J. Chem. Sci., Vol. 122, No. 5, September 2010, pp. 677–685.

Analysis of Cl…Cl and C–H…Cl intermolecular interactions involving chlorine in substituted 2-chloroquinoline derivatives

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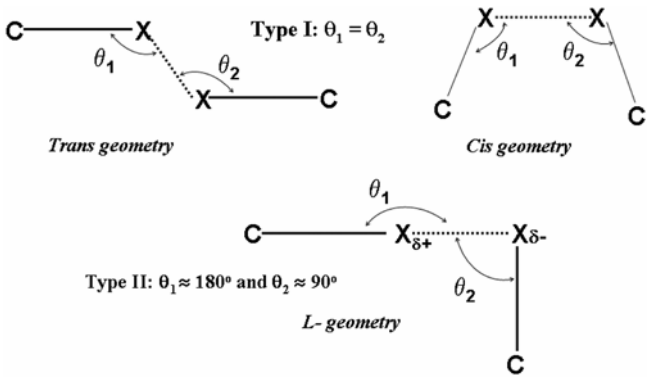
Abstract. Six crystal structures of substituted 2-chloroquinoline derivatives have been analysed to evaluate the role of Cl atom as a self recognizing unit resulting in the formation of Cl…Cl and C–H…Cl interactions to generate supramolecular assembly in the solid state. The features of Type I and Type II geometries associated with Cl…Cl interactions have been analysed to show directional preferences leading to differences in the packing motifs in these crystal structures. C–H…Cl interactions are generated exclusively in structures depicting Type II Cl…Cl interaction have been observed in these structures.

Keywords. Intermolecular interactions; halogen…halogen contacts; C–H…Cl hydrogen bonds; supramolecular assemblies.

1. Introduction

The presence of halogen atom, in particular chlorine in place of methyl group on simple aromatic compounds has been shown to significantly alter the crystal structure.[1] Even though both chlorine and methyl groups are of similar size and occupy about the same volume, dichloro substitution on aromatic molecules produce crystal structures with one of the axis being 4 Å.[2] Recent *ab initio* calculations show that halogen…halogen contacts are controlled by electrostatic forces and indeed display directional preferences.[3] In a recent article, concerning overcrowding of halogens as in the case of hexachlorobenzene, both chemical and geometrical models appear to dictate halogen…halogen interactions.[4] In general C–X_1…X_2–C contacts are classified into two types with θ_1 = C–X_1…X_2 and θ_2 = X_1…X_2–C and d = X_1···X_2 distance as Type I (*cis* or *trans* geometry) and Type II (L geometry) (scheme 1).[5]

If the angles are nearly similar, $\theta_1 \cong \theta_2$ the geometry is associated with Type I whereas $\theta_1 \cong 180^o$ and $\theta_2 \cong 90^o$ represents Type II geometry. Desiraju *et al* have demonstrated that Type II contacts dominate in case of X = I whereas Type I dominate in case of X = Cl with X = Br displaying both types of geometries.[6] In case of F, it is generally observed that C–H…F interactions prevail over F…F interactions.[7] However, this feature is disputed both from theory and more recently with large number of experimental observations showing preferences to the formation of F…F interactions.[8] It has become obviously clear that halogen…halogen interaction could very well be utilized as a design element in crystal engineering. Recent studies on the experimental charge density analysis on the nature of Cl…Cl interaction has demonstrated that Type II contacts may be understood as a interaction between electrophilic and nucleophilic region between adjacent halogen atom, a feature which unambiguously sup-



Scheme 1. Schematic representation of Type I (*cis* and *trans* geometries) and Type II (L geometry) halogen… halogen contacts.

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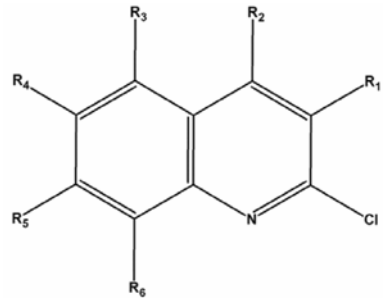
port attractive nature of Cl…Cl interactions.[9] We have recently shown by *in situ* cryo-crystallization technique that the structure of 2-chloro aniline (low melting organic liquid) is stabilized via X_3 synthon resulting in a helical motif along the 3_1 axis.[10]

In this article, we have determined the crystal structure of six 2-chloroquinoline derivatives (scheme 2) and have analysed the directional preference in Cl…Cl interaction in terms of crystal packing and have analysed the propensity of the formation of C–H…Cl contacts in both Type I and Type II geometries. All the six structures are heterocyclic derivatives constituting an interesting class of compounds with synthetic versatility and effective biological activities. Indeed, quinoline and their derivatives have remarkable pharmacological activities and widely used as antiallergic,[11] antimalarial[12] antibacterial,[13] antiproliferative,[14] anticancer[15] and antiparasitic[16] compounds.

