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Synthesis, characterization and in vitro antitumor activity of some arylbismuth triphenylgermylpropionates and crystal structures of $(4\text{-}BrC_6H_4)_3Bi(O_2CCH_2CH_2GePh_3)_2$ and $(4\text{-}BrC_6H_4)_3Bi[O_2CCH(CH_3)CH_2GePh_3]_2$

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Abstract

A series of novel arylbismuth(V) triphenylgermylpropionates with the formula $Ar_3Bi(O_2CCHR^1CHR^2GePh_3)_2$ ($R^1 = H$, CH_3; $R^2 = H$, Ph; Ar = Ph, 4-$CH_3C_6H_4$, 4-FC_6H_4, 4-ClC_6H_4, 4-BrC_6H_4) were synthesized and characterized by elemental analysis, IR, ^{1}H-NMR and mass spectroscopy. The crystal structures of $(4\text{-}BrC_6H_4)_3Bi(O_2CCH_2CH_2GePh_3)_2$ and $(4\text{-}BrC_6H_4)_3Bi[O_2CCH(CH_3)CH_2GePh_3]_2$ were determined by X-ray diffraction. Three human neoplastic cell lines (HCT-8, Bel-7402 and KB) were used to screen these compounds. The results indicate that some compounds at 5 μM show good in vitro antitumor activities.

Keywords: Bismuth; Germanium; Crystal structures; Antitumor activity

1. Introduction

A substantial number of references describing synthesis and applications of R_3BiX_2 (R = alkyl, aryl; X = carboxylate) have appeared in the literature [1–7]. The use of bismuth in medicine has recently been reviewed [8,9]. Bismuth compounds have been used for the treatment of a number of ailments and today is primarily used clinically as antiulcer drugs. Recently, the effectiveness of bismuth has attributed to its bactericidal action against *Helicobacter pylori*. The organism implicated as the pathogen leading to gastric complaint is *H. pylori* and its growth is inhibited by the administration of 'bismuth' [10–15]. This being the case, there is a clear connection established between antitumor activity and bismuth compounds. However, with the exception of a very early report [16], no bismuth(V) compounds have been evaluated for antitumor activity. Moreover as we know very well, organogermanium has a wide range of biological activities [17–20]. Therefore, we have prepared 15 new arylbismuth β-triphenylgermylpropionates in order to examine whether including organogermanium in organobismuth compounds improves their antitumor properties and to investigate the influence of the organic ligands at Bi on their biological activity. At the same time, we were also interested in studying the nature of bonding and the structure of these compounds.

2. Results and discussion

2.1. Preparations

These arylbismuth triphenylgermylpropionates are prepared under mild condition. They were synthesized

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Table 1
IR data of the compounds (cm^{-1})

Compound	$\nu_{asy}(CO_2)$	$\nu_{sym}(CO_2)$	$\Delta\nu(CO_2)$	ν(Bi–C)
1	1606	1368	238	465
2	1588	1360	228	474
3	1582	1380	202	480
4	1584	1372	212	470
5	1603	1381	222	458
6	1621	1384	237	471
7	1579	1381	198	475
8	1575	1378	197	470
9	1599	1368	231	466
10	1629	1366	263	471
11	1595	1377	218	472
12	1598	1374	224	469
13	1630	1380	250	466
14	1618	1385	233	467
15	1601	1367	234	467

by the reaction of triphenylgermylpropionic acid with Ar_3BiCO_3 refluxed in acetone (**1**–**12**) or by the reaction of triphenylgermylpropionic acid with Ar_3BiBr_2 in the presence of triethylamine under an Ar atmosphere (**13**–**15**). The general reaction scheme is as shown as follows:

$$Ph_3GeCHR^2CHR^1COOH + Ar_3BiCO_3 \times \overset{Reflux}{\rightarrow} Ar_3Bi(O_2CCHR^1CHR^2GePh_3)_2 \quad (1)$$

where $R^1 = H$, $R^2 = H$, Ar = Ph (**1**), 4-$CH_3C_6H_4$ (**2**), 4-ClC_6H_4 (**3**), 4-BrC_6H_4 (**4**); $R^1 = CH_3$, $R^2 = H$, Ar = Ph (**5**), 4-$CH_3C_6H_4$ (**6**), 4-ClC_6H_4 (**7**), 4-BrC_6H_4 (**8**); $R^1 =$ H, $R^2 =$ Ph, Ar = Ph (**9**), 4-$CH_3C_6H_4$ (**10**), 4-ClC_6H_4 (**11**), 4-BrC_6H_4 (**12**).

