DOI 10.1007/s10593-022-03111-9

Chemistry of Heterocyclic Compounds **2022**, *58*(8/9), 449–453

Synthesis of sulfolanopyranochromenones by the reaction of 2-benzylidene-3-methyl-4-nitro-2,5-dihydrothiophene 1,1-dioxides with 4-hydroxycoumarin

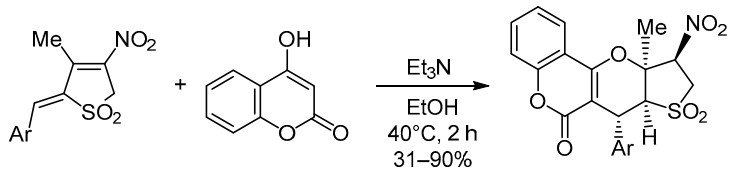
Irina E. Efremova[1]*, Igor I. Savelev[1], Ruslan I. Baichurin[1], Vladislav V. Gurzhiy[2]

[1] *Herzen State Pedagogical University of Russia, 48 Moyka River Embankment, Saint Petersburg 191186, Russia; e-mail: kohrgpu@yandex.ru*

[2] *Saint Petersburg State University, 7/9 University Embankment, Saint Petersburg 199034, Russia; e-mail: vladgeo17@mail.ru*

Translated from Khimiya Geterotsiklicheskikh Soedinenii, 2022, *58*(8/9), 449–453

Submitted July 1, 2022
Accepted after revision August 22, 2022



A number of tetracyclic compounds with annulated nitrosulfolane and pyranochromenone rings were synthesized by reacting 2-benzylidene-3-methyl-4-nitro-2,5-dihydrothiophene 1,1-dioxides with 4-hydroxycoumarin. Structural features of the resulting polycyclic compounds were established on the basis of IR, ^{1}H, ^{13}C NMR, ^{1}H–^{13}C HMQC, ^{1}H–^{13}C HMBC, NOESY spectroscopy and X-ray structural analysis data.

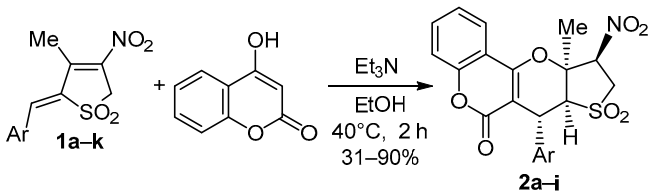
Keywords: 2-benzylidene-3-methyl-4-nitro-2,5-dihydrothiophene 1,1-dioxides, enolizable cyclic CH acids, 4-hydroxycoumarin, sulfolenes, domino process.

Construction of polycyclic systems based on 4-hydroxycoumarin is relevant due to their potential biological activity.[1–3] Various synthetic approaches are employed to assemble such compounds using functionalized alkenes[4–6] and alkynes,[7] conjugated nitroalkenes.[8–11] However, the reactions of 4-hydroxycoumarin with dienes are represented by single examples.[12]

In order to create a new type of polycyclic structures combining the coumarin (2*H*-chromen-2-one) fragment together with the nitrosulfolane ring, we studied the reactions of 4-hydroxycoumarin with 2,5-dihydrothiophene 1,1-dioxide nitrosulfodiene derivatives, 2-benzylidene-3-methyl-4-nitro-2,5-dihydrothiophene 1,1-dioxides (BNTD).[13] Previously, these dienes were shown to be effective substrates for the construction of annulated sulfolane-containing polycyclic compounds by reactions with hydrazine and its analogs,[14–17] as well as dimedone.[18]

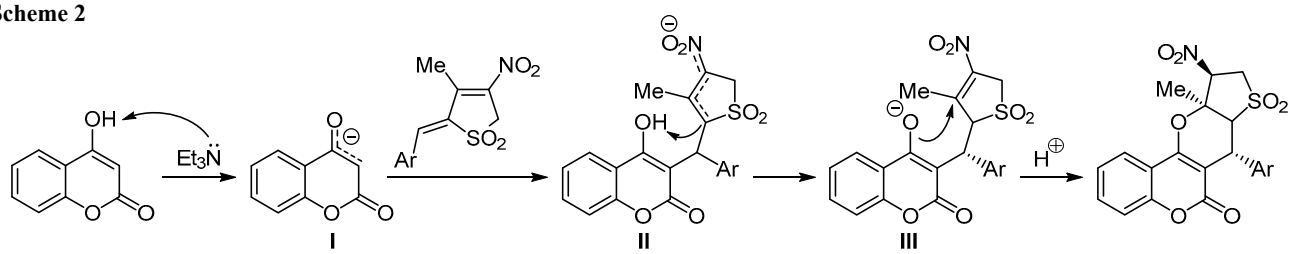
The reaction of BNTDs **1a**–**k** with 4-hydroxycoumarin, as well as dimedone,[18] proceeded in EtOH in the presence of catalytic amounts of Et_3N at 40°C for 2 h and resulted in the synthesis of the target sulfolanopyranochromenones **2a**–**i** isolated as single diastereomers. It turned out that the yields of the resulting polycyclic compounds depend on the degree of conjugation of the nitrodiene system of the starting diene (Scheme 1). The highest yields (79–90%) were noted for polycyclic compounds **2b**,**d**,**e**,**g**–**i** synthesized from dienes **1b**,**d**,**e**,**g**–**i** with electron-withdrawing aromatic groups;[13] however, BNTDs **1j**,**k** containing electron-donating aromatic substituents did not react under these conditions. An increase in the reactivity of dienes **1b**–**d** with disturbed coplanarity is also noted;[13] for example, the yield of tetracyclic compound **2c** obtained from *ortho*-substituted BNTD **1c** was 34% higher than the yield of *para*-substituted isomer **2f**.

