

## Proton NMR Determination of $Mg^{2+}$ and $Ca^{2+}$ Concentrations Using Tetrasodium EDTA Complexes

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### Abstract

The quantitative determination of metal ion concentration was previously achieved using disodium EDTA and proton NMR spectroscopy. One drawback using disodium EDTA arose from the determination of group II A metal ions. It was not feasible to distinguish between the chemical shifts of the free EDTA and complexed EDTA. It was found that by using a stronger chelator, tetrasodium EDTA, the chemical shift separation of the free EDTA and the  $Mg^{2+}$  and  $Ca^{2+}$  EDTA complexes in the proton NMR spectra was readily achieved, which facilitates the determination of these metal ions by proton NMR spectroscopy.

**Keywords:** Concentrations of  $Mg^{2+}$  and  $Ca^{2+}$ ; Proton NMR; Tetrasodium EDTA.

### Introduction

Many metal cations can bind to chelates to form stable one-to-one complexes. Depending on the number of dentates present in a chelate, usually more stability is achieved with more metal-oxygen and metal-nitrogen bonds in its corresponding coordination complex. Some common chelates include NTA (nitrilotriacetic acid), EDTA (ethylenediamine tetraacetic acid), *trans*-CDTA (*trans*-1,2-diaminocyclohexane-N, N, N',N'-tetraacetic acid), EGTA (ethylenebis-(oxyethylenenitrilo)-tetraacetic acid) and HEDTA (N-(2-hydroxyethyl)ethylenediamine triacetic acid). Under favorable conditions, a metal commonly forms a 6-coordinate complex, but 5, 7 and 8 coordinate complexes are also possible. More noticeably, solvent water molecules can also coordinate with a metal ion in the complex.<sup>(1-3)</sup> EDTA is quite commonly used in analytical chemistry because it is the popular titrant to determine

metal ion concentrations. EDTA has six key  $pK_a$  values:  $pK_{a1}=0$ ,  $pK_{a2}=1.2$ ,  $pK_{a3}=2$ ,  $pK_{a4}=2.66$ ,  $pK_{a5}=6.12$ , and  $pK_{a6}=10.28$ .<sup>(4-5)</sup> In complexometric titrations with EDTA, two common metal cations frequently encountered are magnesium and calcium cations. In hard water, for example, both magnesium and calcium are most commonly analyzed.<sup>(6)</sup> Using EDTA titration for this type of analysis, one needs to have an appropriate indicator, such as Eriochrome Black T, along with an appropriate pH buffer. For both magnesium and calcium, the right buffer has a pH=10. The endpoint is determined by observation of the indicator's color change. Because the color change for calcium's titration is insensitive, determination of the calcium ion concentration is accomplished by the so called 'Back Titration' method after adding extra magnesium ions at the beginning. It is known that human error in detecting the color change is the most common source of error as encountered in any analytical teaching lab. To tackle this inconvenience, we have introduced an NMR spectroscopic method in our previous study to determine the concentrations of various metal cations.<sup>(7)</sup>

In our method, proton NMR spectral area integration of disodium EDTA complexes was performed.<sup>(7)</sup> The NMR spectra showed clear distinction between the free EDTA and the EDTA in the complexes.

This method introduces no error due to the color sensitivity of human's naked eyes and does not rely on indicators and their required buffer solutions. This method was effective for group IIB, IIIA, IIIB, IVA metal cations, but not feasible for group IIA metal cations. The problem arises from the indistinguishable NMR spectra of the free EDTA and the EDTA complexes due to the fast intra and inter molecular exchanges. In search for a solution, a stronger chelator, such as tetrasodium EDTA, was found to be feasible. Spectral distinction was achieved due to the stronger chelating ability of the tetrasodium EDTA.