$$Ph_3GeCHR^2CHR^1COOH + (4\text{-}FC_6H_4)_3BiBr_2 \times \overset{Et_3N}{\rightarrow} (4\text{-}FC_6H_4)_3Bi(O_2CCHR^1CHR^2GePh_3)_2 \quad (2)$$

where $R^1 = H$, $R^2 = H$ (**13**); $R^1 = CH_3$, $R^2 = H$ (**14**), $R^1 = H$, $R^2 = Ph$ (**15**).

All compounds are white crystals and stable under ordinary conditions. They are easily soluble in organic solvents such as benzene, toluene, chloroform, and dichloromethane, but not soluble in ether, methanol, ethanol, hexane and petroleum ether.

When Ar is Ph, 4-$CH_3C_6H_4$, 4-ClC_6H_4 or 4-BrC_6H_4, Ar_3BiCO_3 is synthesized by the reaction of Ar_3BiBr_2 with K_2CO_3 and the yields are almost 100%. However, when Ar is 4-FC_6H_4, $(4\text{-}FC_6H_4)_3BiCO_3$ fails to be synthesized by the same method. We use the second method to synthesize 4-fluorophenylbismuth triphenylgermylpropionates. The yields of compounds **1**–**12** are higher than those of compounds **13**–**15**.

2.2. IR

The IR spectra of these compounds have been recorded in the range 4000–400 cm^{-1}. The absorption bands can be assigned on the basis of earlier publications and the important data are listed in Table 1.

The IR spectroscopic data provide further support for the molecular constitution of the title compounds. In majority of organobismuth(V) compounds, bismuth has generally a coordination number of 5. Because the vacant 6d-orbital of bismuth atom can accept lone electron pairs of ligands, in some cases bismuth may have a coordination number of 6 or 7 [5]. The IR stretching vibration frequencies of carbonyl groups in organobismuth carboxylates are very important for determining their structures. When there are interac-

Table 2
^{1}H-NMR data of the compounds

Compound	CHR^1CO	$GeCHR^2$	R^1	R^2	Ph_3Ge, Ar_3Bi
1	2.15–2.54 (4H, t)	1.50–1.81 (4H, t)			7.31–8.54 (45H, m)
2	2.41–2.61 (4H, t)	1.75–1.82 (4H, t)			7.34–8.36 (42H, m); 2.40 (9H, s)
3	2.26–2.45 (4H, t)	1.63–1.81 (4H, t)			7.35–8.49 (42H, m)
4	2.16–2.24 (4H, t)	1.50–1.58 (4H, t)			7.32–7.92 (42H, m)
5	2.61–2.74 (2H, m)	1.60–2.09 (4H, m)	1.13–1.17 (6H, d)		7.35–8.54 (45H, m)
6	2.35–2.64 (2H, m)	1.20–1.78 (4H, m)	0.75–0.80 (6H, d)		7.26–8.39 (42H, m); 2.35 (9H, s)
7	2.25–2.70 (2H, m)	1.21–1.76 (4H, m)	0.76–0.80 (6H, d)		7.24–8.50 (42H, m)
8	2.37–2.47 (2H, m)	1.28–1.75 (4H, m)	0.74–0.77 (6H, d)		7.24–8.03 (42H, m)
9	2.58–2.82 (4H, m)	3.44–3.50 (2H, m)		6.68–7.04 (10H, m)	7.19–7.96 (45H.m)
10	2.80–2.94 (4H, m)	3.40–3.64 (2H, m)		6.74–7.07 (10H, m)	7.24–8.33(42H, m); 2.37 (9H, s)
11	2.55–2.80 (4H, m)	3.39–3.45 (2H, m)		6.57–7.07 (10H, m)	7.18–7.89 (42H, m)
12	2.55–2.82 (4H, m)	3.41–3.49 (2H, m)		6.64–7.03 (10H, m)	7.14–7.82 (42H, m)
13	2.17–2.26 (4H, t)	1.51–1.62 (4H, t)			7.16–8.21 (42H, m)
14	1.64–2.39 (2H, m)	1.31–1.88 (4H, m)	0.72–0.76 (6H,.d)		7.11–8.02 (42H, m)
15	2.59–2.85 (4H, m)	3.43–3.48 (2H, m)		6.57–6.97 (10H,.m)	7.14–7.96 (42H, m)