2. Experimental

2.1 *Synthesis*

2.1a *Compound* **QN1**: *2,4-dichloro 5-methyl quinoline:* 3-Methylaniline (1 mmol), malonic acid (1 mmol) and 10 ml of dry $POCl_3$ were taken in a RB flask and the resulting mixture was heated at 453 K for 1 h. The reaction mixture after completion of reaction (monitored by TLC) was poured into the crushed ice and residue containing mixture of isomers was extracted with dichloromethane. The pure required isomer product **QN1** was obtained through column chromatography, ethyl acetate/petroleum ether was used as the eluant. Routine IR, NMR and Mass analysis confirmed the formation of compound **QN1**. Single crystals of suitable quality for single crystal X-ray diffraction were grown by solvent evaporation technique from 1 : 1 mixture of ethyl acetate/hexane solvents.



Scheme 2. (i) Compound **QN1** where R_2 = Cl, R_3 = Methyl (CH_3); $R_1 = R_4 = R_5 = R_6$ = H. (ii) Compound **QN2** where R_2 = Cl, R_4 = Methyl (CH_3); $R_1 = R_3 = R_5 = R_6$ = H. (iii) Compound **QN3** where R_1 = Hydroxymethyl (CH_2OH); $R_1 = R_2 = R_3 = R_4 = R_5$ = H. (iv) Compound **QN4** where R_1 = Hydroxymethyl (CH_2OH) and R_5 = Methyl (CH_3); $R_2 = R_3 = R_4 = R_6$ = H. (v) Compound **QN5** where R_1 = Chloromethyl (CH_2Cl) and R_4 = Methyl (CH_3), $R_2 = R_3 = R_5 = R_6$ = H. (vi) Compound **QN6** where R_1 = Chloromethyl (CH_2Cl) and R_6 = Methyl (CH_3), $R_2 = R_3 = R_4 = R_5$ = H.

2.1b *Compound* **QN2**: *2,4-dichloro 6-methyl-quinoline:* 4-Methylaniline (1 mmol), malonic acid (1 mmol) and 10 ml of dry $POCl_3$ were taken in a RB flask and the resulting mixture was heated at 453 K for 1 h. Entire experimental procedure was same as in **QN1**.

2.1c *Compound* **QN3**: *2-Chloro-(quinolin-3-yl) methanol:* 2-Chloro-3-formylquinoline (1 mmol), sodium borohydride (1 mmol) and catalytic amount of montmorillonite K-10 were taken in an open vessel and the resulting mixture was irradiated at 500 W in a domestic microwave oven for 4–5 min. Ethylacetate was poured into the reaction mixture and the catalyst was filtered off. The filtrate was subjected to column chromatography and ethyl acetate/petroleum ether was used as the eluant. IR, NMR and Mass analysis confirmed the formation of compound **QN3**. Single crystals of suitable quality for single crystal X-ray diffraction were grown by solvent evaporation technique from chloroform.

2.1d *Compound* **QN4**: *2-Chloro-(7-methylquinolin-3-yl) methanol:* 2-Chloro-7-methylquinoline-3-carbaldehyde (1 mmol), sodium borohydride (1 mmol) and catalytic amount of montmorillonite K-10 were taken in an open vessel and the resulting mixture was irradiated at 500 W in a domestic microwave oven for 4–5 min. The experimental procedure was similar to compound **QN1**.

2.1e *Compound* **QN5***: 2-Chloro-3-(chloromethyl)-6-methylquinoline:* 2 mL of thionyl chloride was added to 2-chloro-(6-methylquinolin-3-yl) methanol (0·5 mmol) and refluxed at 349 K for 30 min. The progress of the reaction was monitored by thin layer chromatography (TLC). After the completion of reaction, the reaction mixture was cooled and transferred into the crushed ice. The precipitate was filtered and dried in air. The compound was purified by column chromatography using petroleum ether as the eluant. IR, NMR and Mass analysis confirmed the forma-

Table 1. Crystallographic and refinement details for the structures.

Compound	**QN1**	**QN2**	**QN3**
Crystal size (mm)	0·28 × 0·21 × 0·12	0·26 × 0·21 × 0·17	0·24 × 0·18 × 0·15
CCDC number	756830	731569	705547
Molecular Formula	$C_{10}H_7N_1Cl_2$	$C_{10}H_7N_1Cl_2$	$C_{10}H_8N_1O_1Cl_1$
Formula weight (g mol^{-1})	212·07	212·07	193·62
Temperature (K)	295(2)	295(2)	295(2)
Wavelength (Å)	0·71073	0·71073	0·71073
Absorption correction	Multi-scan	Multi-scan	Multi-scan
μ (mm^{-1})	0·650	0·629	0·398
Crystal system	Monoclinic	Triclinic	Triclinic
Space group	$P2_1/c$	P-1	P-1
a (Å)	6·8668(2)	7·1525(2)	7·1181(5)
b (Å)	12·9735(3)	11·5551(3)	7·3518(5)
c (Å)	10·4447(2)	11·9852(3)	9·1811(6)
α (°)	90	90·168(2)	92·803(4)
β (°)	98·476(3)	106·152(3)	106·624(3)
γ (°)	90	91·090(2)	109·900(4)
Volume (Å^3)	920·33(4)	951·25(5)	427·14(5)
Z	4	4	2
Density (g cm^{-3})	1·531	1·481	1·505
F(000)	432	432	200
$\theta_{(min,\ max)}$	2·52, 26	3·00, 25·49	2·35, 25·50
$h_{min,max}$	(–8, 8)	(–8, 8)	(–8, 8)
$k_{min,max}$	(–16 15)	(–13, 13)	(–8, 8)
$l_{min,max}$	(–12,12)	(–14, 14)	(–11, 10)
No. of measured reflections	9527	18705	6896
No. of unique reflections	1810	3542	1578
No. of parameters	119	237	119
$R_{(int)}$	0·0321	0·0310	0·0206
R_all, R_obs	0·0516, 0·0328	0·0531, 0·0376	0·0317, 0·0287
wR_2_all, wR_2_obs	0·0850, 0·0802	0·1082, 0·1038	0·0792, 0·0775
$\Delta\rho_{min,max}$ (e Å^{-3})	–0·244, 0·213	–0·227, 0·209	–0·268, 0·163
G.o.F	1·032	1·067	1·119

