Table 1. *Crystallographic data*

Compound	Space group	*a*	*b*	*c*	*α*	*β*	*γ*	ϱ_o	*Z*	ϱ_c
I	(*a*) $P1$ or $P\bar{1}$	4·83 Å	7·45 Å	11·7 Å	92° 30′	99° 55′	108° 00′	1·30	2	1·30
	(*b*) $P1$ or $P\bar{1}$	9·51	13·0	16·1	129° 50′	94° 55′	94° 10′	1·31	8	1·35
II	$P2_1/c$	4·88	12·63	12·89	—	103° 23′	—	1·57	4	1·58
III	$P2_1/c$	4·72	23·64	10·14	—	132° 47′	—	1·35	4	1·35
IV	$P1$ or $P\bar{1}$	9·45	14·38	15·49	121° 25′	108° 10′	91° 30′	1·38	8	1·39

to the conditions of growth; both lattices are triclinic. (*a*) Acicular crystals were obtained from aqueous solutions evaporated at room temperature. The shortest unit translation occurs along the needle axis. (*b*) Well-shaped parallelepipeds were grown from concentrated aqueous solutions slowly evaporated at 50–60 °C.; the crystals were filtered from the hot mother liquor.

(II) $\mathrm{NHCONHC(CH_3){:}C(CH_2COOH)CO}$ recrystallizes from water in the form of prismatic needles. The shortest unit translation lies parallel to the needle axis.

(III) $\mathrm{NHCONHC(CH_3){:}C(NHCH_3)CO}$ crystallizes in the form of platy orange crystals by slow evaporation of an aqueous solution at room temperature.

(IV) $\mathrm{N(C_6H_5)CONHCOCH_2}$ forms large bladed crystals which were easily obtained by recrystallization from water with the *a* axis chosen parallel to the main morphological axis of the crystal.

Reference

Buerger, M. J. (1942). *X-ray Crystallography*, pp. 375–85. New York: Wiley.

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On the arrangement of the water molecules in the crystal structure of caffeine.*

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Recently Sutor (1958) has determined the crystal structure of caffeine and refined it by the use of data of the type *hk*0 and *hk*1. A surprising result was the finding that although the *hk*0 data indicated the presence of about 80% of a water molecule of crystallization per molecule of caffeine, the *hk*1 data indicated the presence of only 40% of a water molecule. Sutor suggests that the crystals may lose water during the process of photography, but points out that she was unable to detect any change in unit-cell dimensions or density.

A further surprising result of the structure determination was the extremely—indeed, prohibitively—short distance of about 2·25 Å between adjacent sites of the water molecules, which form chains along the *c* axis. Sutor points out that if the water molecules were equally spaced along the *c* axis with only 80% of them present the OH ⋯ O distance would then be about 2·7 Å; however, such an arrangement would either lead to additional layer lines (if the spacing were coherent with respect to the repeat distance c_0) or the contribution of the water molecules to the *hk*1 data would vanish (if the spacing were incoherent or the arrangement were disordered). Furthermore, such a structure would not be consistent with the hydrogen bond between the water molecule and N_9 of the iminazole ring.

We propose an alternative arrangement for the water molecules which agrees with all evidence cited by Sutor and which is based on an analogy with the distribution of the water molecules in the crystal structure of thymine monohydrate (Gerdil, 1960). In our proposed arrangement the water molecules form relatively short zig-zag chains with a more reasonable OH ⋯ O distance. Although within each chain the positions of the several water molecules are fixed, the overall structure can be pictured in terms of a random distribution of sites about an average position.

We first assume that all crystals of the hydrated caffeine contain approximately the same amount of water—presumably about 80% of a molecule of water per molecule of caffeine. The fact that the *hk*1 data indicate the presence of only 40% of a water molecule can then be explained in two ways: (1) the water molecules have a large anisotropic temperature factor such that $\exp(-\gamma l^2) = \exp(-\gamma) = \frac{1}{2}$; (2) the water molecules are distributed in a random fashion over a number of sites having varying *z* coordinates but with a well-defined average coordinate (z_0) of about 0·258 (Sutor, 1958). The root mean square displacement of the water molecule as implied by the anisotropic temperature factor in (1) would correspond to about 0·7 Å, clearly an improbable value if to be attributed to the actual thermal movement of a single atom. However, as pointed out in the crystal structure of thymine monohydrate (Gerdil, 1960), such an apparently high anisotropy can be simulated by a localized disorder of the type described under (2). In the case of thymine, where a similar arrangement of water molecules seems to prevail, the electron density associated with the water molecule, calculated from complete three-dimensional data, is highly elongated in the direction of the chain of water molecules and the apparent

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temperature-factor anisotropy of the water molecule is absurdly high.

