New Cholesterol-based Gelators with Light- and Metal-responsive Functions

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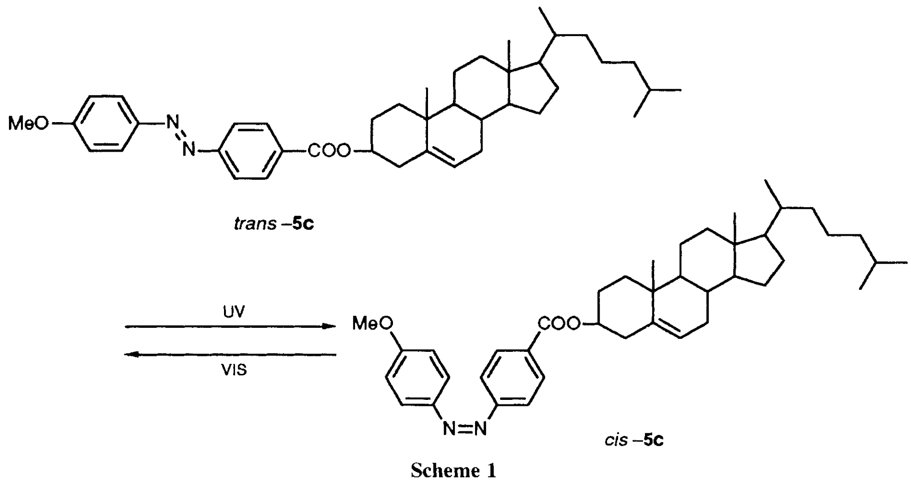
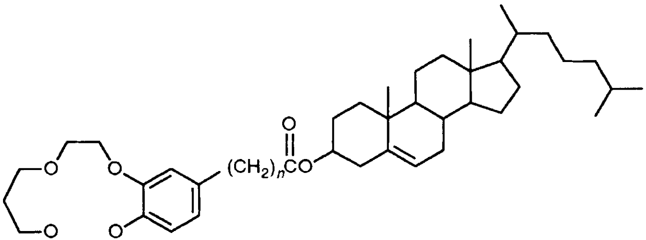
Cholesterol derivatives containing a benzocrown ether moiety or an azobenzene moiety coupled to C-3 of a steroidal moiety through an ester linkage are synthesized; some of them act as thermally reversible gelators of organic fluids and show novel light- and metal-responsive functions.

Cholesterols are versatile building blocks, which support the formation of liquid crystals,[1] bilayer membranes,[2,3] *etc.*[4] Recently, Lin *et al.*[5] found a new family of gelators of organic fluids, which contain a 2-substituted anthracenyl-type group coupled to C-3 of a steroidal group. The finding indicates that the aggregative nature of the cholesterol skeleton, which tends to form liquid-crystalline aggregates, is also operative in the gelation of organic fluids. We are currently interested in host–guest chemistry and signal-responsive chemistry in molecular assembly systems.[6,7] We previously synthesized cholesterol derivatives bearing the crown ether moiety or the azobenzene moiety **1–5**.[1,6–9] The purpose of the study was to control the unique characteristics of cholesteric liquid crystals by photoirradiation or crown–metal interactions. For ex-

