On the Chemistry of Iron in Biosystems.
I. Complex Formation Between Fe(III) and Tartaric Acid: a 'Core + Link' Mechanism

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Abstract

The complex formation between Fe(III) and tartaric acid (H_2L) has been studied in 0.5 M $NaNO_3$ medium at 25 °C by using potentiometric techniques in the pH range 1.5–4.5. The results, expressed in terms of complex formation reactions, explain the experimental data obtained at different reagent concentrations and model the system taking into account the following reactions and stability constants:

$$Fe^{3+} + L^{2-} = FeL^+ \qquad \log\beta_{011} = 6.23$$

$$2Fe^{3+} + 2L^{2-} + 3H_2O = Fe_2(OH)_3L_2^- + 3H^+ \qquad \log\beta_{-322} = 8.75$$

$$3Fe^{3+} + 3L^{2-} + 6H_2O = Fe_3(OH)_6L_3^{3-} + 6H^+ \qquad \log\beta_{-633} = 9.55$$

The model considered represents a 'core + link' mechanism for the complex formation process. The species FeL acts as a core of the hypothetical link $Fe(OH)_3L$ species.

The acidity constants of tartaric acid were also determined in separate experiments and used in the analysis of the Fe(III)–tartaric system. Structures are suggested for the complex species formed.

Introduction

Iron is the most abundant minor metal in biosystems. It is known that the uptake of iron by living organisms depends strongly on the presence of metal complexing agents [1] forming either soluble or insoluble metal complexes. In this sense the characterization of the basic chemistry of such compounds is essential to understand these systems so that they can be applied in suitable specific processes.

The formation of strong soluble complexes between Fe(III) and ligands bearing carboxylic groups is widely known. Tartrate (L) is one of those ligands which is used to avoid precipitation of ferric hydroxides in aqueous solutions.

Several authors studied this system by using different techniques and thermodynamic conditions [2–7] (Table I). A discrepancy is found between the reported results about the species formed and their stability constants. Thus, Bobtelsky and Jordan [2] reported the formation of the complexes FeL, FeL_2 and Fe_2L_3 from thermometric measurements; while Green and Parkins [3] found the species FeHL and $FeHL_2$ at $pH < 4$ by using potentiometric data. The complex FeL_2 has been postulated by Stary [4] using spectrophotometric measurements. Timberlake [5] using potentiometric and spectrophotometric data suggests the model containing the species

TABLE I. Summary of Literature Data on Fe(III)–Tartrate Complexes in Aqueous Solutions

Model	Method	References
FeL, FeL_2, Fe_2L_3	thermometric	2
FeHL, $FeHL_2$	potentiometric	3
FeL_2	spectrophotometric	4
FeL, $(OH)_2Fe_2L_2$, $(OH)_3Fe_2L_2$, $(OH)_6Fe_3L_3$	potentiometric	5
Fe_2L, Fe_5L_4, FeL, Fe_2L_3, FeL_2	thermometric	6
FeL	potentiometric	7
FeL, $(OH)_3Fe_2L_2$, $(OH)_6Fe_3L_3$	potentiometric	this work

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FeL, $Fe_2(OH)_2L_2$, $Fe_2(OH)_3L_2$ and $Fe_3(OH)_6L_3$ to explain the behaviour of the system in solutions which contain an excess of tartrate over the total Fe(III) present.

Finally, Gallet and Paris [6], also using thermometric data, postulate the formation of five different complex species which correspond to the molar ratios Fe(III):L equal to 1:0.5, 5:4, 1:1, 1:1.5 and 1:2.

This spread of data shows the difficulty in elucidating the proper behaviour of this system.

The present work has been undertaken in order to elucidate the best complex formation model for this system as well as to determine the stability constants of the species formed in solution. Continuous emf measurements have been performed in order to analyse the equilibrium state of the system. $NaNO_3$ (0.5 mol dm^{-3}) was used as ionic medium. None of the data reported until now were obtained under these thermodynamic conditions, except those of Andrei [7], whose data concern a very narrow pH range: 1 to 1.5. On the other hand, no information on the structure of the aqueous species formed in this system has been reported.

Experimental

Method of Investigation

In order to investigate the complex formation between the ferric and the tartrate ions, the hydrogen ion concentration, h, has been determined by emf measurements at 25 °C in a number of solutions prepared from stock solutions of $Fe(NO_3)_3$, tartaric acid, HNO_3 and $NaNO_3$.