An idealized representation of the proposed configuration of the water molecule in caffeine is shown in Fig. 1. In a space of five repeat distances along the c direction 20%, or two, of the water molecules are missing; the other eight have constantly increasing (or decreasing) z parameters $z_o+\delta_i$ such that the $OH\cdots O$ distance between adjacent sites is appreciably greater than 2·25 Å (2·53 Å in the arrangement shown). In the right-hand column in Fig. 1 are given the deviations δ_i of each water molecule i from the average position z_o; these deviations are given in terms of a unit deviation Δz, so that the displacement in the c direction of one water site with respect to the next is $2\Delta z$. The vertical lines in Fig. 1 represent the range of the permissible sites, presumably defined by the $OH\cdots N_9$ hydrogen bond.

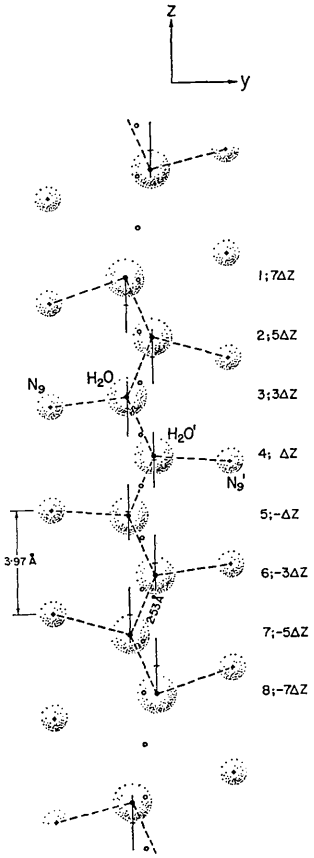

Fig. 1. Orthogonal projection onto (100) of an idealized configuration of the water molecules. The crosses at N_9 and N_9' represent the centers of two nitrogen atoms, each in the iminazole ring of a caffeine molecule. The subscript digit '9' refers to the numbering system of Sutor (1958). The heavy dots represent the oxygen atoms of water molecules, e.g., H_2O and H_2O'. The horizontal strokes, one at each occupied site, denote the average position z_o of the water molecules. The small circles are centers of symmetry. The water molecules in a chain are separated by a constant distance of 2·53 Å and their centers are assumed to lie within a range of $\pm 7\Delta z = \pm 1{\cdot}06$ Å from the average position z_o.

We can estimate the magnitude of Δz by the following consideration: in order that the contribution of the water molecules to the hkl structure factors be only half as great as their contribution to the $hk0$'s, the quantity

$$\sum_{i=1}^{N} \cos 2\pi\delta_i$$

summed over all N water molecules in the structure must be equal to $N/2$. For a chain of eight atoms the sum must be 4, and the resulting value of Δz is 0·038.* Since $z_o=0{\cdot}258$, the z parameters of the eight molecules within this chain (all referred to the general space-group position x, y, z) would be −0·008, 0·068, 0·144, 0·220, 0·296, 0·372, 0·448, and 0·524. With these parameters, the distance $OH\cdots O$ between adjacent water molecules is 2·53 Å, and the $OH\cdots N_9$ distance ranges from 2·86 Å to 3·09 Å. The root mean-square displacement associated with this distribution of z parameters is about 0·69 Å, which is in good agreement with the value obtained above from the apparent anisotropic temperature factor.

The structure we have formulated here is idealized; we have chosen an eight-atom chain only on the basis of 80% water content. A seven-atom chain, corresponding to 78% water content, would lead to slightly longer $OH\cdots O$ distances of 2·57 Å; in all probability the chain length is (within limits) variable, leading to an overall random occupation of many sites along the z direction.

References

Gerdil, R. (1960). *Acta Cryst.* (In press.)
Sutor, D. T. (1958). *Acta Cryst.* **11**, 453.

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* The average displacement Δz can easily be derived from the partial structure factor expression

$$\sum_{i=1}^{N} \begin{Bmatrix}\cos\\ \sin\end{Bmatrix} 2\pi l(z_o+\delta_i)\,,$$

where N is the number of different sites for the water molecules. For an arrangement of parameters $z_o+\delta_i$ which are symmetric with respect to the average parameter z_o, as in the assumed structure, this expression reduced to

$$\begin{Bmatrix}\cos\\ \sin\end{Bmatrix} 2\pi l z_o \cdot \sum_{i=1}^{N} \cos 2\pi l\delta_i\,.$$

Thus, for all structure factors of the type hkl the contribution of the water molecules will need to be multiplied by

$$\frac{1}{N}\cdot\sum_{i=1}^{N} \cos 2\pi\delta_i$$

to go from the ideal structure to the proposed structure. Now in the case of caffeine the H_2O's only contribute 0·4 to the $F(hkl)$'s compared with 0·8 for the $F(hk0)$'s; accordingly (N even):

$$\sum_{i=1}^{N} \cos 2\pi\delta_i/8$$
$$=[2\,(\cos 2\pi\Delta z+\cos 6\pi\Delta z+\cos 10\pi\Delta z+\cos 14\pi\Delta z)]/8=\tfrac{1}{2}\,.$$

This leads to $\Delta z=0{\cdot}0379$ or a displacement of 0·151 Å in the c direction.