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Hydrogen Bonds in the 1:1 and 2:1 Complexes of Trigonelline with Mineral Acids Studied by FTIR, ^{1}H and ^{13}C NMR Spectroscopies[*]

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The 1:1 and 2:1 complexes of trigonelline (TRG) with HBr, HI, HNO_3, $HClO_4$ and HBF_4 have been synthesized and their FTIR, ^{1}H and ^{13}C NMR spectra were analyzed. The 1:1 complexes are divided into two groups. The first group includes complexes with HBr, HI and HNO_3, in which a proton is transferred from the acid to TRG and the anions are bonded with the carboxylic group, $COOH\cdots X^-$ (**1**). The second comprises complexes with $HClO_4$ and HBF_4, with two molecules of protonated TRG forming dimer, like benzoic acid, and the anions interacting exclusively with the positively charged nitrogen atoms (**2**). All 2:1 complexes crystallized with one water molecule and their FTIR spectra are of Had0i type iii, characterized by an intense broad (continuum) absorption below 1600 cm^{-1} typical of a short-strong hydrogen bond (SSHB) with a delocalized proton and a single νC=O band. In these complexes the water molecule interacts electrostatically with one positively charged nitrogen atom and the anions with the second one (**3**). The water molecule additionally forms a hydrogen bond with Br, I and NO_3 ions. The proton and carbon chemical shifts of the complexes in D_2O have been determined and discussed.

Key words: trigonelline, H-bond complexes, FTIR, ^{1}H and ^{13}C NMR spectra

Trigonelline, N-methyl-3-carboxy-pyridine (TRG), is a natural betaine isolated from various plants, seeds and the western rock lobster [1–5]. Trigonelline crystallizes as monohydrate and its structure has been determined by X-ray diffraction [5].

In this paper, the 1:1 and 2:1 complexes of trigonelline with HBr, HI, HNO_3, $HClO_4$ and HBF_4 were synthesized (Scheme 1) and their powdered FTIR and solution (D_2O) ^{1}H and ^{13}C NMR spectra were analyzed. The aim of this investigation is to get information on the π-electronic conjugation on hydrogen bond and structure of betaine complexes. In previously investigated complexes of betaines containing pyridine, N-methylpiperidine and N-methylpyrrolidine rings, the positively charged nitrogen atom and the negatively charged carboxylate group were not electronically conjugated because they were separated by 1–5 methylene groups [6–12]. In trigonelline the formally charged groups are typically electronically conjugated with each other *via* π-electrons of pyridine ring.

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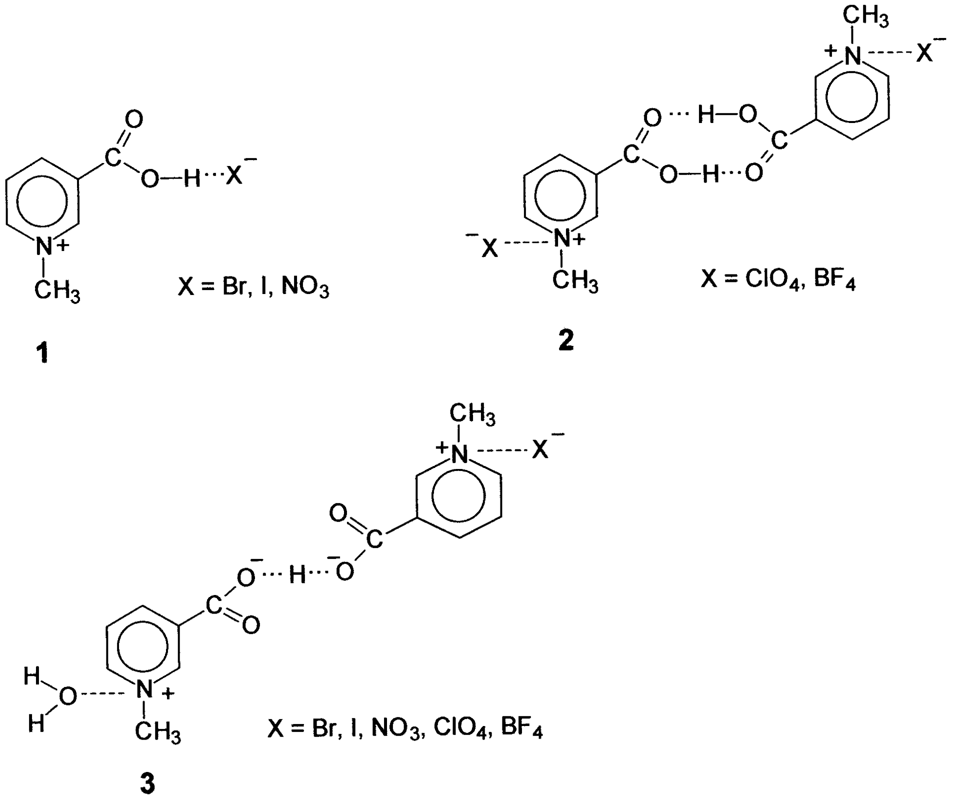
Scheme 1