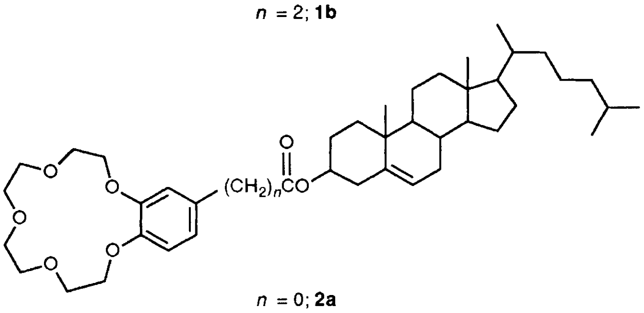


Scheme 1

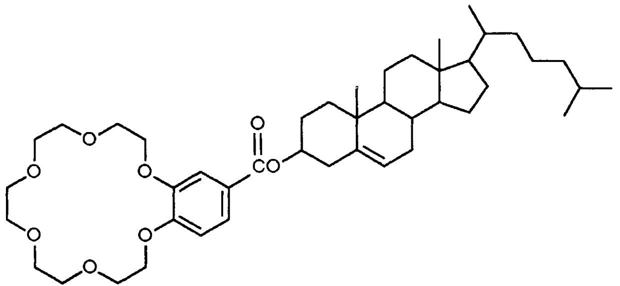
ample, the helical pitch of cholesteric liquid crystals containing **2** or **3** is changed when alkali metal cations are bound to the crown ether ring.[6] In particular, when optically active ammonium salts are added, the helical pitch is changed in an enantioselective manner.[7] It thus becomes possible to determine the chirality by a colour change.[7] The report by Lin *et al.*[5] encouraged us to develop cholesterol-based gelators with light- and metal-responsive functions. We report here that **1a**, **3**, **4b** and **5c** act as gelators of organic fluids and the gels 'respond' to photoirradiation and added metal cations.



n = 0; **1a**
n = 2; **1b**



n = 0; **2a**
n = 2; **2b**



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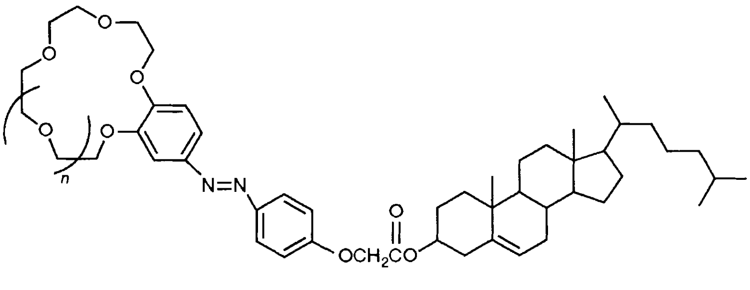
The gelation test was carried out as follows: the cholesterol derivative (**1–5**; 20 mg) was mixed with solvent (1.0 g) in a septum-capped test tube and the mixture was heated until the solid was dissolved. The solution was cooled to room temperature and left for one day in the dark (G in Table 1 denotes that the gel is formed at this stage). In case the gel was not formed at room temperature, the solution was cooled in a refrigerator (at −6 °C) for one day (CG in Table 1 denotes that the gel is formed at this stage). The results are summarized in Table 1.

Examination of Table 1 reveals that **1a**, **3**, **4b** and **5c** act as gelators of certain solvents. In particular, **4b** and **5c** are excellent gelators of cyclohexane and certain aliphatic alcohols. For example, only 0.5 mg of **5c** could gelatinize 1.0 ml of butanol at 15 °C. Interestingly, the aggregates formed from **5c** in butanol could be directly observed by an optical microscope (Fig. 1). When the homogeneous solution was

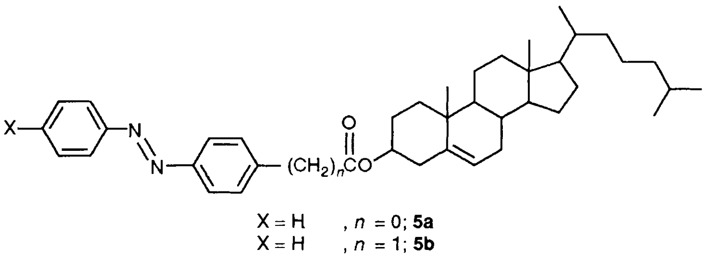
Table 1 Organic fluid tested for gelation by **1–5**[a]