Compound	**QN4**	**QN5**	**QN6**
Crystal size (mm)	0·40 × 0·15 × 0·10	0·35 × 0·31 × 0·21	0·21 × 0·16 × 0·12
CCDC number	725752	731573	746771
Molecular formula	$C_{11}H_{10}N_1O_1Cl_1$	$C_{11}H_9N_1Cl_2$	$C_{11}H_9N_1Cl_2$
Formula weight (g mol^{-1})	207·65	226·09	226·09
Temperature (K)	295(2)	295(2)	295(2)
Wavelength (Å)	0·71073	0·71073	0·71073
Absorption correction	Multi-scan	Multi-scan	Multi-scan
μ (mm^{-1})	0·356	0·588	0·578
Crystal system	Monoclinic	Triclinic	Monoclinic
Space group	$P2_1/c$	P-1	$P2_1/c$
a (Å)	19·978(2)	6·6003(8)	15·1752(3)
b (Å)	7·2814(12)	7·6250(10)	4·6020(1)
c (Å)	13·7772(13)	11·1333(14)	14·9781(3)
α (°)	90	84·018(2)	90
β (°)	104·593(10)	74·507(2)	94·357(2)
γ (°)	90	71·764(2)	90
Volume (Å^3)	1939·5(4)	512·70(11)	1042·99(4)
Z	8	2	4
Density (g cm^{-3})	1·422	1·465	1·440
F(000)	864	232	464
$\theta_{(min,\ max)}$	3·06, 25·50	1·90, 25·50	3·13, 26·00

Contd…

Table 1. (*Contd...*)

Compound	QN4	QN5	QN6
$h_{min,max}$	(–23, 24)	(–7, 7)	(–18, 18)
$k_{min,max}$	(–8, 8)	(–9, 9)	(–5, 5)
$l_{min,max}$	(–16, 16)	(–13, 13)	(–18, 18)
No. of measured reflections	19752	5078	9881
No. of unique reflections	3600	1895	2051
No. of parameters	257	128	128
$R_{(int)}$	0·0632	0·0168	0·0192
R_all, R_obs	0·0851, 0·0428	0·0391, 0·0346	0·0406, 0·0312
wR_2_all, wR_2_obs	0·1089, 0·1005	0·0941, 0·0916	0·0974, 0·0942
$\Delta\rho_{min,max}$ (eÅ^{-3})	–0·199, 0·230	–0·302, 0·195	–0·205, 0·177
G.o.F	0·906	1·042	1·136

Table 2. Intermolecular Cl…Cl contacts in studied six compounds.

Compound	C–X_1…X_2–C	X_1…X_2 Å	∠C–X_1…X_2° (θ_1)	∠X_1…X_2–C° (θ_2)	Symmetry operation
QN1	C1–Cl1…Cl1–C1	3·545(2)	144·0	144·0	$-x+1, -y+2, -z-1$
QN2	C3A–Cl2A…Cl1B–C1B	3·662(1)	168·0	107·2	$x, y-1, z+1$
	C3B–Cl1A…Cl2B–C1A	3·813(1)	156·8	109·1	$x, y, z+1$
QN3	C1–Cl1…Cl1–C1	3·661(2)	150·4	150·4	$-x+1, -y+2, -z+1$
QN4	C1B–Cl1B…Cl1A–C1A	3·546(1)	142·2	122·5	$x-1, -y+1/2, z+1/2$
QN5	C10–Cl2…Cl2…C10	3·613(1)	155·6	155·6	$-x+2, -y, -z$
	C1–Cl1…Cl2–C10	3·614(2)	167·5	100·1	$-x+1, -y+1, -z$
	C1–Cl1…Cl1–C1	3·575(2)	132·0	132·0	$-x+1, -y+1, -z$
QN6	C10–Cl2…Cl1–C1	3·538(1)	167·8	104·9	$-x+1, -y+2, -z+1$

tion of compound **QN5**. Single crystals of suitable quality for single crystal X-ray diffraction were grown by solvent evaporation technique from chloroform.

2.1f *Compound* **QN6**: *2-Chloro-3-(chloromethyl)-8-methylquinoline:* To 2-chloro-(8-methylquinolin-3-yl) methanol (0·5 mmol), 2 mL of thionyl chloride was added and refluxed at 349 K for 30 min. The workup procedure was similar to compound **QN5**.