The general composition of the test solutions, TS, was as follows: TS = B M for Fe(III); L M for tartrate; H M for H^+; $(0.5-H-3B)$ M for Na^+; 0.5 M for NO_3^-. The emf measurements were performed in the form of titrations using the cell

$$\text{RE}||\text{TS}|\text{GE} \qquad \text{(I)}$$

where GE indicates a glass electrode and RE represents the reference half-cell

$$\text{Ag,AgCl (s)}|1 \text{ mM } Ag^+, 0.5\text{–}0.001 \text{ M } Na^+,$$
$$0.5 \text{ M } NO_3^-|0.5 \text{ M } NaNO_3$$

In each experiment the total Fe(III) concentration, B, as well as the L values were kept at a constant level, whereas H was decreased stepwise by the addition of basic NaOH solution. Back titrations were performed by using HNO_3 solutions as a titrant. A nitrogen gas stream was passed through the test solution while carrying out the experiment in order to keep an inert environment.

$NaNO_3$ was added in such quantities as to keep NO_3^- concentration at 0.5 M in all solutions in order to ensure reasonable constancy of the activity coefficients of the reacting species. The emf, E_I, of the cell (I) was measured after each addition. At equilibrium, E_I can be written as

$$E_I = E^\circ_I + 59.16 \log h + E_j \qquad (1)$$

where E°_I is a constant and E_j is a term which accounts for the liquid junction potential between the test solution and 0.5 mol dm^{-3} $NaNO_3$. Both parameters were determined by a Gran titration [8] (when no ferric and tartrate ions were present) into the test solution. E_j was found to have a negligible contribution to the experimental conditions used. Taking into account these values in eqn. (1), the value of h could be calculated. Figure 1 shows the experimental data plotted in the form Z *versus* $-\log h$ at the different B and L levels. Z represents the number of H^+ ions bound to the total tartrate defined by

$$Z = (H - h + K_w h^{-1})/L \qquad (2)$$

The equilibrium position of the system during the titration procedure was determined by applying a stability criterium to the measured potential E_I. This criterium consisted of having a constant value of E_I for a minimum period of 10 min. In order to verify our equilibrium data, back titrations were performed under the same analytical composition of the system. These data are plotted in Fig. 1 by

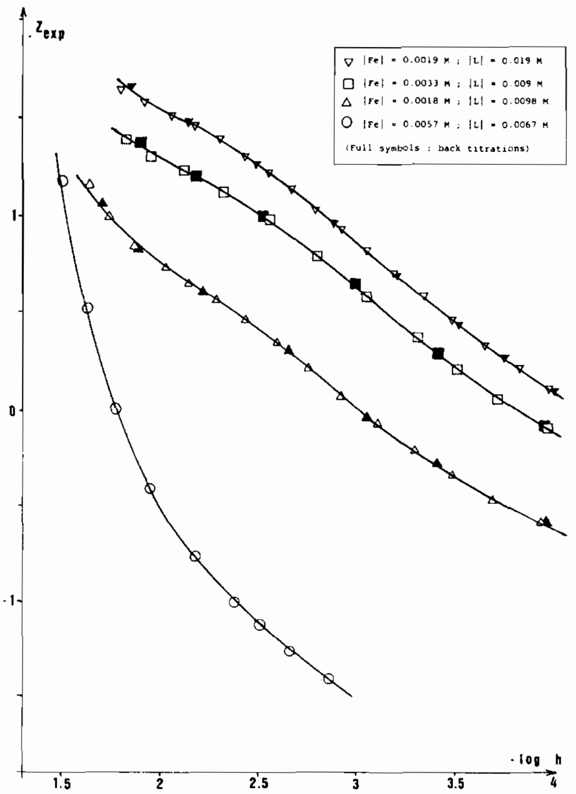

Fig. 1. Z plotted *vs.* $-\log h$ for the different sets of experiments. Full points represent back titrations. Solid lines have been calculated by the model proposed in the present work.

TABLE II. Results Obtained for the Behaviour of Tartaric Acid in Aqueous 0.5 M $NaNO_3$, by Different Graphical and Numerical Methods

Method	$\log K_1$	$\log K_2$
Sillén[a] [9]	3.68	2.68
Ciavatta-Ferri[a] [10]	3.68	2.68
Letagrop[b]	3.69 ± 0.01	2.68 ± 0.01

[a]Graphical. [b]Numerical.