Organic fluid	1a	1b	2a	2b	3	4a	4b	5a	5b	5c
Hexane	CG	N	N	N	N	N	PG	N	N	N
Heptane	N	N	N	N	N	N	PG	N	N	N
Cyclohexane	N	N	N	N	N	N	G	N	N	G
Ethanol	N	N	N	N	N	N	N	N	N	N
Propanol	N	N	N	N	CG	N	G	N	N	PG
Butanol	N	N	N	N	CG	N	CG	N	N	G
Octanol	N	N	N	N	N	N	N	N	N	N
Benzene	N	N	N	N	N	N	N	N	N	N
Hexane/benzene (4 : 1 v/v)	N	N	N	N	N	N	G	N	N	N
Cyclohexane/benzene (9 : 1 v/v)	—	—	—	—	—	—	G	—	—	G
Cyclohexane/benzene (5 : 1 v/v)	—	—	—	—	—	—	PG	—	—	G
Cyclohexane/benzene (3 : 1 v/v)	—	—	—	—	—	—	PG	—	—	PG
Cyclohexane/benzene (2 : 1 v/v)	—	—	—	—	—	—	N	—	—	N

[a] [gelator] = 20 mg g^{-1}; G = gel formed at room temperature, CG = gel formed when cooled in a refrigerator: (−6 °C), PC = gel partly formed when cooled in a refrigerator, N = gel not formed.



n = 1; **4a**
n = 2; **4b**



X = H , *n* = 0; **5a**
X = H , *n* = 1; **5b**
X = CH_3O, *n* = 0; **5c**

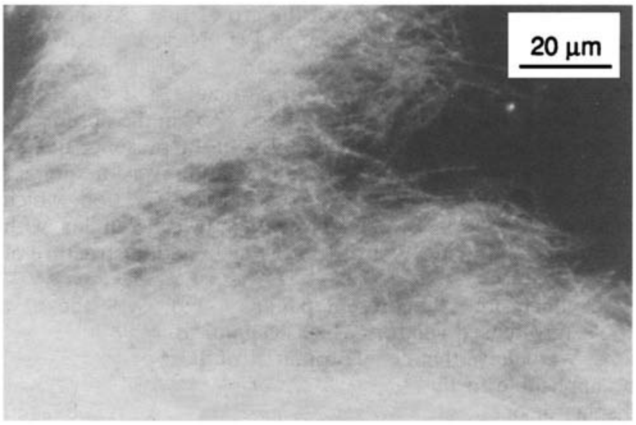


Fig. 1 Optical micrograph of **5c** in butanol at room temperature; [**5c**] = 2.0 mg g^{-1}. The bar indicates the 20 μm length.

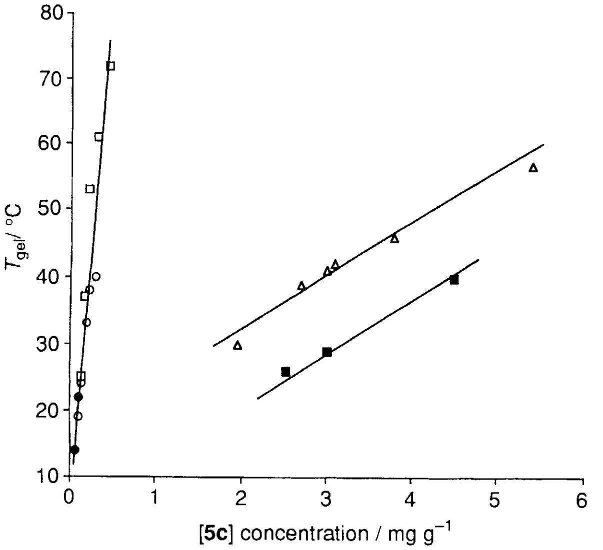


Fig. 2 Plot of T_{gel} *vs.* [**5c**]; △ cyclohexane : benzene = 9 : 1 v/v (method A), ■ cyclohexane : benzene = 6 : 1 (method B), ☐ butanol (method A), ○ butanol (method B) and ● butanol (method C)

cooled below T_{gel}, the fibrillar aggregates with *ca.* 0.1 μm diameter appeared. When the gel was heated above T_{gel}, the aggregates disappeared.

Next, we determined T_{gel} of **5c** by three different methods: the test-tube tilting method (method A),[10] the ball-drop method (method B)[10] and the spectroscopic turbidity method (method C). In method A, a test tube containing the gel was immersed inversely in a thermostatted water-bath. In method B, a steel ball with a 3 mm diameter was put on the gel. In method C, we prepared the gel in a 10 mm optical cell and measured the transmittance at 600 nm where the cholesterol derivatives do not absorb. Here, the T_{gel} was defined as the temperature at which the gel disappears. In every case the temperature was raised at a rate of 0.5 °C min^{-1}. The results are shown in Fig. 2.