## Theory

A standardized EDTA solution is used in this method.<sup>(7)</sup> The volume of the EDTA solution is fixed, and different volumes of a fixed concentration of a metal ion solution are added to the standardized EDTA solution. Then, proton NMR spectrum is measured for each of the mixtures. Because the NMR peaks from the remaining free EDTA and the EDTA metal complex can be distinguished, we are able to use spectral area integration to find the ratio of the two components. Using this ratio, just a single mixture of the metal solution with the tetrasodium EDTA is able to determine the metal concentration, or the average value of more points can be used for a higher accuracy. However, using the following linear plotting method is better preferred. If the molarity of the standardized EDTA solution is denoted by  $M_{EDTA}$ , its volume by  $V_{EDTA}$  and the volume of the metal solution by  $V_M$ , then in an equilibrium condition, it is found that:

$$\frac{A_{EDTA}}{A_{MEDTA}} = \left( \frac{1}{M_M} \right) \frac{V_{EDTA} M_{EDTA}}{V_M} - 1 \quad (1)$$

where  $A_{EDTA}$  and  $A_{MEDTA}$  represent the NMR spectral areas of the corresponding components. The area ratio  $A_{EDTA}/A_{MEDTA}$  versus  $V_{EDTA}M_{EDTA}/V_M$  is then plotted. Thus, the metal's concentration can be obtained from the reciprocal of the slope. The theoretical intercept of this line is -1.