EXPERIMENTAL

Trigonelline monohydrate, TRG·H_2O, was prepared according to the method reported in [13]. The 1:1 complexes were prepared by mixing TRG·H_2O (0.01 mol) in about 5 cm^3 of ethanol with small excess of the aqueous acids. The solid formed was recrystallized from methanol or ethanol. The 2:1 complexes were obtained by recrystallizing stoichiometric amounts of TRG·H_2O with the 1:1 complex from a little amount of methanol or ethanol. The melting points are given in Table 1. The complexes deuterated were prepared by twice exchange with an excess of D_2O followed by removal of excess D_2O in vacuum. The residue was recrystallized from CH_3OD.

Anhydrous trigonelline, TRG, was obtained by dehydration of monohydrate in vacuum at 110° over P_2O_5 for 5 h. The anhydrous trigonelline is very hygroscopic and converts to monohydrate left in open vessel overnight.

FTIR spectra were recorded on a Bruker IFS 113v spectrometer at a 2 cm^{-1} resolution in Nujol and Fluorolube mulls.

^1H and ^{13}C NMR spectra were recorded on a Varian Gemini 300 VT spectrometer operating at 300.07 and 75.46 MHz for proton and carbon-13, respectively. The ^1H and ^{13}C chemical shifts were measured in D_2O solution relative to internal dioxane and were recalculated relative to TMS by adding 3.55 and 67.40 ppm, respectively. The assignments of the chemical shifts were confirmed by COSY, HETCOR and NEODIF experiments.

RESULTS AND DISCUSSION

Infrared spectra: The two broad bands at 3410 and 3230 cm^{-1} in the spectrum of TRG·H_2O correspond to the νOH vibration of the water molecule. The bending frequency of the water molecule is at 1673 cm^{-1} and the ν_{as}COO mode appears at 1640 cm^{-1}. In anhydrous trigonelline the ν_{as}COO band is at 1650 cm^{-1} (Fig. 1a), while in sodium salt of nicotinic acid at *ca.* 1620 cm^{-1} [14]. Similar bands have been observed in monohydrates of betaine [15] and pyridine betaine [6].

In the spectra of the 1:1 complexes the νC=O band is observed between 1733–1700 cm^{-1} and indicates that a proton from the acids is transferred to TRG (Table 1). The νOH absorption is located in the 3000–1800 cm^{-1} region and the spectra can be divided into two groups (Figs. 1b, 2). The first group includes complexes with HI, HBr and HNO_3 and the second one with $HClO_4$ and HBF_4. The frequency and shape of the νOH absorption in the spectra of the first group of complexes (Figs. 1b, 2a–b) correlate well with the proton acceptor properties of the anion and