Scheme 1



2 a Ar = Ph (70%), **b** Ar = 2-BrC_6H_4 (87%), **c** Ar = 2-MeC_6H_4 (65%), **d** Ar = 2-ClC_6H_4 (85%), **e** Ar = 4-BrC_6H_4 (79%), **f** Ar = 4-MeC_6H_4 (31%), **g** Ar = 4-$O_2NC_6H_4$ (78%), **h** Ar = 4-ClC_6H_4 (77%), **i** Ar = 4-$MeO_2CC_6H_4$ (90%), **j** Ar = 4-HOC_6H_4 (0%), **k** Ar = 4-$MeOC_6H_4$ (0%)

Scheme 2



The formation of polycyclic compounds **2a**–**i** can be represented by the proposed route involving a domino process of the addition of hydroxycoumarin anion **I** at the most electrophilic center of the BNTD diene system to form an intermediate delocalized *aci*-nitro anion **II**. Its subsequent protonation by the enol hydroxyl at the carbon atom bonded to the sulfonyl group to form intermediate **III** and the final intramolecular Michael addition completes the heterocyclization process (Scheme 2).

It should be assumed that such a sequence of transformations is characteristic of all BNTD reactions leading to annulated polycyclic sulfolane derivatives with pyrazolidine,[14–16] isoxazolidine,[17] and hydrochromenone rings.[18] A specific feature of these processes is the diastereomeric homogeneity of the isolated polycyclic products containing four chiral centers. This rule, of course, requires a more thorough study.

The structure of the synthesized products **2a**–**i** was established on the basis of a data set from IR, ^{1}H and ^{13}C NMR spectroscopy, and two-dimensional homo- (NOESY) and heteronuclear (^{1}H–^{13}C HMQC, ^{1}H–^{13}C HMBC) experiments.

According to ^{1}H and ^{13}C NMR spectroscopy, products **2a**–**i** were isolated as a single diastereomer. In the ^{1}H NMR spectra of these compounds, the signals of all groups of protons are observed. For example, in the ^{1}H NMR spectrum of polycyclic compound **2h** the methyl group protons appear as a singlet at 1.41 ppm. The methylene protons of the sulfolane ring, resonating as a doublet at 4.06 ppm, and the nitromethine proton, appearing as a triplet at 5.83 ppm, form a spin-spin system (^{3}J = 9.2 Hz). The benzyl proton 7-CH and the bridgehead proton 7a-CH are recorded as singlets at 4.42 and 4.54 ppm, respectively, which may be due to the torsion angle H–C(7)–C(7a)–H being close to 90°. The protons of the aromatic ring appear as doublets and a multiplet at 7.34–7.51 ppm and a doublet of doublets of doublets at 7.71 ppm (^{3}J = 8.0, ^{3}J = 7.8, ^{4}J = 1.5 Hz).

The assignment of the signals of protons and carbon atoms in the ^{1}H and ^{13}C NMR spectra was carried out on the basis of the data of ^{1}H–^{13}C HMQC, ^{1}H–^{13}C HMBC heterocorrelation experiments. In the ^{1}H–^{13}C HMBC spectra, the most important correlations for identifying the signals in the ^{1}H and ^{13}C NMR spectra are as follows: the proton 7-CH, in contrast to the proton 7a-CH, correlates with two carbon atoms C-6 and C-11a, which appear in the ^{13}C NMR spectra in the ranges of 160.9–161.1 and 158.7–159.2 ppm, respectively, as well as with the *ortho* carbon atoms of the benzene ring. The *ortho* protons, in turn, are reliably interpreted by the presence of a cross peak with the C-7 carbon atom; the closely located signals of C-6 and C-11a carbon atoms are reliably correlated by the presence of the 1-CH/C-11a cross peak (Fig. 1).

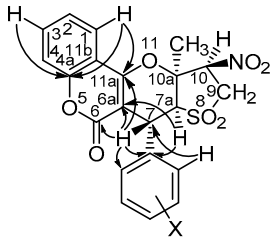


Figure 1. The major correlations in the ^{1}H–^{13}C HMBC spectra of polycyclic compounds **2a**–**i**.

The configurational homogeneity of these compounds made it possible to establish the stereochemistry of the synthesized polycyclic compounds based on the data of NOESY experiments (mixing time variation). Thus, the NOESY spectrum of product **2h** contains 7a-CH/10-CH, 10-CH/CH_3, and 7a-CH/CH_3 cross peaks (Fig. 2) due to NOE, while the absence of a cross peak between the signals of the protons 7-CH and 7a-CH indicates their spatial remoteness.

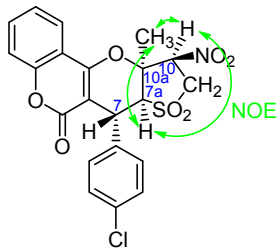


Figure 2. The major correlations in the NOESY spectrum of compound **2h**.