Table 3
Fragment ions observed for compound **4**

m/z	Fragment
1428	$(4\text{-}BrC_6H_4)_3Bi(O_2CCH_2CH_2GePh_3)_2^+$
1051	$(4\text{-}BrC_6H_4)_3Bi(O_2CCH_2CH_2GePh_3)^+$
674	$Bi(4\text{-}BrC_6H_4)_3^+$
519	$Bi(4\text{-}BrC_6H_4)_2^+$
378	$Ph_3GeCH_2CH_2CO_2H^+$
377	$Ph_3GeCH_2CH_2CO_2^+$
364	$Bi(4\text{-}BrC_6H_4)^+$
333	$Ph_3GeCH_2CH_2^+$
305	Ph_3Ge^+
303	$[Ph_3Ge-2H]^+$
301	$[Ph_3Ge-4H]^+$
299	$[Ph_3Ge-6H]^+$
228	Ph_2Ge^+

tions between the bismuth atom and the carbonyl oxygen atoms of the carboxylate groups, the asymmetric absorption vibration frequencies [$\nu_{asy}(CO_2)$] of carbonyl groups decrease and the symmetric absorption vibration frequencies [$\nu_{sym}(CO_2)$] increase. Therefore their differences [$\Delta\nu(CO_2)$] decrease [1,3,6,7]. In the IR spectra of the title compounds, the carboxylate bands are observed in the characteristic regions: $\nu_{asy}(CO_2)$ between 1630 and 1575 cm^{-1} and $\nu_{sym}(CO_2)$ between 1385 and 1360 cm^{-1}. On the basis of the whole $\Delta\nu(CO_2)$, these compounds show low $\Delta\nu(CO_2)$ values (between 197 and 263 cm^{-1}). To this we can assume that there are stronger interactions between the carbonyl oxygen atoms of the carboxylate groups and the bismuth atom (confirmed by crystal structures of compounds **4** and **8**). In addition, the frequencies of Bi–C deformations appear between 458 and 480 cm^{-1}, this is consistent with the literature [21–24].

2.3. ^{1}H-NMR

The ^{1}H-NMR data of the title compounds are listed in Table 2. From Table 2, we find when one β proton is substituted with a phenyl group there is a significant downfielding shift for α and β protons due to the deshielding effects. C(1) is a chiral center and C(2) is a prochiral center. The three hydrogens on C(1) and C(2) comprise an ABX system. However, the ABX system cannot be identified in 200 MHz spectra. Here the three hydrogens show a multiplet in most cases. All the protons in the compounds have been identified and the total number of protons calculated from the integration curve tallies with what was expected from the molecular formula.

2.4. Mass spectra

The main mass spectra data of compound **4** are listed in Table 3. For **4** there is a weak molecular ion peak. The fragment ions found are in agreement with the expected structure of the compounds. Decarboxylation and dephenylation from metal atom are the main breakdown patterns for the compound.