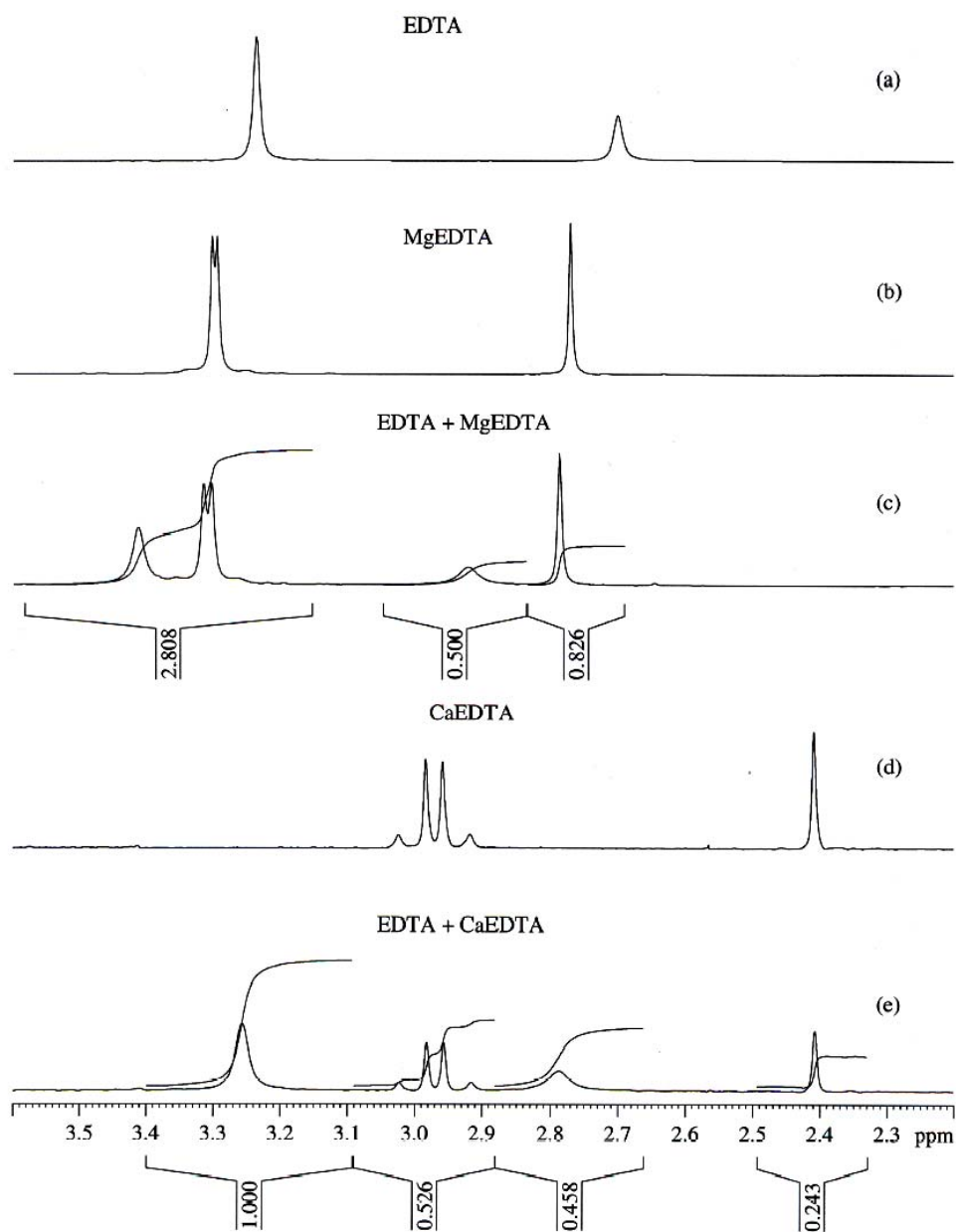
## Experimental Section

Magnesium nitrate hexahydrate, calcium nitrate tetrahydrate and tetrasodium EDTA are all of ACS grade supplied by Sigma-Aldrich. All the solutions were prepared in deuterium oxide (99.8% supplied by Fisher Scientific, USA). The standardized EDTA concentration used was 0.0100M. The concentrations for magnesium and calcium solutions were prepared approximately to 0.01M. The volume ratios for a metal solution to the EDTA solution were prepared at 0.10, 0.12, 0.16, 0.20, 0.24, 0.30, and 0.40mL with original volume of 0.40mL tetrasodium EDTA solution.

All experiments were carried out using a Bruker Avance DRX 400 MHz NMR spectrometer with an inverse 5mm high resolution probe. The recycling delay was set to be 5s and 32 scans were used. The 5s recycling delay guaranteed the correct area ratios because the proton longitudinal relaxation times ( $T_1$ ) of the EDTA and its complexes were found to be less than 1s. The HOD peak at 4.8 ppm in the solvent was used as the secondary reference for measuring the chemical shifts.

## Results and Discussion

Figure 1 shows the proton NMR spectra of the tetrasodium EDTA solution (labeled as EDTA), the MgEDTA solution, the mixture of (0.2ml) of Mg solution in (0.4 ml) of EDTA solution (labeled as MgEDTA + EDTA), CaEDTA, and the mixture of (0.12ml) of Ca solution in (0.40ml) of EDTA solution (labeled as CaEDTA + EDTA). In the free EDTA spectrum, the two chemical shifts at 3.2 ppm and 2.7 ppm indicating the acetate-methylene protons and the amine-methylene protons, respectively. The MgEDTA spectrum shows an AB pattern centered at 3.3 ppm ( $J = 16.4$  Hz) for the acetate-methylene protons and a singlet at 2.8 ppm for the amine-methylene protons. In the MgEDTA + EDTA spectrum, the corresponding free EDTA peaks shifted to 3.4 ppm and 2.9 ppm while no change in chemical shift for the MgEDTA complex was observed. It shows that the chemical shifts and line-widths changed with the ratio of Mg to EDTA. However, the spectral pattern allows us to easily distinguish between the