It can be seen from Fig. 2 that the T_{gel} values determined by three different methods are all in good accord within the experimental error (±2 °C) and rise with increasing **5c** concentration. The gelation of butanol was observed at the very low **5c** concentration and the slope [= $\Delta T_{gel}/\Delta C$ = 180 °C (mg **5c** per g solvent: mg $g^{-1})^{-1}$] was much greater than those for the cyclohexane–benzene mixed system [$\Delta T_{gel}/\Delta C$ = 7 °C (mg $g^{-1})^{-1}$]. The steep slope implies that the sol–gel transition of the **5c**–butanol system is sensitively affected by the change in the gelator concentration. Another finding suggests that the sol–gel transition of the **5c**–butanol system is also affected by the slight change in the gelator structure (*e.g.* by the *cis–trans* photoisomerization of the azobenzene moiety). We prepared the gel ([**5c**] = 0.5 mg g^{-1}) in a 10 mm optical cell, which was photoirradiated by a 400 W high-pressure Hg-lamp through a colour glass filter (Toshiba UV-D35, 330< λ <380 nm). The spectral change was followed at 15 °C by a dual wavelength spectrophotometer. The absorption maximum at 365 nm (*trans*-**5c**) disappeared gradually with a tight isosbestic point at 416 nm to give rise to a new absorption maximum at 445 nm (*cis*-**5c**). The proportion of *cis* at the photostationary state was estimated to be 38%. The thermal *cis*-to-*trans* isomerization in the dark was very slow. On the other hand, *cis*-**5c** was rapidly isomerized to *trans*-**5c** using the same Hg-lamp through a colour glass filter (Toshiba Y-46, λ > 460 nm). T_{gel} values determined by method C were 16°C for *trans*-**5c** and below 2 °C for the *cis–trans* mixture (containing 38% cis-**5c**). We thus

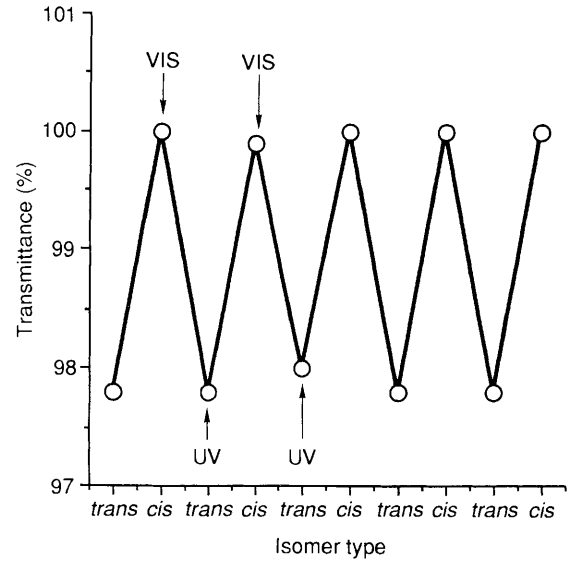


Fig. 3 Photocontrol of the sol–gel phase transition; UV denotes irradiation of UV light (330< λ <380 nm) and VIS denotes irradiation of visible light (λ >460 nm)