Considering the rigidity of the cyclic condensed system of compounds **2a**–**i**, these correlations make it possible to unambiguously determine the configuration of chiral centers as 7*R**,7a*S**,10*R**,10a*S**.

According to X-ray structural analysis data, the structure of compound **2h** contains one crystallographically nonequivalent molecule of sulfolanopyranochromenone **2h** (Fig. 3). In the crystal structure of compound **2h**, the cyclic fragments C(7A)–C(7)–C(6A)–C(11A)–O(11)–C(10A) and C(10A)–C(10)–C(9)–S(8)–C(7A) have an envelope conformation, so that five atoms of the first ring and four of the second one form planes, while the atoms C(7A) and C(10A) deviate by 0.495(7) Å and 0.632(7) Å, respectively. The torsion angle H–C(7)–C(7A)–H is 86.6° which explains the features of the appearance of the signals of protons 7-CH and 7a-CH in the ^{1}H NMR spectrum.

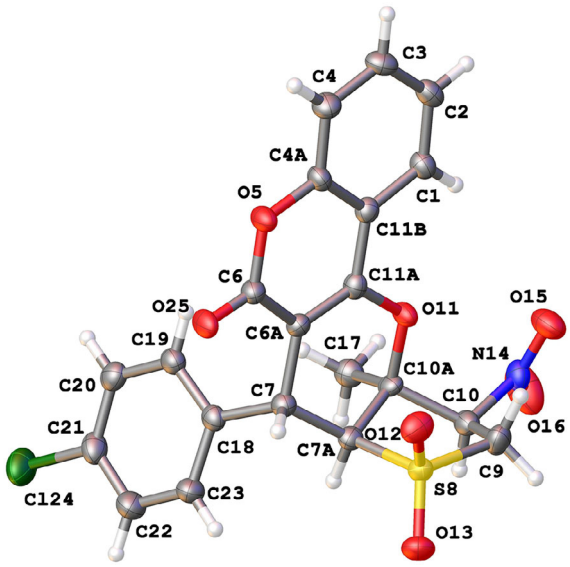


Figure 3. The molecular structure of compound **2h** with atoms represented as thermal vibration ellipsoids of 50% probability.

In the solid state the molecules of compound **2h** are packed into columns along the (1 0 0) direction (Fig. 4), the connection within which is realized due to π-stacking between the equivalent benzene rings (C(1)–C(2)–C(3)–C(4)–C(4A)–C(11B)) of neighboring molecules so that the normal distance between the rings is 3.697(3) Å, and the angle between the planes is 11.0(2)°. Additionally, the connection inside the columns is maintained by weak hydrogen bonding (C(2)–H(2)···O(12) and C(17)–H(17B)···O(15)). Molecules of adjacent columns in the (1 0 0) plane are held together by weak hydrogen bonds (C(7A)–H(7A)···O(25), C(10)–H(10)···O(25), and C(17)–H(17A)···O(25)).

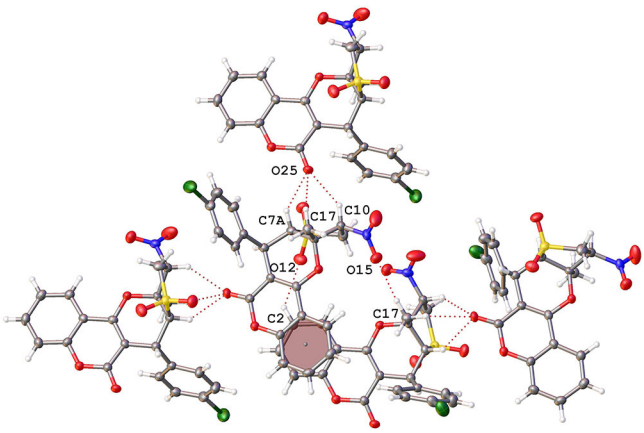


Figure 4. A fragment of the crystal structure of compound **2h** in projection along the (1 0 0) plane. Molecules are linked *via* a system of hydrogen bonds (shown by dotted lines).

To conclude, as a result of the study, a preparatively convenient method for the synthesis of novel tetracyclic structures with annulated nitrosulfolane and 3,4-dihydropyrano[3,2-*c*]chromen-5(2*H*)-one rings was developed based on the reaction of 4-hydroxycoumarin with 2,5-dihydrothiophene 1,1-dioxide nitrosulfodienes. The dependence of the efficiency of this reaction on the structural features of the starting diene has been established.

Experimental

IR spectra were registered on a Shimadzu IRPrestige-21 spectrometers with samples in KBr pellets. ^{1}H, ^{13}C NMR spectra, ^{1}H–^{13}C HMQC, ^{1}H–^{13}C HMBC as well as NOESY (mixing time from 0.5 to 2 s) experiments were recorded on a Jeol ECX400A spectrometer (400 MHz for ^{1}H nuclei and 100 MHz for ^{13}C nuclei) in DMSO-d_6. The residual signals of the solvent (DMSO-d_6: 2.50 ppm for ^{1}H nuclei and 39.6 ppm for ^{13}C nuclei) were used as internal standard. Elemental analysis was performed on a Euro Vector EA-3000 CHNS-analyzer (CHN Dualmode). Melting points were determined on a PTP-M apparatus.