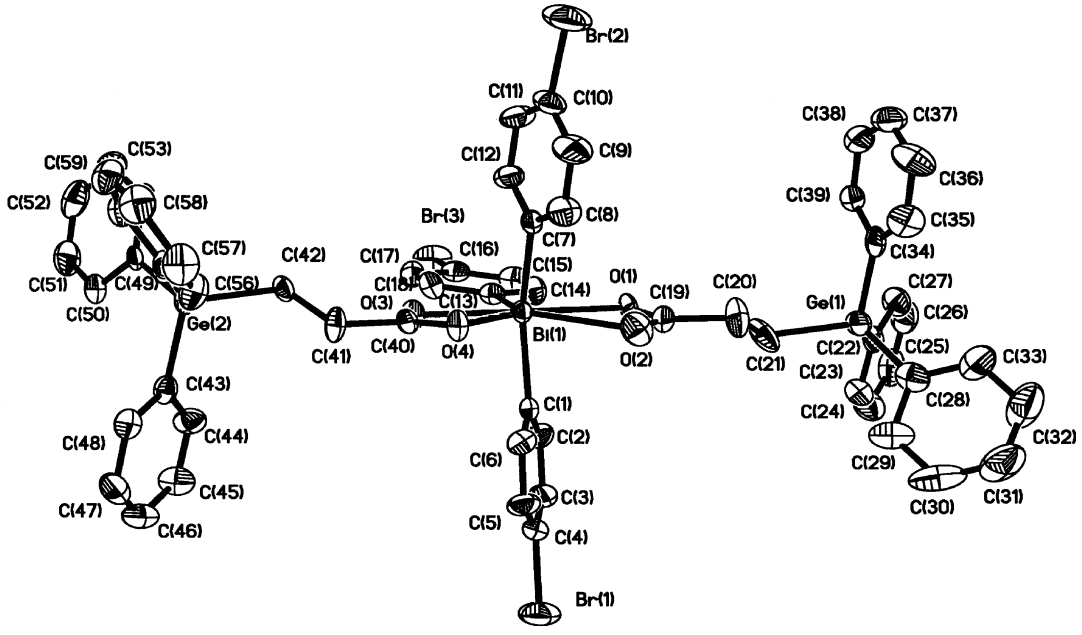

Fig. 1. The molecular structure of $(Ph_3GeCH_2CH_2CO_2)_2Bi(4\text{-}BrC_6H_4)_3$.

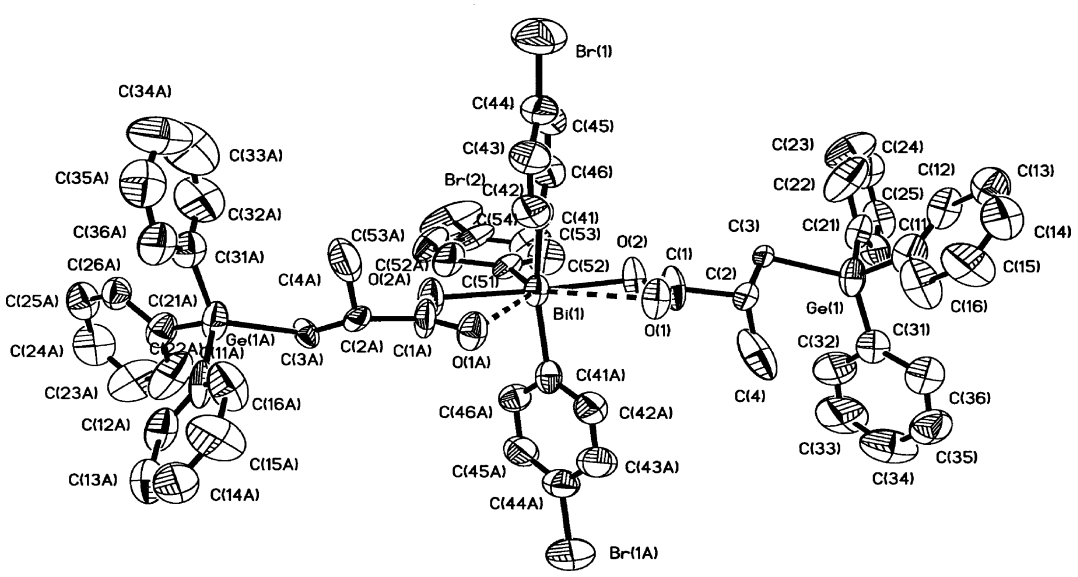

Fig. 2. The molecular structure of $[Ph_3GeCH_2CH(CH_3)CO_2]_2Bi(4\text{-}BrC_6H_4)_3$.

Table 4
Selected bond distances and bond angles of compound **4**

Bond distance (Å)	
Bi(1)–C(1)	2.191(8)
Bi(1)–C(13)	2.215(8)
Bi(1)–C(7)	2.193(9)
Bi(1)–O(3)	2.249(5)
Bi(1)–O(1)	2.317(5)
Bi(1)–O(2)	2.668(6)
Bi(1)–O(4)	2.781(6)
Ge(1)–C(28)	1.899(12)
Ge(1)–C(22)	1.953(9)
Ge(1)–C(34)	1.939(10)
Ge(1)–C(21)	1.987(9)
O(2)–C(19)	1.210(10)
O(1)–C(19)	1.303(11)
O(3)–C(40)	1.280(9)
O(4)–C(40)	1.227(9)
Br(1)–C(4)	1.882(10)
Br(3)–0(2)	2.897
Bond angles (°)	
C(1)–Bi(1)–C(7)	149.3(3)
C(7)–Bi(1)–C(13)	104.6(3)
C(1)–Bi(1)–C(13)	106.1(3)
C(1)–Bi(1)–O(1)	90.6(2)
C(13)–Bi(1)–O(1)	86.8(3)
C(1)–Bi(1)–O(2)	76.5(3)
C(13)–Bi(1)–O(2)	138.4(3)
O(1)–Bi(1)–O(2)	51.6(2)
C(1)–Bi(1)–C(13)	106.1(3)
C(1)–Bi(1)–O(3)	90.7(2)
C(13)–Bi(1)–O(3)	86.7(3)
C(7)–Bi(1)–O(1)	90.6(2)
O(3)–Bi(1)–O(1)	173.4(2)
C(7)–Bi(1)–O(2)	80.3(3)
O(3)–Bi(1)–O(2)	134.9(2)
C(28)–Ge(1)–C(22)	107.1(4)
C(34)–Ge(1)–C(22)	113.0(4)
O(2)–C(19)–O(1)	121.6(8)
O(4)–C(40)–O(3)	122.4(7)