2.2 *X-ray diffraction*

The single crystal X-ray diffraction data of all crystals were collected on an Oxford Xcalibur (Mova) diffractometer with Eos CCD detector.[17] The X-ray generator was operated at 50 kV and 1mA using Enhanced MoKα radiation. Data were collected with ω scan width of 1°. The data reduction, an empirical absorption correction and space group determination were done using CrysAlisPro RED of Oxford Diffraction.[17] The crystal structures were solved by direct method using either SIR92[18] or SHELXS[19] and refined by full matrix least-squares method using SHELXL97,[19] present in the program suite WinGx (version 1.63.04a).[20] The molecular diagrams were generated using POV-ray (version 3.6)[21] and the packing diagrams were generated using CAMERON.[22] Geometrical calculations were done using PARST95[23] and PLATON.[24] The positions of all hydrogen atoms were fixed geometrically and refined isotropically using the riding hydrogen atom model. The details of the data collection and refinement are given in table 1, Cl…Cl contacts and other intermolecular interactions are listed in tables 2 and 3, respectively.

3. Result and discussion

3.1 *Structure of 2,4-dichloro 5-methylquinoline* (**QN1**)

The substitution of methyl moiety to 2-chloroquinoline structure at position R_3 resulted in compound **QN1** (scheme 2), which crystallizes in the space group $P2_1/c$ with $Z = 4$. Figure 1a gives the ORTEP diagram of **QN1** with ellipsoids drawn at 50% probability. Intermolecular Cl…Cl contacts of Type I *trans* geometry (figure 1b, table 2) along with

Table 3. Intermolecular interactions in studied six compounds.

Crystal	D–H…A	D–H/Å	H…A/Å	D…A/Å	∠D–H…A/°	Symmetry
QN1	C6–H6…N1	0·930	2·610	3·530(1)	169·0	$x, -y + 1/2 + 1, z + 1/2$
QN2	C10A–H10C…Cl2B	0·960	2·956	3·719(2)	137·0	$-x, -y + 1, -z$
QN3	O1–H1O…N1	0·820	2·220	2·956(2)	149·0	$x - 1, y, z$
	C4–H4…O1	0·930	2·685	3·146(2)	136·0	$-x, -y + 1, -z + 2$
	C10–H10A…Cg(2)	0·970	2·790	3·689(1)	154·0	$-x + 1, -y + 2, -z$
QN4	O1A–H1OA…N1A	0·820	2·160	2·921(2)	155·0	$x, -y + 1/2, z + 1/2$
	O1B–H1OB…N1B	0·820	2·220	2·978(3)	153·0	$x, -y + 1/2 + 1, z + 1/2 - 1$
	C11A–H11A…O1A	0·960	2·650	3·420(3)	137·0	$-x + 1, y - 1/2, z + 1/2 + 1$
	C4B–H4B…O1B	0·930	2·689	3·454(3)	140·0	$-x + 2, -y + 1, -z + 1$
QN5	C10–H10A...Cl1	0·970	2·868	3·747(2)	151·0	$x + 1, y, z$
QN6	C10–H10B…Cl2	0·970	2·942	3·899(2)	169·0	$-x + 1, y + 1/2, -z + 1/2 + 1$
	C10–H10A…Cg(1)	0·970	2·970	3·563(2)	121·0	$x, y - 1, z$

In compound **QN3**, Cg(2) is centroid of C4/C9 ring whereas in compound **QN6**, Cg(1) is centroid of N1–C1–C2–C3–C9–C8 ring.

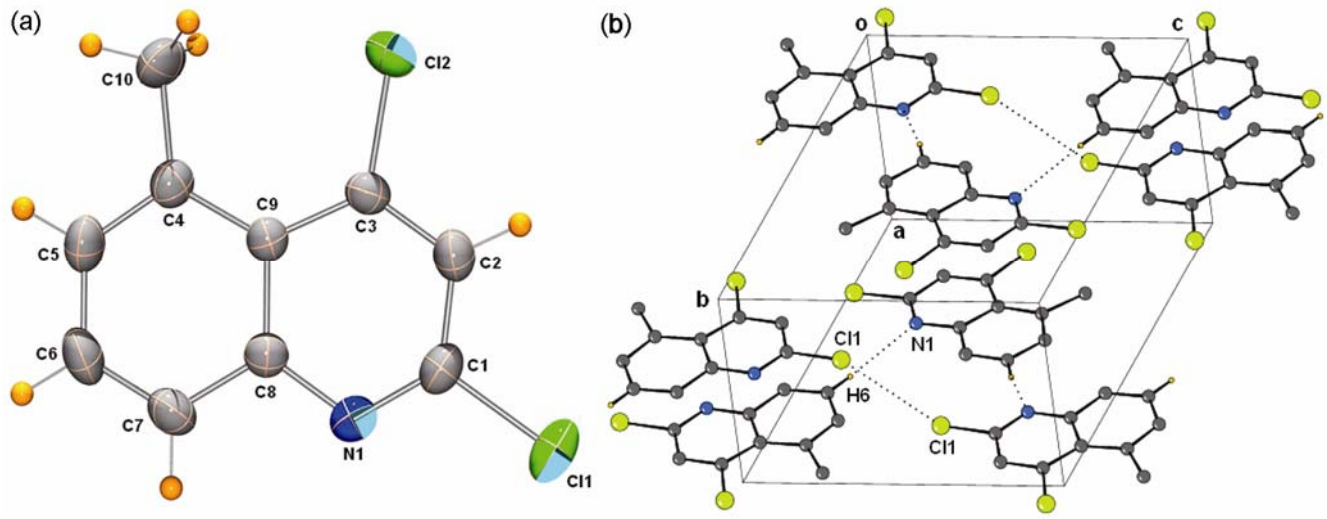


Figure 1. (**a**) *ORTEP* of compound **QN1** drawn with 50% ellipsoidal probability. (**b**) Packing diagram of compound **QN1** depicting intermolecular Cl…Cl contacts and C–H…N hydrogen bonds.

