measured respectively. It was found that the variation of the concentration of the internal solution does not cause any significant differences in the potential response of the electrode, except for an expected change in the intercept of the resulting Nernstian plots. A 1.0×10^{-3} M concentration of the reference CaCl_2 solution is quite appropriate for the smooth functioning of the electrode system.

The optimum equilibrium time for the membrane electrode, in the presence of 1.0×10^{-2} M CaCl_2 , was 12 h, after which it would generate stable potentials in contact with calcium solutions. The electrode shows a linear response to the activity of CaCl_2 ions in the range of 8.0×10^{-7} to 1.0×10^{-1} M (Fig. 4). The slope of the calibration graph was 29.5 ± 0.5 mV per decade. The limit of detection, as determined from the intersection of the two extrapolated segments of the calibration graph, was 5.0×10^{-7} M.

The pH response profile for the electrode was tested by use of a 1.0×10^{-3} M CaCl_2 solution over the pH range 1.0 - 13.0. The pH was adjusted by introducing small drops of hydrochloric acid (0.1 M) or sodium hydroxide (0.1 M) into the test solution. The influence of the pH response on the PVC membrane electrode is shown in Figure 5. As it is seen, the potential remained constant from pH 3.0 to 11.0, beyond which some drifts in the potentials were observed. The observed drift at higher pH values could be due to the formation of some hydroxy complexes of Ca^{2+} in the solution. At the lower pH values, the potentials increased, indicating that the membrane sensor responded to hydronium ions, as a result of the some extent protonation of nitrogen atoms of the ionophore.

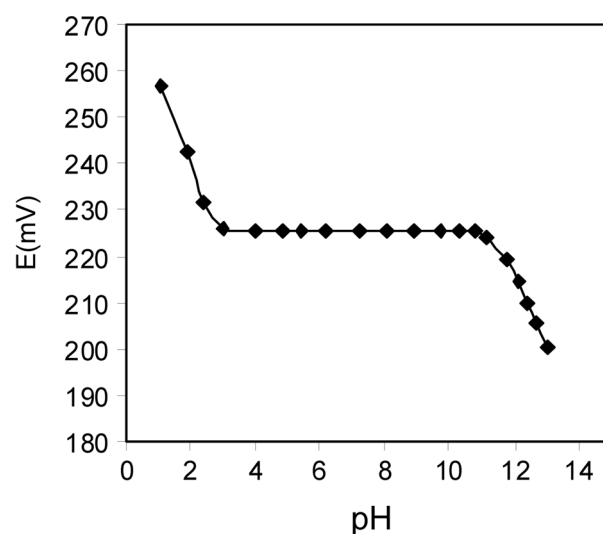


Figure 5. The effect of the pH of the test solution on the potential response of the calcium sensor.

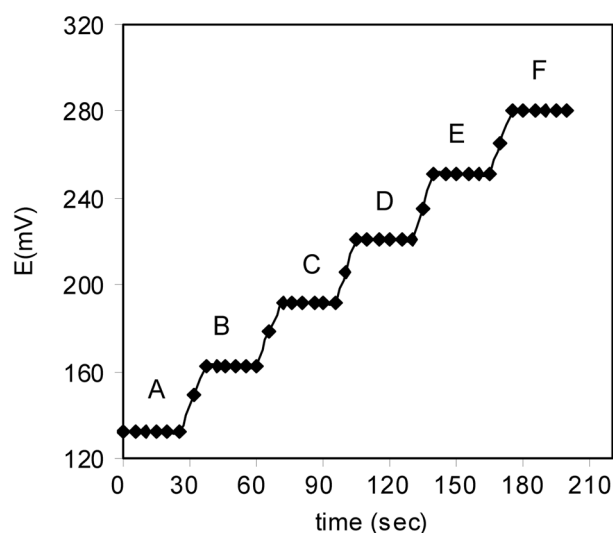


Figure 6. Dynamic response time of the calcium electrode for step changes in the concentration of Ca^{2+} : A) 1.0×10^{-6} M, B) 1.0×10^{-5} M, C) 1.0×10^{-4} M, D) 1.0×10^{-3} M, E) 1.0×10^{-2} M, F) 1.0×10^{-1} M.

Dynamic response time is an important factor, for the evaluation any sensor. In this study, the practical response time was recorded by changing solutions with different calcium concentrations. The measurement sequence was from the lower (1.0×10^{-6} M) to the higher (1.0×10^{-1} M) concentration. The actual potential versus time traces is shown in Figure 6. As it is seen, the electrode reaches its equilibrium response in a short time of about 10 s.

For evaluation of stability and lifetime of the proposed membrane sensor, four same electrodes were chosen and tested over a period of 10 weeks. During this period, the electrodes were used over extended period of time (one hour per day and after using, the electrodes were washed with distilled water, dried and stored). The electrodes were

the best response characteristics with Nernstian behavior over a wide concentration range of 8.0×10^{-7} - 1.0×10^{-1} M Ca^{2+} and a fast response time of 10 s. The sensor works well in a pH range of 3.0-11.0. Consequently, the proposed sensor is superior to the previous reported Ca^{2+} sensors in term of selectivity coefficient.

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