Synthesis of 2-benzylidene-3-methyl-4-nitro-2,5-dihydrothiophene 1,1-dioxides **1a**–**k** was carried out according to a previously described method.[13]

Synthesis of 7-aryl-10a-methyl-10-nitro-7a,9,10,10a-tetrahydro-6*H*,7*H*-thieno[2',3':5,6]pyrano[3,2-*c*]chromen-6-one 8,8-dioxides 2a–k (General method). 4-Hydroxycoumarin (162 mg, 1 mmol) and Et_3N (2 drops; 18 mg, 0.18 mmol) were added to a suspension of 2-benzylidene-3-methyl-4-nitro-3-thiolene 1,1-dioxide **1a**–**i** (0.5 mmol) in EtOH (10 ml). The reaction mixture was stirred at 40°C for 2 h. The formed colorless precipitate was separated on a Schott filter, washed with EtOH, air-dried, and recrystallized from EtOH.

(7*R,7a*S**,10*R**,10a*S**)-10a-Methyl-10-nitro-7-phenyl-7a,9,10,10a-tetrahydro-6*H*,7*H*-thieno[2',3':5,6]pyrano-[3,2-*c*]chromen-6-one 8,8-dioxide (2a)**. Yield 149 mg (70%), white powder, mp 212–215°C (EtOH). IR spectrum, ν, cm^{-1}: 1135, 1326 (SO_2), 1339, 1561 (NO_2), 1635 (C=C), 1708 (C=O). ^{1}H NMR spectrum, δ, ppm (*J*, Hz): 1.41 (3H, s, CH_3); 4.06 (2H, d, ^{3}J = 9.2, 9-CH_2); 4.42 (1H, s, 7-CH); 4.54 (1H, d, *J* = 0.6, 7a-CH); 5.85 (1H, t, ^{3}J = 9.2, 10-CH); 7.24–7.31 (3H, m, H-19,21,23 Ar); 7.32–7.38 (2H, m, H-20,22 Ar); 7.44 (1H, ddd, ^{3}J = 7.9, ^{3}J = 7.1, ^{4}J = 0.9, H-2 Ar); 7.47–7.51 (2H, m, H-1,4 Ar); 7.71 (1H, ddd, ^{3}J = 8.5, ^{3}J = 7.1, ^{4}J = 1.6, H-3 Ar). ^{13}C NMR spectrum, δ, ppm: 21.4 (CH_3); 31.9 (C-7); 50.5 (C-9); 66.9 (C-7a); 80.8 (C-10a); 84.6 (C-10); 99.4 (C-6a); 114.7 (C-11b); 117.2; 122.6 (C-1,4); 125.3 (C-2); 127.8 (C-21); 128.3 (C-19,23); 129.4 (C-20,22); 133.8 (C-3); 138.8 (C-18); 152.6 (C-4a); 158.8 (C-11a); 161.1 (C-6). Found, %: C 59.21; H 3.87; N 3.23. $C_{21}H_{17}NO_7S$. Calculated, %: C 59.01; H 4.01; N 3.28.

(7*R,7a*S**,10*R**,10a*S**)-7-(2-Bromophenyl)-10a-methyl-10-nitro-7a,9,10,10a-tetrahydro-6*H*,7*H*-thieno[2',3':5,6]-pyrano[3,2-*c*]chromen-6-one 8,8-dioxide (2b)**. Yield 220 mg (87%), white powder, mp 248–250°C (EtOH). IR spectrum, ν, cm^{-1}: 1134, 1329 (SO_2), 1345, 1552 (NO_2), 1639 (C=C), 1696 (C=O). ^{1}H NMR spectrum, δ, ppm (*J*, Hz): 1.51 (3H, s, CH_3); 4.04 (1H, dd, ^{2}J = 13.7, ^{3}J = 10.4, 9-CH_2); 4.11 (1H, dd, ^{2}J = 13.7, ^{3}J = 8.6, 9-CH_2); 4.49 (1H, s, 7a-CH); 4.61 (1H, s, 7-CH); 5.91 (1H, dd, ^{3}J = 10.4, ^{3}J = 8.6, 10-CH); 7.20–7.30 (2H, m, H Ar); 7.40–7.56 (4H, m, H Ar); 7.68–7.78 (2H, m, H Ar). ^{13}C NMR spectrum, δ, ppm: 21.4 (CH_3); 33.4 (C-7); 50.8 (C-9); 64.6 (C-7a); 81.6 (C-10a); 84.4 (C-10); 99.2 (C-6a); 114.7 (C-11b);

117.2; 122.7; 124.1; 125.3; 128.4; 130.4; 131.0; 133.6; 134.1; 137.0 (C Ar); 152.6 (C-4a); 159.1 (C-11a); 160.9 (C-6). Found, %: C 49.91; H 3.08; N 2.69. $C_{21}H_{16}BrNO_7S$. Calculated, %: C 49.82; H 3.19; N 2.77.