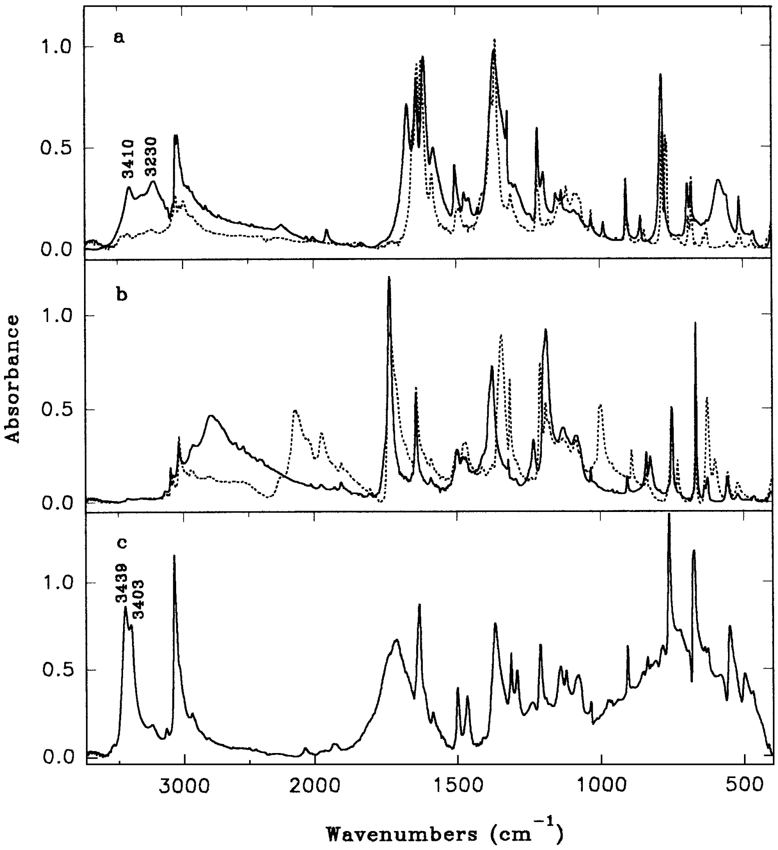


Figure 1. FTIR spectra of (**a**) trigonelline (———) monohydrate and (- - - -) anhydrous, (**b**) trigonelline·HBr, dotted line with DBr, (**c**) (trigonelline)$_2$HBr·H_2O.