TABLE III. Results Obtained on the Numerical Treatment of the Experimental Data for the System Fe(III)–Tartaric Acid

Model	(p, q, r)	U	σ	$\log \beta_{pqr}$
1	(0, 1, 1)			6.49 max. 6.94
	(−2, 2, 2)			rejected
	(−3, 2, 2)			9.04 max. 9.38
	(−6, 3, 3)	0.36×10^3	1.87	9.48 ± 0.20
2	(0, 1, 1)			6.49 ± 0.17
	(0, 1, 2)			rejected
	(−3, 2, 2)			9.05 ± 0.20
	(−6, 3, 3)	0.61×10^2	2.47	9.48 ± 0.20
3	(0, 1, 1)			6.47 max. 6.68
	(−1, 1, 1)			rejected
	(−2, 1, 1)			0.8363 ± 0.25
	(−3, 2, 2)			9.07 max. 9.39
	(−6, 3, 3)	0.60×10^2	1.28	9.81 max. 10.20
4	(0, 1, 1)			6.23 ± 0.08
	(−3, 2, 2)			8.73 ± 0.08
	(−6, 3, 3)	0.30×10^2	0.75	9.54 ± 0.09

means of full symbols. The good agreement between the forward and back titration data also shows that no irreversible processes take part in the complexation reactions.

The titration experiments were carried out using the titration solutions T_1 and T_2 of general composition

$$T_1 = A_1\ \text{mM OH}^-;\ C_l\ \text{mM}\ L;\ (500-A_1)\ \text{mM NO}_3^-$$

$$T_2 = A_2\ \text{mM H}^+;\ B_2\ \text{mM}\ B;\ 500\ \text{mM NO}_3^-$$

in order to keep B and L constant throughout the titration procedure. The $-\log h$ value was varied in the range −1.5 to −4.5. For the different experiments B and L range from 2.0 to 6.0 mM and 5.0 to 20 mM respectively. The experiments were carried out in a thermostatted bath at 25 ± 0.1 °C.

The acidity equilibria of tartaric acid were determined in separate experiments in the absence of Fe(III). The results are collected in Table II.

Results

The formation of complexes between Fe(III) and tartaric acid can be expressed by the general equation

$$p\text{H} + q\text{Fe} + r\text{L} = \text{H}_p\text{Fe}_q\text{L}_r \qquad \beta_{pqr} \tag{3}$$

where β_{pqr} represents the formation constant of the species formed having different p, q and r values. Charges are omitted for reasons of simplicity.

The stoichiometry of the complexes as well as the constant β_{pqr} have been determined by means of numerical analysis of the obtained data. For this purpose the computer program LETAGROP-NYTIT [11, 12] was used. The treatment is based on the minimization of the error square sum U, defined by

$$U = \sum_{Np} (E_{\text{calc}} - E_{\text{exp}})^2 \tag{4}$$

where E_{exp} represents the experimental emf values (E_I), E_{calc} is a corresponding value calculated by the program assuming a determined model of species formed and corresponding stability constants, Np stands for the number of experimental points. The calculation has been initially performed by considering the previously found results [2–8] to fit our experimental data. In this sense the results obtained are collected in Table III (models 1 to 4). As seen, only Timberlake's results seem to fit our experimental data to a reasonable degree. In spite of this agreement the species $(OH)_2Fe_2L_2$, also reported by Timberlake, has been rejected in our treatment. Thus, the best fit of the experimental data corresponds to the model where the species FeL, $Fe_2L_2(OH)_3$ and $Fe_3L_3(OH)_6$ are formed. This result is expressed by the following equations and the corresponding β_{pqr} values are given

$$\text{Fe} + \text{L} \longrightarrow \text{FeL} \qquad \log \beta_{011} = 6.23 \tag{5}$$

$$2\text{Fe} + 2\text{L} + 3\text{H}_2\text{O} \longrightarrow \text{Fe}_2(\text{OH})_3\text{L}_2 + 3\text{H}^+ \qquad \log \beta_{-322} = 8.75 \tag{6}$$

$$3\text{Fe} + 3\text{L} + 6\text{H}_2\text{O} \longrightarrow \text{Fe}_3(\text{OH})_6\text{L}_3 + 6\text{H}^+ \qquad \log \beta_{-633} = 9.25 \tag{7}$$

Figure 2 shows the individual values of ($E_{\text{calc}} - E_{\text{exp}}(E_\text{I})$) in mV. As seen, there is no evidence of systematic deviation from the proposed model.