(7*R,7a*S**,10*R**,10a*S**)-10a-Methyl-7-(2-methylphenyl)-10-nitro-7a,9,10,10a-tetrahydro-6*H*,7*H*-thieno[2',3':5,6]-pyrano[3,2-*c*]chromen-6-one 8,8-dioxide (2c)**. Yield 143 mg (65%), white powder, mp 242–245°C (EtOH). IR spectrum, ν, cm^{-1}: 1129, 1337 (SO_2), 1337, 1558 (NO_2), 1641 (C=C), 1704 (C=O). ^{1}H NMR spectrum, δ, ppm (*J*, Hz): 1.50 (3H, s, CH_3); 2.43 (3H, s, CH_3 Ar); 4.08 (2H, d, ^3J = 9.3, 9-CH_2); 4.43 (2H, br. s, 7,7a-CH); 5.80 (1H, t, ^3J = 9.3, 10-CH); 7.02–7.09 (1H, m, H Ar); 7.14–7.22 (2H, m, H Ar); 7.25–7.30 (1H, m, H Ar); 7.41–7.53 (3H, m, H-1,2,4 Ar); 7.70 (1H, ddd, ^3J = 8.3, ^3J = 7.1, ^4J = 1.5, H-3 Ar). ^{13}C NMR spectrum, δ, ppm: 19.1 (CH_3 Ar); 21.7 (CH_3); 30.0 (C-7); 50.5 (C-9); 64.3 (C-7a); 80.9 (C-10a); 84.8 (C-10); 100.0 (C-6a); 114.8 (C-11b); 117.1; 122.6 (C-1,4); 125.2 (C-2); 126.5 (C Ar); 128.2 (C Ar); 128.3 (C Ar); 131.9 (C Ar); 133.5 (C-3); 136.1 (C Ar); 136.2 (C Ar); 152.5 (C-4a); 158.8 (C-11a); 160.9 (C-6). Found, %: C 59.65; H 4.21; N 3.12. $C_{22}H_{19}NO_7S$. Calculated, %: C 59.86; H 4.34; N 3.17.

(7*R,7a*S**,10*R**,10a*S**)-7-(2-Chlorophenyl)-10a-methyl-10-nitro-7a,9,10,10a-tetrahydro-6*H*,7*H*-thieno[2',3':5,6]-pyrano[3,2-*c*]chromen-6-one 8,8-dioxide (2d)**. Yield 196 mg (85%), white powder, mp 239–241°C (EtOH). IR spectrum, ν, cm^{-1}: 1134, 1329 (SO_2), 1345, 1553 (NO_2), 1638 (C=C), 1696 (C=O). ^{1}H NMR spectrum, δ, ppm (*J*, Hz): 1.51 (3H, s, CH_3); 4.06 (1H, dd, ^2J = 13.8, ^3J = 9.7, 9-CH_2); 4.11 (1H, dd, ^2J = 13.8, ^3J = 9.1, 9-CH_2); 4.51 (1H, s, 7a-CH); 4.61 (1H, s, 7-CH); 5.89 (1H, dd, ^3J = 9.7, ^3J = 9.1, 10-CH); 7.22 (1H, t, ^3J = 7.5, H Ar); 7.35 (1H, t, ^3J = 7.2, H Ar); 7.44 (1H, d, ^3J = 7.6, H Ar); 7.57 (1H, d, ^3J = 7.9, H Ar); 7.45–7.53 (3H, m, H-1,2,4 Ar); 7.71 (1H, ddd, ^3J = 8.2, ^3J = 7.1, ^4J = 1.2, H-3 Ar). ^{13}C NMR spectrum, δ, ppm: 21.3 (CH_3); 30.7 (C-7); 50.7 (C-9); 64.4 (C-7a); 81.4 (C-10a); 84.4 (C-10); 98.9 (C-6a); 114.8 (C-11b); 117.2; 122.6; 125.3; 127.8; 130.2; 130.6; 130.7; 133.2; 133.7; 135.6 (C Ar); 152.6 (C-4a); 159.2 (C-11a); 160.9 (C-6). Found, %: C 54.36; H 3.35; N 2.97. $C_{21}H_{16}ClNO_7S$. Calculated, %: C 54.61; H 3.49; N 3.03

(7*R,7a*S**,10*R**,10a*S**)-7-(4-Bromophenyl)-10a-methyl-10-nitro-7a,9,10,10a-tetrahydro-6*H*,7-thieno[2',3':5,6]-pyrano[3,2-*c*]chromen-6-one 8,8-dioxide (2e)**. Yield 200 mg (79%), white powder, mp 210–212°C (EtOH). IR spectrum, ν, cm^{-1}: 1133, 1341 (SO_2), 1341, 1558 (NO_2), 1635 (C=C), 1700 (C=O). ^{1}H NMR spectrum, δ, ppm (*J*, Hz): 1.41 (3H, s, CH_3); 4.07 (2H, d, ^3J = 9.2, 9-CH_2); 4.39 (1H, s, 7-CH); 4.54 (1H, br. s, 7a-CH); 5.84 (1H, t, ^3J = 9.2, 10-CH); 7.28 (2H, d, ^3J = 8.4, H-19,23 Ar); 7.53 (2H, d, ^3J = 8.4, H-20,22 Ar); 7.44 (1H, ddd, ^3J = 7.8, ^3J = 7.3, ^4J = 0.7, H-2 Ar); 7.46–7.51 (2H, m, H-1,4 Ar); 7.71 (1H, ddd, ^3J = 8.5, ^3J = 7.1, ^4J = 1.6, H-3 Ar). ^{13}C NMR spectrum, δ, ppm: 21.3 (CH_3); 31.5 (C-7); 50.6 (C-9); 66.5 (C-7a); 80.8 (C-10a); 84.6 (C-10); 99.1 (C-6a); 114.7 (C-11b); 121.0 (C-21); 117.2; 122.6 (C-1,4); 125.3 (C-2); 130.7 (C-19,23); 132.2 (C-20,22); 133.7 (C-3); 138.3 (C-18); 152.6 (C-4a); 158.9 (C-11a); 161.0 (C-6). Found, %: C 50.01; H 3.09; N 2.74. $C_{21}H_{16}BrNO_7S$. Calculated, %: C 49.82; H 3.19; N 2.77.