an intermolecular C–H…N hydrogen bond (table 3) hold the molecules together in the crystal lattice. This results in a parallel arrangement of molecules generation $\pi\ldots\pi$ stacking interactions with a separation distance of 3·614(1)–3·724(2) Å between aromatic rings leading to further stabilization of the crystal structure.

3.2 *Structure of 2,4-dichloro 6-methylquinoline* (**QN2**)

Compound **QN2** is an isomer of compound **QN1** with the methyl group now at position R_4 (scheme 2). The cell parameters are almost identical to **QN1** and the compound crystallizes in a triclinic P-1 space group with two independent molecules in the asymmetric unit. The ORTEP diagram of **QN2** (figure 2a) shows the two independent molecules and the dihedral angle between the least squares planes of these molecules is 15·88(2)°. Cl…Cl intermolecular interactions develop between Cl1A and Cl2B (figure 2b, table 2) connecting the two independent molecules in a two-dimensional motif through the entire crystal. An additional short Cl…Cl contact (slightly larger than the van der Waal radii sum, table 2) develops as a consequence. Indeed this contact appears as a surrogate to the C–H…Cl interaction (figure 2b). $\pi\ldots\pi$ stacking interactions of 3·578(1)–3·768(2) Å between aromatic rings stabilize the packing in the lattice. It is noteworthy

that the nitrogen atom does not participate in an intermolecular interaction like in **QN1**.

3.3 *Structure of 2-Chloro-(quinolin-3-yl) methanol* (**QN3**)

The substitution of hydroxymethyl group at the position R_1 of 2-chloroquinoline gives compound **QN3** (scheme 2) which crystallizes in the space group P-1 with $Z = 2$ (figure 3a). Type I Cl…Cl contacts with *trans* geometry (figure 3b) hold the molecules together along with strong intermolecular O–H…N and C–H…O hydrogen bonds (figure 3b, table 3). C–H…π (figure 3b, table 3) interactions provide further stability by holding molecular dimers across the centre of inversion. π…π aromatic stacking interactions of 3·674(1)–3·774(1) Å between aromatic rings exist as in the previous cases.

3.4 *Structure of 2-Chloro-(7-methylquinolin-3-yl) methanol* (**QN4**)

The substitution of an additional methyl group at position R_3 to **QN3** gives compound **QN4** (scheme 2, figure 4a), which crystallizes in the space group $P2_1/c$ with $Z = 8$ and resulting in two independent molecules at asymmetric unit. The dihedral angle between the least squares plane of two independent molecules in asymmetric unit is 6·17(2)°. Cl…Cl contacts have Type II geometry, however θ_1 and θ_2 deviate significantly from the ideal values of Type II contact (figure 4b, table 2). O–H…N and C–H…O hydrogen bonds add further stability to the packing (figure 4b, table 3). π…π aromatic stacking interac-

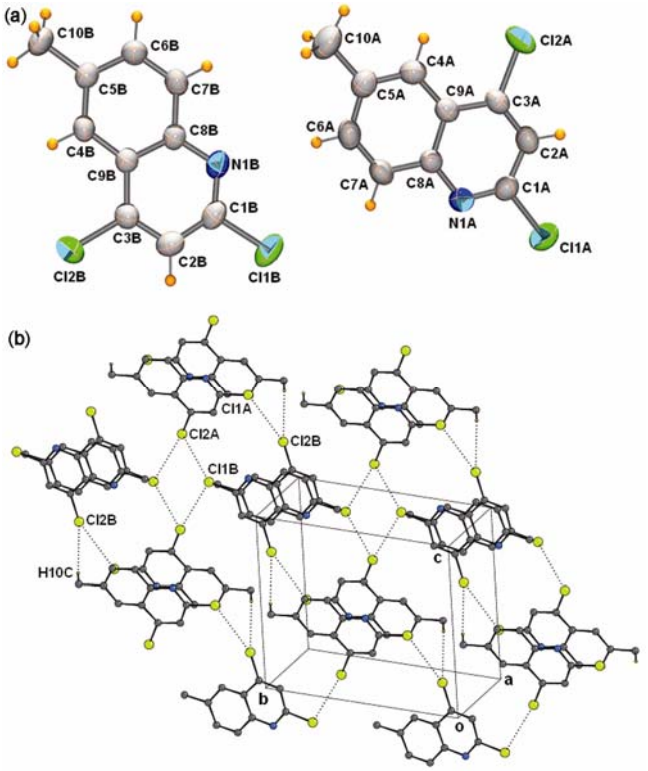


Figure 2. (**a**) *ORTEP* of compound **QN2** drawn with 50% ellipsoidal probability. (**b**) Packing diagram of compound **QN2** depicting intermolecular Cl…Cl contacts and C–H…Cl hydrogen bonds.