Discussion and Conclusions

The results obtained in the present work correspond to complex formation between Fe(III) and tartaric acid in aqueous solution of 0.5 M $NaNO_3$ ionic medium. The experimental data are shown to belong to the equilibrium state of the system and

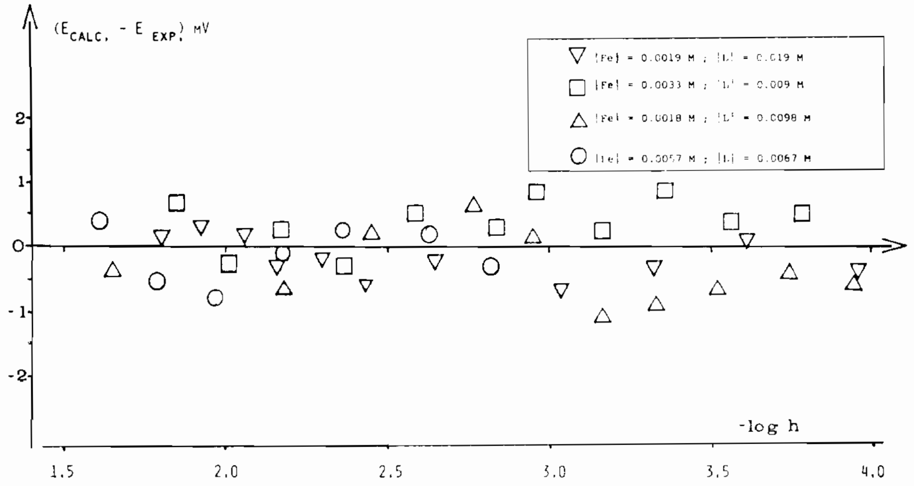

Fig. 2. The ($E_{calc} - E_{exp}$) mV values are plotted *vs.* $-\log h$ for the different experimental values analysed.

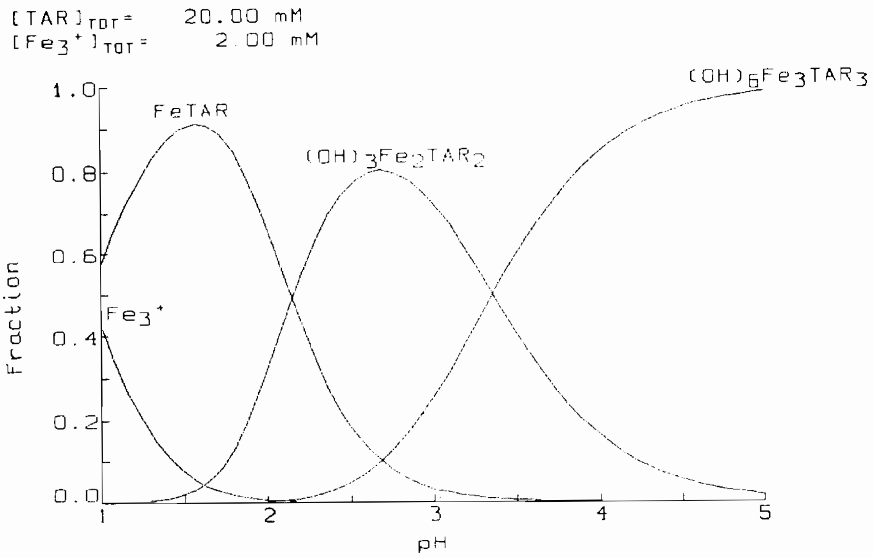

Fig. 3. Fraction diagram of the Fe(III)–tartaric complex species as a function of $-\log h$.

also that no irreversible processes or side reactions take part in the reactions studied. The complex species formed are represented by eqns. (5) to (7).

This model is partially in agreement with the results previously reported by Timberlake [5], but the species $(OH)_2Fe_2L_2$ considered in his work has not been found in our analysis. The values of the formation constants, β_{pqr}, are also different from those reported by Timberlake (the different thermodynamic conditions with both the ionic media and temperature used in these studies could account for these differences).