(7*R,7a*S**,10*R**,10a*S**)-10a-Methyl-7-(4-methylphenyl)-10-nitro-7a,9,10,10a-tetrahydro-6*H*,7*H*-thieno[2',3':5,6]-pyrano[3,2-*c*]chromen-6-one 8,8-dioxide) (2f)**. Yield 68 mg (31%), white powder, mp 229–232°C (EtOH). IR spectrum, ν, cm^{-1}: 1133, 1332 (SO_2), 1342, 1556 (NO_2), 1635 (C=C), 1700 (C=O). ^{1}H NMR spectrum, δ, ppm (*J*, Hz): 1.42 (3H, s, CH_3); 2.26 (3H, s, CH_3 Ar); 4.06 (2H, d, ^3J = 9.2, 9-CH_2); 4.39 (1H, s, 7-CH); 4.51 (1H, s, 7a-CH); 5.86 (1H, t, ^3J = 9.2, 10-CH); 7.15 (4H, s, H-19,20,22,23 Ar); 7.43 (1H, ddd, ^3J = 7.8, ^3J = 7.3, ^4J = 0.6, H-2 Ar); 7.45–7.52 (2H, m, H-1,4 Ar); 7.70 (1H, ddd, ^3J = 8.4, ^3J = 7.2, ^4J = 1.5, H-3 Ar). ^{13}C NMR spectrum, δ, ppm: 21.1 (CH_3 Ar); 21.5 (CH_3); 31.5 (C-7); 50.5 (C-9); 66.9 (C-7a); 80.8 (C-10a); 84.6 (C-10); 99.6 (C-6a); 114.7 (C-11b); 117.2; 122.6 (C-2,3); 125.2 (C-2); 128.1 (C-19,23); 130.0 (C-20,22); 133.5 (C-3); 135.7 (C-18); 137.0 (C-21); 152.6 (C-4a); 158.7 (C-11a); 161.0 (C-6). Found, %: C 59.91; H 4.23; N 3.21. $C_{22}H_{19}NO_7S$. Calculated, %: C 59.86; H 4.34; N 3.17.

(7*R,7a*S**,10*R**,10a*S**)-10a-Methyl-10-nitro-7-(4-nitrophenyl)-7a,9,10,10a-tetrahydro-6*H*,7*H*-thieno[2',3':5,6]-pyrano[3,2-*c*]chromen-6-one 8,8-dioxide (2g)**. Yield 184 mg (78%), white powder, mp 221–223°C (EtOH). IR spectrum, ν, cm^{-1}: 1133, 1320 (SO_2), 1347, 1521, 1556 (NO_2), 1637 (C=C), 1705 (C=O). ^{1}H NMR spectrum, δ, ppm (*J*, Hz): 1.41 (3H, s, CH_3); 4.10 (2H, d, ^3J = 9.2, 9-CH_2); 4.57 (1H, s, 7-CH); 4.64 (1H, s, 7a-CH); 5.84 (1H, t, ^3J = 9.2, 10-CH); 7.65 (2H, d, ^3J = 8.7, H-19,23 Ar); 7.45 (1H, ddd, ^3J = 7.8, ^3J = 7.3, ^4J = 0.6, H-2 Ar); 7.48–7.53 (2H, m, H-1,4 Ar); 7.73 (1H, ddd, ^3J = 8.4, ^3J = 7.1, ^4J = 1.6, H-3 Ar); 8.19 (2H, d, ^3J = 8.7, H-20,22 Ar). ^{13}C NMR spectrum, δ, ppm: 21.2 (CH_3); 31.9 (C-7); 50.6 (C-9); 66.3 (C-7a); 80.8 (C-10a); 84.5 (C-10); 98.7 (C-6a); 114.7 (C-11b); 117.2; 122.7 (C-2,3); 124.4 (C-20,22); 125.3 (C-2); 130.1 (C-19,23); 133.8 (C-3); 146.7 (C-18); 147.2 (C-21); 152.7 (C-4a); 159.2 (C-11a); 161.1 (C-6). Found, %: C 53.10; H 3.33; N 5.84. $C_{21}H_{16}N_2O_9S$. Calculated, %: C 53.39; H 3.41; N 5.93.