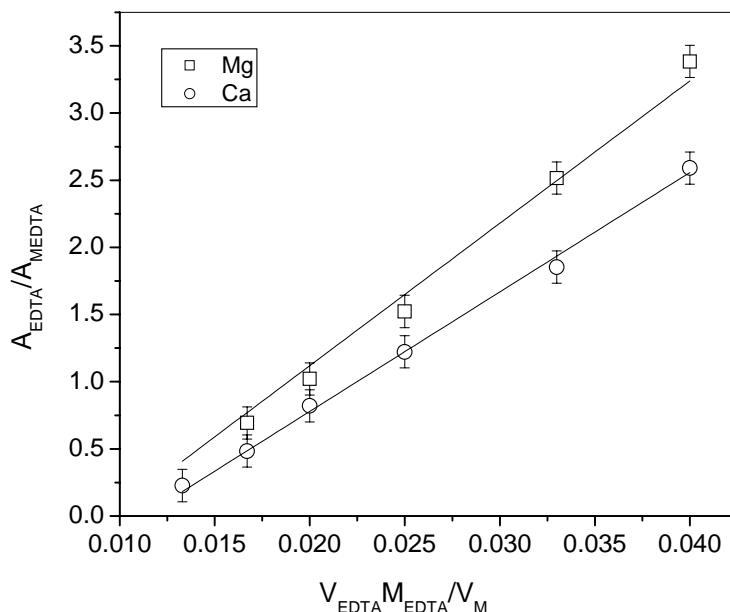


**Figure 1.** Proton NMR spectra of a) EDTA, b) MgEDTA, c) EDTA + MgEDTA, d) CaEDTA and e) EDTA + CaEDTA.

Peaks belonging to EDTA and MgEDTA. The CaEDTA spectrum also shows an AB pattern comprising of chemical shifts centered at 3.0 ppm ( $J = 16.1$  Hz) for the acetate-methylene protons and a singlet at 2.4 ppm for the amine-methylene protons. In the CaEDTA + EDTA spectrum, the corresponding free EDTA peaks slightly shifted to 3.3 ppm and 2.8 ppm while no observable change occurred for the CaEDTA peaks.

Figure 2 shows the plots of the experimental points of  $A_{EDTA}/A_{MEDTA}$  versus  $V_{EDTA}M_{EDTA}/V_M$  for determining the concentrations of  $Mg^{2+}$  and  $Ca^{2+}$  solutions, where the squares represent those of  $Mg^{2+}$  and the circles represent those of  $Ca^{2+}$ . The corresponding linear curve fittings result in a

concentration of  $0.0094 \pm 0.0001$  M for  $\text{Mg}^{2+}$  and  $0.0112 \pm 0.0001$  M for  $\text{Ca}^{2+}$ . The errors were generated through the theoretical fittings.



**Figure 2.**  $A_{\text{EDTA}}/A_{\text{MEDTA}}$  versus  $V_{\text{EDTA}}M_{\text{EDTA}}/V_M$  for determining the concentrations of  $\text{Mg}^{2+}$  and  $\text{Ca}^{2+}$  solutions.

In an aqueous solution, tetrasodium EDTA has a stronger chelating ability to metal ions due to the two extra lone pairs of electrons present in the additional free oxygen's anions in comparison to the disodium EDTA where the two oxygen atoms are protonated. This explains why tetrasodium EDTA is able to determine the concentrations of  $\text{Mg}^{2+}$  and  $\text{Ca}^{2+}$  solutions. Much like in previous studies with disodium EDTA, tetrasodium EDTA when bound to a metal cation can form an octahedral coordinated complex. The presence of an AB pattern observed for the acetate-methylene proton of the metal complex is due to the fact that a fast  $\Delta$ ,  $\Lambda$  interconversion and a slow nitrogen inversion exist at room temperature.<sup>8</sup> The former process led to the two AB patterns (one from the acetate groups out of the N-M-N plane and one in the N-M-N plane) to be averaged to one AB pattern.

Although successful for the  $\text{Mg}^{2+}$  and  $\text{Ca}^{2+}$ , the chelating effect of the tetrasodium EDTA is still not strong enough to determine the concentrations of the other group II A metal ions. Thus, an even stronger chelating agent is needed to do so. An ongoing study is in progress using *trans*-CDTA. In looking at the ligand's backbone, there are no  $\Delta$ ,  $\Lambda$  interconversion and slow nitrogen inversion was seen at room temperature.<sup>9,10</sup> This gives two AB patterns observed for the acetate-methylene group of the complexes. As a result, it is easy to distinguish between the acetate-methylene protons of free CDTA and the metal-CDTA complex.

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