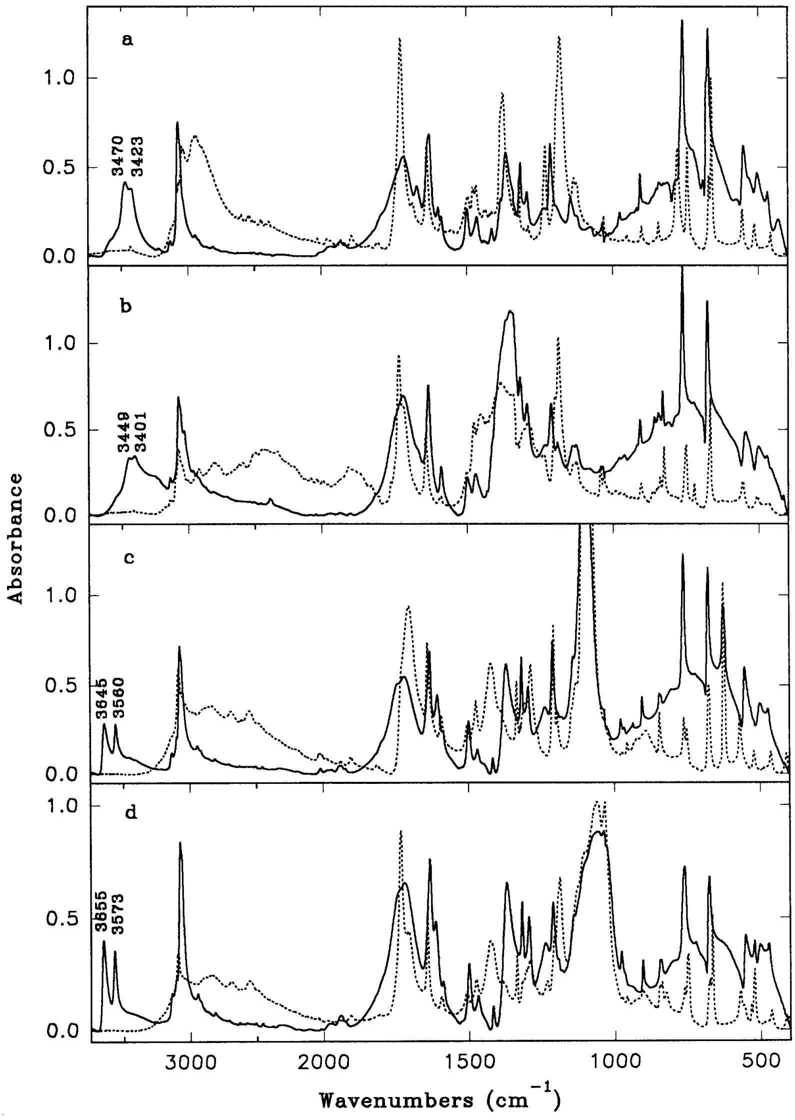


Figure 2. FTIR spectra of the 2:1 (——) and 1:1 (- - - -) complexes of trigonelline with (**a**) HI, (**b**) HNO_3, (**c**) $HClO_4$, (**d**) HBF_4.

indicates that a proton from the acids is transferred to TRG and anions are bonded with the carboxylic group, COOH···X^- (**1**). The hydrogen bond strength in these complexes decreases in the order HNO_3 > HBr > HI. A similar variation of absorption with anion was observed in the spectra of 1:1 complexes of pyridine betaine [6].

The spectra of TRG·HBr and TRG·DBr are compared in Fig. 1b. The νOH absorption is at *ca*. 2785 cm^{-1} and νOD at *ca*. 2143 cm^{-1}. Their shapes are probably due to the anharmonic coupling of the stretching vibration (νAH) of the proton in the

A-H···B complex to the hydrogen bond stretching vibration (ν(AHB)) [16]. Further contribution to the band shape comes from the Fermi resonance of the νOH vibration with overtones. Another characteristic feature is the presence of the bands at 1377 (νC–O), 1187 (δOH) and 824 cm^{-1} (γOH). On deuteration they are shifted to 1345, 998 and 626 cm^{-1}, respectively. The isotope effect (δOH/δOD = 1.19) is very close to that in carboxylic acids and suggests a coupling of δOH with νC–O [17].

The spectra of the second group complexes ($TRG·HClO_4$ and $TRG·HBF_4$) show a broad absorption with many sub-bands in the 3000–2400 cm^{-1} region (Fig. 2c–d), which is very similar to these in the spectra of N-(4-carboxybutyl)-pyridinium perchlorate [8] and dimers of carboxylic acids. In the spectrum of pyridine betaine·HBF_4, the νOH band is at *ca.* 3100 cm^{-1} [9]. Thus, the IR spectra indicate that two molecules of protonated trigonelline form dimer, like benzoic acid, and ClO_4 and BF_4 ions interact electrostatically with the positively charged nitrogen atoms (**2**) like in N-(4-carboxybutyl)-pyridinium perchlorate [8].

All 2:1 complexes crystallize with one molecule of water and their spectra are different from those of the 1:1 complexes (Fig. 1 and 2). The spectra are dominated by a broad and strong absorption in the range 1500–400 cm^{-1}, typical of hydrogen bonds shorter than 2.5 Å. A similar broad absorption appears in the spectra of 2:1 complexes of other betaines [6] and type A acid salts of carboxylic acids [9,18]. Had0i *et al.* [19] attributed this absorption to the ν_{as}(OHO) stretching vibration of a short hydrogen bond.

The shape of the absorption of the water molecule in the 2:1 complexes depends on the anion. In the spectrum of water (monomer) in solid argon at 20 K the asymmetric (ν_3) vibration occurs at 3728 cm^{-1} and the symmetric (ν_1) at 3640 cm^{-1} [20]. The frequencies of the water molecule vibrations in $(TRG)_2·HBF_4·H_2O$ (3655 and 3573 cm^{-1}) are very close to the free OH vibrations in polymeric water (3675 and 3580 cm^{-1} [20]). The similarity of the OH frequencies suggests that the water molecule in $(TRG)_2·HBF_4·H_2O$ is not engaged in the H-bond. This suggests that the water molecule interacts electrostatically with one positively charged nitrogen atom and BF_4 ion with the other (**3**). In $(TRG)_2·HBr·H_2O$ the water molecule also interacts electrostatically with the positive nitrogen atom and additionally forms a hydrogen bond with Br ion. Thus, the νOH bands are shifted *ca.* 216 and 170 cm^{-1} towards the lower vavenumbers than in the spectra of $(TRG)_2·HBF_4·H_2O$. Hydrogen bonds in water trimer caused similar shifts of the νOH frequencies [20].