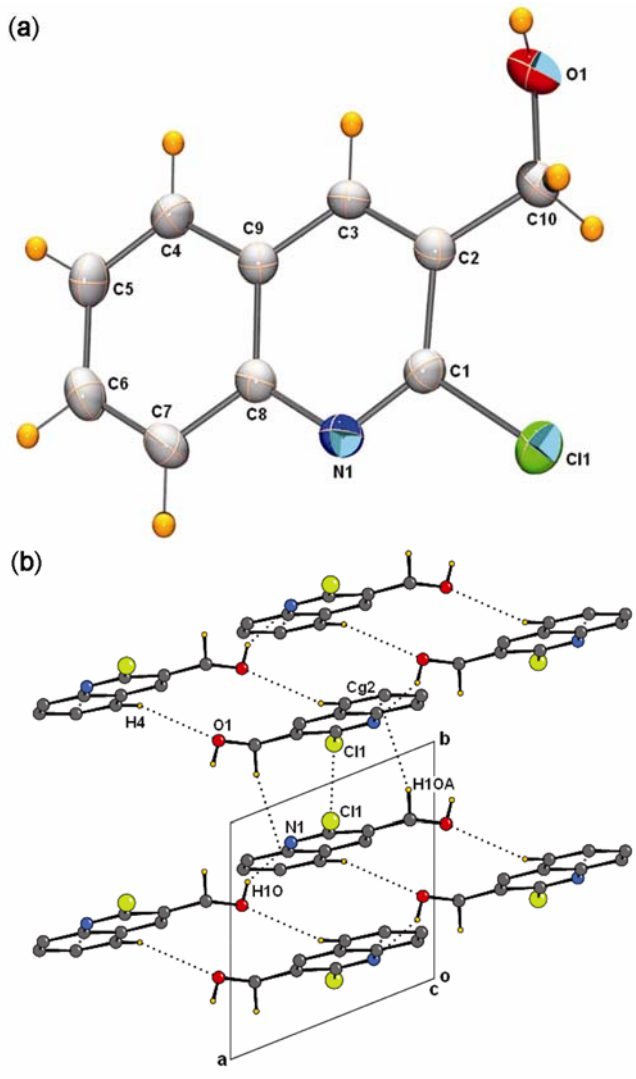


Figure 3. (**a**) *ORTEP* of compound **QN3** drawn with 50% ellipsoidal probability. (**b**) Packing diagram of compound **QN3** depicting intermolecular Cl…Cl contacts, O–H…N hydrogen bonds along with C–H…O and C-H…π [Cg(2)] interactions which generate molecular dimers.

tions of 3·842(1)–3·887(2) Å between aromatic rings stabilise the packing.

3.5 *2-Chloro-3-(chloromethyl)-6-methylquinoline* (**QN5**)

The substitution of chloromethyl group at position R_1 and methyl group at R_4 respectively to 2-chloroquinoline resulted in compound **QN5** (scheme 2, figure 5a), which crystallises in the space group P-1 with $Z = 2$. The crystal structure is stabilized by Cl…Cl interactions and C–H…Cl halogen bonds only. Cl1 and Cl2 generate 'bifurcated' Cl…Cl short contacts resulting in a 'sawtooth' type supramolecular network in the crystal lattice (figure 5b). Both Type I and Type II Cl…Cl intermolecular interactions coexist in this structure. The C–H…Cl hydrogen bond generates a one dimensional molecular chain along the crystallographic '*a*' axis (figure 5b, table 3). $\pi\ldots\pi$ aromatic stacking interactions in the range of 3·718(1)–3·764(2) Å between aromatic rings provide further stability as in the previous cases.

3.6 *Structure of 2-chloro-3-(chloromethyl)-8-methylquinoline* (**QN6**)

Compound **QN6** is an isomer of compound **QN5.** (scheme 2). The compound (figure 6a) crystallizes in the space group $P2_1/c$ with $Z = 4$. Cl…Cl interactions with Type II geometry are generated by involving chlorine atoms Cl1 and Cl2, resulted in a molecular dimer formation across the centre of inversion (figure 6b, table 2). C–H…Cl hydrogen bonds generate a 'sinusoidal' molecular chain (figure 6b). C–H…π intermolecular interactions generate a 1D molecular chain as in **QN5** while one $\pi\ldots\pi$ stacking interaction of 3·614(1) Å is conserved in the crystal packing.