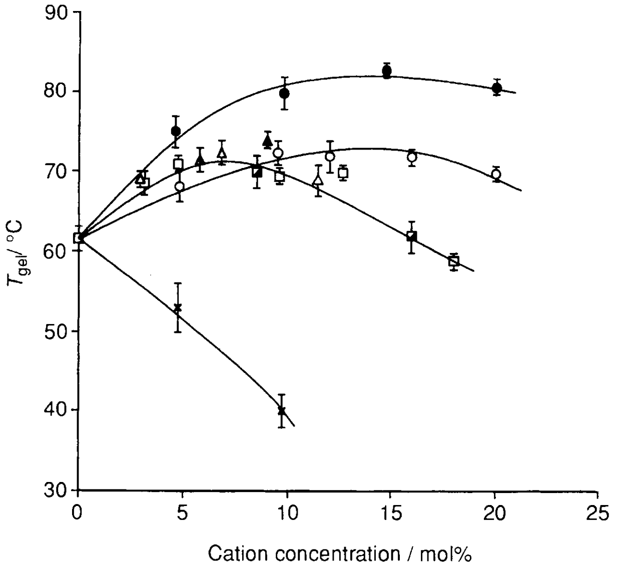


Fig. 4 T_{gel} *vs.* alkali metal cation concentration for **4b**–methylcyclohexane–benzene (4 : 1) system; ○ $Li^+(SCN^-)$, ☐ $Na^+(SCN^-)$, ◩ $Na^+(ClO_4^-)$, △ $K^+(SCN^-)$, ▲ $K^+(ClO_4^-)$, ● $Rb^+(ClO_4^-)$, × $Cs^+(ClO_4)$

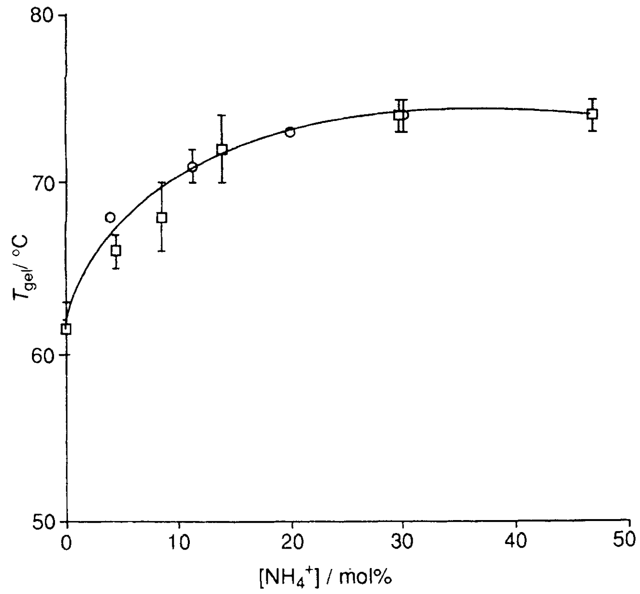


Fig. 5 T_{gel} *vs.* ammonium cation concentration for **4b**-methylcyclohexane–benzene (4 : 1) system; ○ $CH_3CO_2NH_4$, □ $C_6H_5CO_2NH_4$

fixed the temperature at 10 °C and photoirradiated the cell alternately by UV and VIS. As shown in Fig. 3, *trans*-**5c** provided the gel with 97.8 ± 0.2% transmittance whereas the *cis–trans* mixture provided the sol with 100% transmittance. Hence, the sol–gel phase transition could be repeated reversibly by a light switch, Scheme 1.

Figs. 4 and 5 show the T_{gel} dependence of the **4b**-methylcyclohexane–benzene (4 : 1 v/v) system on added alkali metal and ammonium cations. The concentration of **4b** was 4.7 wt%. Since the alkali metal and ammonium salts used herein ($MClO_4$, MSCN and $RCOONH_4$) are scarcely soluble in the gelation solvents, these metal salts should be solubilized through the complexation with the crown ring. As shown in Fig. 4, the T_{gel} in the presence of Li^+, Na^+, K^+, Rb^+ and NH_4^+ rose with increasing metal or ammonium concentration and then gradually decreased. In particular, the T_{gel} in the presence of Rb^+ increased to 82 from 62 °C in the absence of the metal cation. In contrast, the T_{gel} in the presence of Cs^+ decreased monotonously and the gelation was no longer observed above 15 mol%. We consider that Cs^+ ion, which tends to form a 1 : 2 metal–crown sandwich complex with 18-crown-6, effectively disorders the aggregation structure of **4b**.

In conclusion, the present paper demonstrates the new cholesterol-based gelators which respond to light and added ions. We believe that novel properties of these gelators would be applicable to the development of new optical storage or display devices since the transmittance is reversibly changed by light.

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