The above proposed structure of the 2:1 trigonelline complexes was confirmed by a DFT calculations and a preliminary X-ray diffraction study of $(TRG)_2·HCl·H_2O$. In this complex the distances are: N^+- - - OH_2, 3.299 Å; N^+- - - Cl^-, 3.514 Å; HOH···Cl^-, 3.185 Å [21]. In the case of 2:1 complexes of pyridine betaine only hydrochloride crystallized as monohydrate, $(C_5H_5N^+CH_2COO)_2HCl·H_2O$ [9,22]. In this complex the water molecule is bonded to chloride ion and generate a planar zigzag chain running parallel to the *a* axis. The 2:1 complexes with other acids (large ions) are anhydrous. The 2:1 complexes of trigonelline crystallized as monohydrate independent of a size of counter-ion and their structures differ from that of bis(pyridine betaine) hydrochloride monohydrate [22]. The observed tendency of the 2:1 complexes of trigonelline to crystallized as monohydrate may be a consequence of π-electron conjugation between the positively charged groups.

^{1}H and ^{13}C NMR spectra: The proton chemical shifts assignments, listed in Table 1, were based on 2D COSY experiments, in which the proton-proton connectivities are observed through the off-diagonal peaks in the counter plot. The 2D heteronuclear shift correlated counter map (HETCOR) were used to identify resonances in the ^{13}C NMR spectra (Table 2). In the 1:1 complexes the proton chemical shifts are negligibly influenced by the anions and their values are slightly higher than in the spectrum of TRG·H_2O. The 2:1 complexes in D_2O dissociate to the 1:1 complexes and TRG·D_2O. This process is responsible for the observed lowering of chemical shifts (Table 1). The carbon chemical shifts are more influenced by the anions than the proton chemical shifts (Table 2). The protonation of TRG caused deshielding of most carbon atoms, except C-3 and COO, which are shielded. In the 2:1 complexes chemical shifts are intermediate between those in the spectra of TRG and 1:1 complexes.

Table 1. ^{1}H chemical shifts (ppm) in D_2O for trigonelline (TRG) and its 1:1 and 2:1 complexes with mineral acids, νC=O frequencies and melting points.

HX	H-2	H-4	H-5	H-6	N-CH_3	νC=O	m.p (°C)
1:1 complexes							
H_2O	8.87	8.58	7.83	8.60	4.20	(1640)[a]	218
HCl[b]	9.21	8.83	8.00	8.80	4.30	1700	222–224 dec.
HBr	9.18	8.81	7.98	8.81	4.28	1733	253–254 dec.
HI	9.18	8.81	7.99	8.78	4.28	1726	224–225 dec.
HNO_3	9.19	8.81	7.98	8.79	4.29	1716	202–203
$HClO_4$	9.17	8.80	7.97	8.77	4.28	1704	166–8
HBF_4	9.17	8.80	7.97	8.80	4.27	1705	164
2:1 complexes							
HCl[b]	9.09	8.75	7.95	8.73	4.28	1702	204 dec.
HBr	9.06	8.73	7.94	8.73	4.27	1708	218–220
HI	9.06	8.67	7.94	8.73	4.27	1717	234–235
HNO_3	9.07	8.74	7.94	8.72	4.27	1720	214–215
$HClO_4$	9.06	8.73	7.93	8.71	4.26	1722	220
HBF_4	9.06	8.72	7.93	8.72	4.27	1722	204–205

[a] $\nu_{as}COO^-$, [b] data from [21].

Table 2. ^{13}C chemical shifts (ppm) in D_2O for trigonelline (TRG) and its 1:1 and 2:1 complexes with mineral acids.