On the other hand, the model proposed in the present work shows behaviour corresponding to a specific stepwise polynuclear complex formation of the type 'core + link'. This mechanism, proposed by Sillén [13], assumes a certain species, 'core', which is linked stepwise by another group of associated molecules producing new complex species. In our case, the species FeL represents the 'core' and the species $(OH)_3Fe_2L_2$ and $(OH)_6Fe_3L_3$ result as a 'core + link' mechanism where the group $(OH)_3FeL$ is the responsible link. This mechanism is represented by the following reactions

$$FeL + (OH)_3FeL \longrightarrow (OH)_3Fe_2L_2$$

$$(OH)_3Fe_2L_2 + (OH)_3FeL \longrightarrow (OH)_6Fe_3L_3$$

Thus, this stepwise complex formation is consistent with the speciation proposed in this work and our treatment reveals that other models cannot explain such consistency. On the other hand, as seen in Table III, our results do not include the species $(OH)_3FeL$. This species has been rejected on consid-

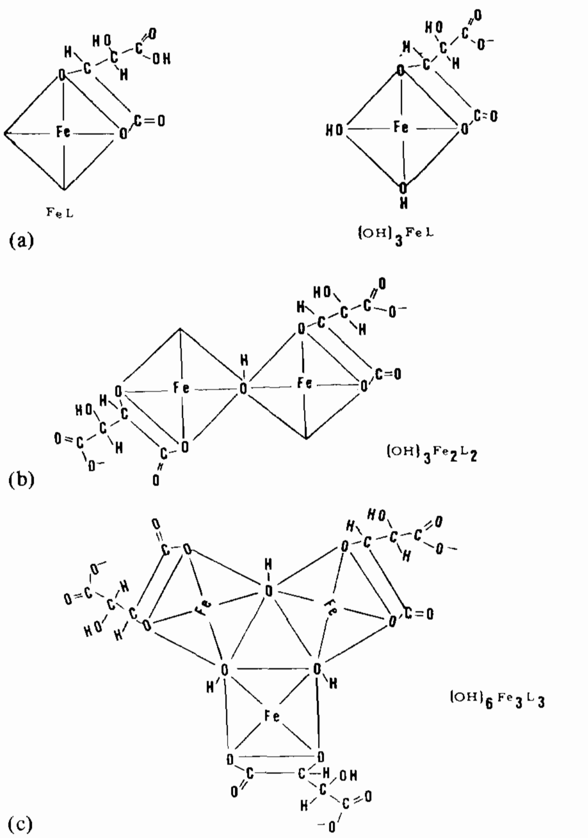

Fig. 4. Suggested structures for the Fe(III)–tartaric complexes.

eration of the calculations. This indicates that either the $(OH)_3FeL$ is not thermodynamically stable or it exists at a relatively small concentration under the conditions studied.

In Fig. 1 the full lines represent calculated values of Z *versus* $-\log h$ using the proposed model (eqns. (5), (6) and (7)). The agreement with the experimental values shows a high confidence level for the model.

Figure 3 shows the distribution diagram of the species, calculated by the program HALTAFALL [14], in the range studied. As seen, the species of higher nuclearity, $(OH)_6Fe_3L_3$, predominates over the higher values of the pH range studied.

As was mentioned earlier, no structural study has been previously reported on this system. However, from the studies of the formation of complexes of iron with other carboxylic ligands it is possible to speculate on a probable structure for the suggested species. As iron prefers an octahedral coordination geometry [15] and as the hydroxyl group of the tartrate is known to be directly bound to the Fe^{3+} [16], the species FeL and $(OH)_3FeL$ may have the configuration given in Fig. 4a. Using the 'core + link' mechanism, the species $(OH)_3Fe_2L_2$ and $(OH)_6Fe_3L_3$ may have the configuration given in Fig. 4b and 4c, respectively, as a consequence of successive link additions. According to this speculation, the 'core + link' mechanism could be reformulated as follows

$$FeHLH_{-1} + (OH)_2FeLH_{-1} \rightleftharpoons (OH)Fe_2L_2H_{-2} + H_2O$$

$$(OH)Fe_2L_2H_{-2} + (OH)_2FeLH_{-1} \rightleftharpoons (OH)_3Fe_3L_3H_{-3}$$

At any rate, independent structural studies would be needed in order to confirm the suggested configurations.

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