4. Conclusion

The above studies bring out an interesting feature in substituted 2-chloroquinolines. Type II Cl…Cl interactions generate C–H…Cl interactions in the supramolecular assembly in the crystal lattice. This

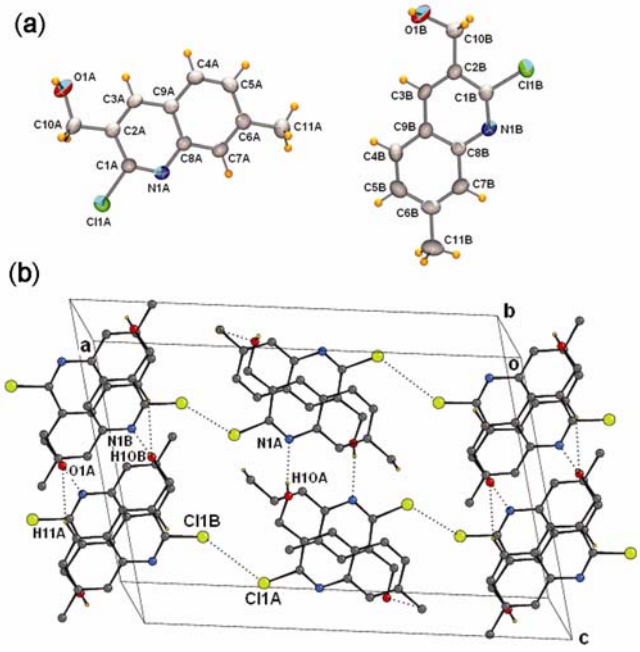


Figure 4. (**a**) *ORTEP* of compound **QN4** drawn with 50% ellipsoidal probability. (**b**) Packing diagram of compound **QN4** depicting intermolecular Cl…Cl interactions, O–H…N and C-H…O hydrogen bonds.

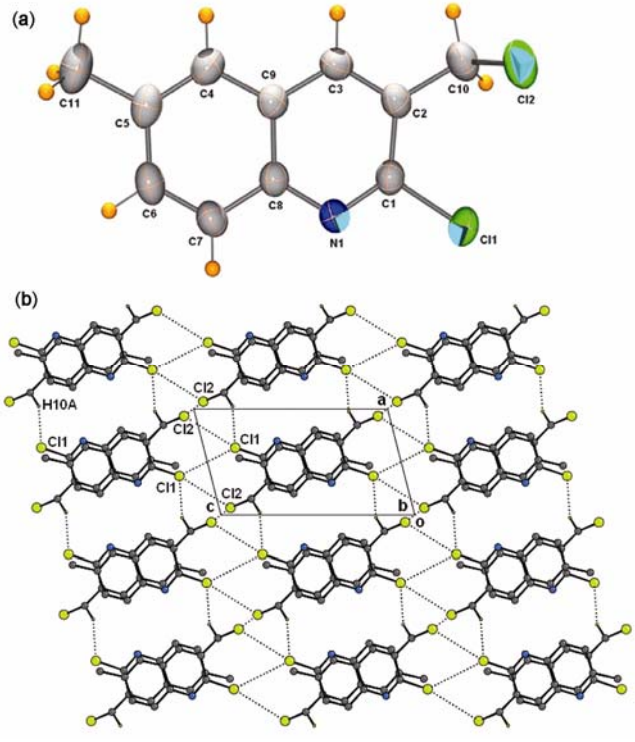


Figure 5. (**a**) *ORTEP* of compound **QN5** drawn with 50% ellipsoidal probability. (**b**) Packing diagram of compound **QN5** showing 'bifurcated' Cl…Cl short contacts generating a 'saw tooth' type network. C–H…Cl hydrogen bonds form a molecular chain along '*a*' axis.

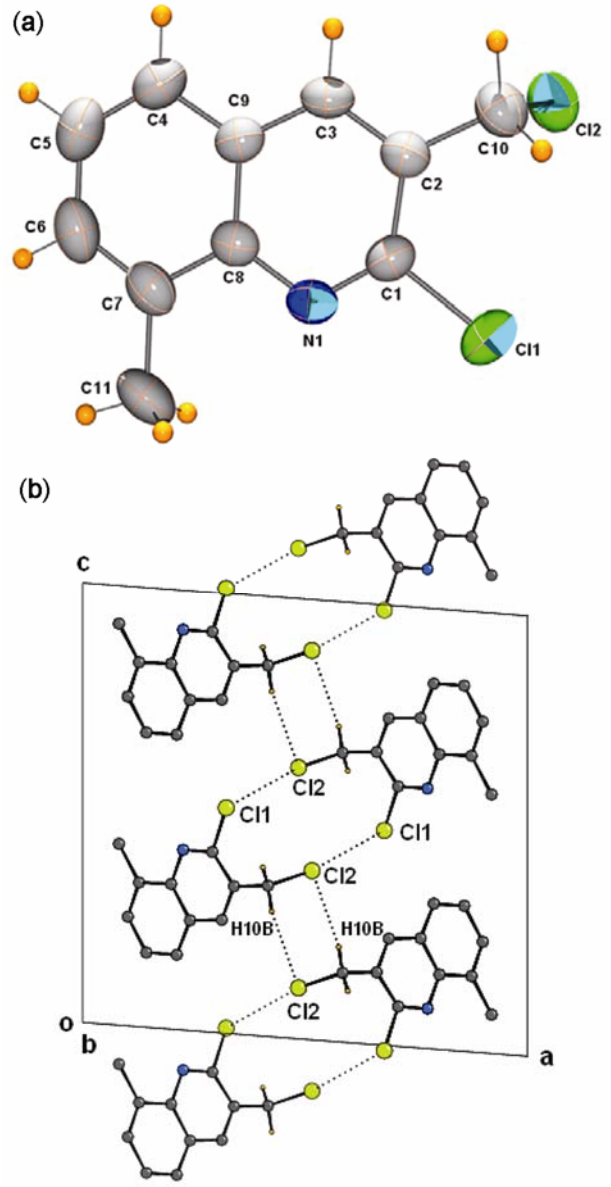


Figure 6. (**a**) *ORTEP* of compound **QN6** drawn with 50% ellipsoidal probability. (**b**) Packing diagram of compound **QN6** depicting intermolecular Cl…Cl contacts and C-H…Cl hydrogen bonds forming molecular dimmer across the center of inversion.

in fact avoids formation of other types of both weak and strong hydrogen bonds. In all Type I contacts other hydrogen bonds, both strong and weak appear to add stability to the packing features.