(7*R,7a*S**,10*R**,10a*S**)-7-(4-Chlorophenyl)-10a-methyl-10-nitro-7a,9,10,10a-tetrahydro-6*H*,7*H*-thieno[2',3':5,6]-pyrano[3,2-*c*]chromen-6-one 8,8-dioxide (2h)**. Yield 178 mg (77%), white powder, mp 228–231°C (EtOH). IR spectrum, ν, cm^{-1}: 1133, 1319 (SO_2), 1342, 1558 (NO_2), 1634 (C=C), 1700 (C=O). ^{1}H NMR spectrum, δ, ppm (*J*, Hz): 1.41 (3H, s, CH_3); 4.06 (2H, d, ^3J = 9.2, 9-CH_2); 4.42 (1H, s, 7-CH); 4.54 (1H, br. s, 7a-CH); 5.83 (1H, t, ^3J = 9.2, 10-CH); 7.34 (2H, d, ^3J = 8.6, H-19,23 Ar); 7.40 (2H, d, ^3J = 8.6, H-20,22 Ar); 7.43–7.51 (3H, m, H-1,2,4 Ar); 7.71 (1H, ddd, ^3J = 8.0, ^3J = 7.8, ^4J = 1.5, H-3 Ar). ^{13}C NMR spectrum, δ, ppm: 21.3 (CH_3); 31.4 (C-7); 50.6 (C-9); 66.6 (C-7a); 80.8 (C-10a); 84.6 (C-10); 99.1 (C-6a); 114.7 (C-11b); 117.2; 122.6 (C-1,4); 125.3 (C-2); 129.3 (C-20,22); 130.4 (C-19,23); 132.4 (C-21); 133.6 (C-3); 137.9 (C-18); 152.6 (C-4a); 158.9 (C-11a); 161.0 (C-6). Found, %: C 54.76; H 3.42; N 2.99. $C_{21}H_{16}ClNO_7S$. Calculated, %: C 54.61; H 3.49; N 3.03.

Methyl 4-((7*R,7a*S**,10*R**,10a*S**)-10a-methyl-10-nitro-8,8-dioxido-6-oxo-7a,9,10,10a-tetrahydro-6*H*,7*H*-thieno-[2',3':5,6]pyrano[3,2-*c*]chromen-7-yl)benzoate (2i)**. Yield 218 mg (90%), white powder, mp 232–234°C (EtOH). IR spectrum, ν, cm^{-1}: 1113, 1338 (SO_2), 1347, 1562 (NO_2), 1639 (C=C), 1669, 1716 (C=O). ^{1}H NMR spectrum, δ, ppm

(*J*, Hz): 1.40 (3H, s, CH_3); 3.82 (3H, s, OCH_3 Ar); 4.09 (2H, d, ^3J = 9.2, 9-CH_2); 4.49 (1H, s, 7-CH); 4.60 (1H, s, 7a-CH); 5.85 (1H, t, ^3J = 9.2, 10-CH); 7.48 (2H, d, ^3J = 8.3, H-19,23 Ar); 7.44 (1H, ddd, ^3J = 7.9, ^3J = 7.3, ^4J = 0.6, H-2 Ar); 7.46–7.52 (2H, m, H-1,4 Ar); 7.72 (1H, ddd, ^3J = 8.4, ^3J = 7.1, ^4J = 1.6, H-3 Ar); 7.92 (2H, d, ^3J = 8.3, H-20,22 Ar). ^{13}C NMR spectrum, δ, ppm: 21.3 (CH_3); 32.0 (C-7); 50.6 (C-9); 52.8 (OCH_3); 66.5 (C-7a); 80.8 (C-10a); 84.5 (C-10); 98.9 (C-6a); 114.7 (C-11b); 117.2; 122.6 (C-1,4); 125.3 (C-2); 128.9 (C-21); 129.2 (C-19,23); 130.2 (C-20,22); 133.7 (C-3); 144.3 (C-18); 152.6 (C-4a); 159.0 (C-11a); 161.1 (C-6); 166.4 ($\underline{C}O_2CH_3$). Found, %: C 56.65; H 3.94; N 2.92. $C_{23}H_{19}NO_9S$. Calculated, %: C 56.91; H 3.95; N 2.89

X-ray structural analysis of compound 2h was carried out on a Rigaku Oxford Diffraction XtaLab Synergy single crystal diffractometer equipped with a HyPix-3000 (hybrid photon counting) 2D hybrid reflected X-ray detector at 100K using monochromatic microfocus CuKα radiation.

The unit cell parameters (space group $Pna2_1$; *a* 7.63898(13), *b* 18.6741(3), *c* 13.8969(3) Å; *V* 13.8969(3) Å; *V* 1982.41(6) Å^3; *Z* 4) were refined by the least-squares technique on the basis of 10914 reflections with 2θ in the range of 7.93–140.00°. The data were integrated with corrections for the background, Lorentz factor, and polarization effects in the CrysAlisPro software package.[19] The absorption correction was introduced empirically in the CrysAlisPro software package[19] using spherical harmonics implemented in the SCALE3 ABSPACK scaling algorithm. The structure was solved using the double space algorithm and refined to R_1 0.045 (wR_2 0.121) for 3310 independent reflections with $|F_o| \geq 4\sigma_F$ using the SHELX program[20,21] built into the OLEX2 software complex.[22] The positions of hydrogen atoms were calculated according to the algorithms incorporated in the SHELX software package, where U_{iso}(H) was set as $1.5U_{eq}$(C) and C–H 0.98 Å for CH_3 groups, U_{iso}(H) was set as $1.2U_{eq}$(C) and C–H 0.99 Å for CH_2 groups, U_{iso}(H) was set as $1.2U_{eq}$(C) and C–H 0.95 Å for CH groups of the cyclic fragments, and U_{iso}(H) was set as $1.2U_{eq}$(C) and C–H 1.00 Å for tertiary CH groups. The X-ray structural data was deposited at the Cambridge Crystallographic Data Center (deposit CCDC 2144506).