HX	C-2	C-3	C-4	C-5	C-6	N-CH_3	COO
1:1 complexes							
H_2O	146.66	137.86	145.58	128.50	146.83	49.08	168.43
HCl[a]	147.38	132.27	146.19	128.82	148.63	49.40	165.32
HBr	147.49	132.59	146.21	128.94	148.71	49.35	165.62
HI	148.68	132.69	146.36	129.00	147.47	49.48	165.62
HNO_3	147.33	132.25	146.13	128.60	148.57	49.31	165.28
$HClO_4$	147.37	132.38	146.14	128.78	148.55	49.34	165.36
HBF_4	147.32	132.38	146.13	128.77	148.54	49.30	165.34

Table 2 (cotinuation)

2:1 complexes							
HCl[a]	147.14	134.73	146.02	128.77	147.95	49.22	166.81
HBr	147.08	135.14	145.98	128.57	147.80	49.21	166.98
HI	147.07	135.11	145.99	128.77	147.80	49.31	166.95
HNO_3	146.97	134.66	145.81	128.58	147.73	49.22	166.66
$HClO_4$	146.98	134.72	145.81	128.60	147.73	49.24	166.71
HBF_4	146.98	134.69	145.81	128.59	147.74	49.23	166.70

a) data from [21].

REFERENCES

1. Beilstein, **22**(1), E III/IV, page 463–4.
2. Florkin M., in *Comprehensive Biochemistry*, ed. Stotz E.H., Elsevier Publ. Comp., Amsterdam, 1965, p. 224
3. Robertson A.V. and Marion L., *Can. J. Chem*., **37,** 1043 (1959).
4. Knowles W.S. and Elderfield R.C., *J. Org. Chem*., **7**, 389 (1942).
5. Cannon J.R., Edmonts J.S., Francesconi K.A, Raston C.L., Saunders J.B., Skelton B.W. and White A.H., *Aust. J. Chem.,* **34**, 787 (1981).
6. Dega-Szafran Z., Gdaniec M., Grundwald-Wyspiańska M., Kowalczyk I. and Szafran M., *J. Mol. Struct.*, **322**, 297 (1994).
7. Szafran M., Dega-Szafran Z., Katrusiak A., Buczak G., Głowiak T., Sitkowski J. and Stefaniak L., *J. Org. Chem.*, **63**, 2898 (1998).
8. Dega-Szafran Z., Katrusiak A. and Szafran M., *J. Mol. Struct.*, **513**, 15 (1999).
9. Szafran M., Kowalczyk I. and Barczyński P., *Israel. J. Chem.*, **39**, 253 (1999).
10. Szafran M., Koput J., Dega-Szafran Z. and Kwiatkowski J.S., *Vibrational Spectrosc*., **23**, 1 (2000).
11. Dega-Szafran Z., Dulewicz E. and Szafran M., *Magn. Res. Chem.*, **38**, 43 (2000).
12. Dega-Szafran Z., Katrusiak A. and Szafran M., *J. Mol. Struct.*, **570**, 165 (2001).
13. Szafran M., Koput J., Dega-Szafran Z. and Pankowski M., *J. Mol. Struct*. (in press).
14. Aldrich Library of FT-IR Spectra, Edition II, 1997, Vol. 3.
15. Harmon K.M. and Avci G.K., *J. Mol. Struct.,* **117**, 295 (1984).
16. Bratos S., Ratajczak H. and Viot P., in *Hydrogen-Bonded Liquids,* eds. Dore J.C. and Teiseire J., Kluver Academic Publishers, (1991), p. 221, and ref. cited therein.
17. Had0i D. and Sheppard N., *Proc. Roy. Soc.,* **A216**, 247 (1953).
18. Had0i D. and Bratos S., in *The Hydrogen Bond. Recent Developments in Theory and Experiments*, eds. Schuster P., Zundel G. and Sandorfy C., North-Holland, Amsterdam, (1976) Vol. 2, p. 565.
19. Had0i D., Obradovic M., Orel B. and Solmayer T., *J. Mol. Struct.,* **14***,* 439 (1972).
20. Luck A.P., in *The Hydrogen Bond. Recent Developments in Theory and Experiments*, eds. Schuster P., Zundel G. and Sandorfy C., North-Holland, Amsterdam, (1976) Vol. 2, p. 527.
21. Unpublished results.
22. Chen X-M. and Mak T.C.W., *J. Mol. Struct.*, **221**, 265 (1990).