Supplementary material

Crystallographic details (excluding structure factors) on the structure analysis of the all compounds (**QN1–QN5**) reported in this paper have been deposited with the Cambridge Crystallographic Data Center, 12 Union Road, Cambridge, CB2, 1E-Z,UK (Fax: +44-1223-336-033; email: deposit@ccdc.sam.ac.uk). The depository numbers are given in the tables.

Acknowledgements

We thank Department of Science and Technology (DST), FIST level II for providing the XCaliber Mova Oxford diffraction machine at SSCU, Indian Institute of Science (IISc), Bangalore. FNK thanks DST for Fast Track proposal funding.

References

1. Desiraju G R and Sarma J A R P 1986 *Proc. Indian Acad. Sci., Chem. Sci.* **96** 599
2. Green B S and Schmidt G M J 1971 *Israel Chemical Society Annual Meeting Abstracts* (Israel Chemical Society) p. 190
3. Awwadi F F, Willett R D, Peterson K A and Twamley B 2006 *Chem. Eur. J.* **12** 8952; Price S L, Stone A J, Lucas J, Rowland R S and Thornley A E 1994 *J. Am. Chem. Soc.* **116** 4910
4. Reddy C M, Kirchner M T, Gundakaram R C, Padmanabhan K A and Desiraju G R 2006 *Chem. Eur. J.* **12** 2222
5. Sakurai T, Sundaralingam M and Jeffrey G A 1963 *Acta Crystallogr.* **16** 354; Ramasubbu N, Parthasarathy R and Murray-Rust P 1986 *J. Am. Chem. Soc.* **108** 4308; Desiraju G R and Parthasarathy R 1989 *J. Am. Chem. Soc.* **111** 8725; Saha B K, Nangia A and Nicoud J F 2006 *Cryst. Growth Des.* **6** 1278
6. Pedireddi V R, Reddy D S, Goud B S, Craig D C, Rae A D and Desiraju G R 1993 *J. Chem. Soc. Perkin Trans. 2* 2353
7. Choudhury A R and Row T N G 2004 *Cryst. Growth Des.* **4** 47; Thalladi V R, Weiss H-C, Bläser D, Boese R, Nangia A and Desiraju G R 1998 *J. Am. Chem. Soc.* **120** 8702
8. Chopra D, Cameron T S, Ferrara J D and Row T N G 2006 *J. Phys. Chem. A* **110** 10465
9. Garci_a P, Dahaoui S, Katan C, Souhassou M and Lecomte C 2007 *Faraday Discuss.* **135** 217; Bui T T T, Dahaoui S, Lecomte C, Desiraju G R and Espinosa E 2009 *Angew. Chem. Int. Ed.* **48** 3838
10. Nayak S K, Prathapa S J and Row T N G 2009 *J. Mol. Struct.* **935** 156
11. Cairns H, Cox D, Gould K J, Ingall A H and Suschitzky J L 1985 *J. Med. Chem.* **28** 1832
12. Jain R, Jain S, Gupta R C, Anand N, Dutta G P and Puri S K 1994 *Indian J. Chem.* **B33** 251
13. Mohammed A, Abdel-Hamid N, Maher F and Farghaly A 1992 *Czech. Chem. Comm.* **57** 1547
14. Croisy-Delcey M, Coroisy A, Carrez D, Huel C, Chiaroni A, Ducrot P, Bisagni E, Jin L and Leclercq G 2000 *Bioorg. Med. Chem.* **8** 2629

15. Dlugosz A and Dus D 1996 *Farmaco* **51** 367
16. Abadi A H, Brun R and Arzneimforsch 2003 *Drug Res.* **53** 655
17. Oxford Diffraction 2009, CrysAlisPro CCD and CrysAlisPro RED. Versions 1.171.33.41. Oxford Diffraction Ltd., Abingdon, Oxfordshire, England
18. Altomare A, Cascarano G, Giacovazzo C and Guagliardi A 1993 *J. Appl. Crystallogr.* **26** 343
19. Sheldrick G M 2008 *Acta Crystallogr. Sect. A* **64** 112
20. Farrugia L J 1999 *J. Appl. Crystallogr.* **32** 837
21. The POV-Ray Team, 2004. POV-Ray – The persistence of vision raytracer; http://www.povray.org
22. Watkin D M, Pearce L and Prout C K 1993 CAMERON – A Molecular Graphics Package, Chemical Crystallography Laboratory, Oxford, University of Oxford
23. Nardelli M 1995 *J. Appl. Crystallogr.* **28** 569
24. Spek A L 2003 *J. Appl. Crystallogr.* **36** 7