Supplementary information file containing the ^{1}H, ^{13}C NMR, ^{1}H–^{13}C HMQC, ^{1}H–^{13}C HMBC spectra for all synthesized compounds and the ^{1}H–^{1}H NOESY spectrum for compound **2h** is available at the journal website http://link.springer.com/journal/10593.

The study was supported financially by the Ministry of Education of the Russian Federation (project No. FSZN-2020-0026) and the Russian Foundation for Basic Research within the framework of scientific project No. 20 33-90071.

The spectral characteristics and elemental analysis data of the synthesized compounds were obtained using the equipment of the Center for Collective Use "Physicochemical methods for the study of nitro compounds, coordination compounds, biologically active substances, and nanostructured materials" of the Interdisciplinary Resource Center for Collective Use "Contemporary physico-chemical methods of formation and research of materials for the needs of industry, science, and education" of the Herzen State Pedagogical University of Russia.

X-ray structural analysis was carried out using the equipment of the resource center of the Saint Petersburg State University "Center for X-ray Diffraction Studies".

References

1. Zhang, M.-Z.; Zhang, R.-R.; Wang, J.-Q.; Yu, X.; Zhang, Y.-L.; Wang, Q.-Q.; Zhang, W.-H. *Eur. J. Med. Chem.* **2016**, *124*, 10.
2. Bondock, S.; Khalifa, W.; Fadda, A. A. *Eur. J. Med. Chem.* **2011**, *46*, 2555.
3. Mukherjee, A.; Mahato, S.; Zyryanov, G. V.; Majee, A.; Santra, S. *New J. Chem.* **2020**, *44*, 18980.
4. Jakše, R.; Svete, J.; Stanovnik, B.; Golobič, A. *Tetrahedron* **2004**, *60*, 4601.
5. Gohain, M.; van Tonder, J. H.; Bezuidenhoudt, B. C. B. *Tetrahedron Lett.* **2013**, *54*, 3773.
6. Fedorov, A. Yu.; Nyuchev, A. V.; Beletskaya, I. P. *Chem. Heterocycl. Compd*. **2012**, *48*, 166.
7. Berger, S.; Haak, E. *Tetrahedron Lett.* **2010**, *51*, 6630.
8. Mei, R.-Q.; Xu, X.-Y.; Peng, L.; Wang, F.; Tian, F.; Wang, L.-X. *Org. Biomol. Chem*. **2013**, *11*, 1286.
9. Singh, S.; Srivastava, A.; Mobin, S. M.; Samanta, S. *RSC Adv.* **2015**, *5*, 5010.
10. Pelipko, V. V.; Baichurin, R. I.; Lyssenko, K. A.; Dotsenko, V. V.; Makarenko, S. V. *Mendeleev Commun.* **2022**, *32*, 454.
11. Baichurin, R. I.; Baichurina, L. V.; Aboskalova, N. I.; Berestovitskaya, V. M. *Russ. J. Gen. Chem.* **2013**, *83*, 1787.
12. Ustalar, A.; Yilmaz, M.; Osmani, A.; Keçeli, S. A. *Turk. J. Chem.* **2017**, *41*, 80.
13. Savelev, I. I.; Efremova, I. E.; Lapshina, L. V.; Gurzhiy, V. V.; Belyakov, A. V. *Chem. Heterocycl. Compd.* **2021**, *57*, 861.
14. Berestovitskaya, V. M.; Efremova, I. E.; Lapshina, L. V.; Serebryannikova, A. V.; Gurzhiy, V. V.; Abzianidze, V. V. *Mendeleev Commun.* **2015**, *25*, 191.
15. Efremova, I. E.; Serebryannikova, A. V.; Lapshina, L. V.; Gurzhiy, V. V.; Berestovitskaya, V. M. *Russ. J. Gen. Chem.* **2016**, *86*, 622.
16. Efremova, I. E.; Serebryannikova, A. V.; Belyakov, A. V.; Lapshina, L. V. *Russ. J. Gen. Chem.* **2019**, *89*, 536.
17. Berestovitskaya, V. M.; Efremova, I. E.; Serebryannikova, A. V.; Lapshina, L. V.; Gurzhiy, V. V. *Chem. Heterocycl. Compd.* **2018**, *54*, 76.
18. Savelev, I. I.; Efremova, I. E.; Lapshina, L. V.; Gurzhiy, V. V.; Baichurin, R. I. *Chem. Heterocycl. Compd*. **2022**, *58*, 58.
19. *CrysAlisPro*, *Version 1.171.41.103a*; Rigaku Oxford Diffraction, 2021.
20. Sheldrick, G. M. *Acta Crystallogr.*, *Sect. A*: *Found. Adv.* **2015**, *A71*, 3.
21. Sheldrick, G. M. *Acta Crystallogr.*, *Sect. C*: *Struct. Chem.* **2015**, *C71*, 3.
22. Dolomanov, O. V.; Bourhis, L. J.; Gildea, R. J.; Howard, J. A. K.; Puschmann, H. *J. Appl. Crystallogr.* **2009**, *42*, 339.