2.5. Crystal structures of $(4\text{-}BrC_6H_4)_3Bi(O_2CCH_2CH_2GePh_3)_2$ and $(4\text{-}BrC_6H_4)_3Bi[O_2CCH(CH_3)CH_2GePh_3]_2$

Both colorless crystals were recrystallized from CH_2Cl_2–CH_3OH. Figs. 1 and 2 show the molecular structures of compounds **4** and **8** and give the atom numbering scheme. The selected bond distances and angles of two compounds are listed in Tables 4 and 5, respectively.

Table 5
Selected bond distances and bond angles of compound 8

Bond distance (Å)	
Bi(1)–C(51)	2.134(14)
Bi(1)–C(41)	2.172(13)
Bi(1)–O(2)	2.257(7)
Bi(1)–O(1)	2.813(6)
Ge(1)–C(31)	1.920(15)
Ge(1)–C(11)	1.907(17)
Ge(1)–C(21)	1.968(16)
Ge(1)–C(3)	2.06(2)
O(1)–C(1)	1.200(14)
O(2)–C(1)	1.292(15)
Bond angle (°)	
C(51)–Bi(1)–C(41A)	105.6(4)
C(41A)–Bi(1)–C(41)	148.8(9)
C(51)–Bi(1)–O(2)	86.0(2)
C(41)–Bi(1)–O(2)	92.5(4)
O(2A)–Bi(1)–O(2)	172.1(5)
C(41)–Bi(1)–O(2A)	89.7(4)
C(11)–Ge(1)–C(31)	109.9(8)
C(31)–Ge(1)–C(21)	108.0(7)
C(11)–Ge(1)–C(3)	105.7(9)
O(1)–C(1)–O(2)	122.4(11)

The Ge–C bonds of two compounds are consistent with the literature [25]. The stereochemistry of germanium is typically tetrahedral geometry. Carboxylates are versatile ligands which can be either unidentate or bidentate. Both molecules consist of a monomer with a seven-coordinated bismuth atom surrounded by four oxygens and three phenyl groups. The coordination geometry of bismuth can be described as a distorted pentagonal bipyramid with the plane being defined by four oxygens from two chelating carboxylate groups and one carbon atom from one phenyl group, while the other phenyl groups occupying the axial positions.

The Bi–C bond distances, ranging from 2.191(8) to 2.215(8) Å in compound **4** and from 2.134(14) to 2.172(13) Å in compound **8**, are comparable with those in $Ph_3Bi(O_2CCF_3)_2$ [5]. The distances in $Ph_3Bi(O_2CCF_3)_2$, ranging from 2.138(6) to 2.185(5) Å, are slightly shorter than those in compound **4**, but almost the same as those in compound **8**. The Bi–O bonded distances [2.317(5) and 2.249(5) Å in compound **4** and both 2.257(7) Å in compound **8**] are slightly different from the corresponding distances in $Ph_3Bi(O_2CCF_3)_2$ [2.308(7) and 2.309(7)Å]. In both compounds, there are relatively strong bonding interactions between Bi(1) and the carbonyl oxygens of the carboxylates. The no-bonded Bi–O distances in compound **4** [2.668(6) and 2.781(6) Å] are shorter than the corresponding distances in compound **8** [both 2.813(6) Å]. This can be attributed to the steric effect of the α-methyl in the two bulky triphenylgermylpropionate groups of compound **8**. However, the no-bonded Bi–O distances of two compounds are still shorter than the corresponding distances in $Ph_3Bi(O_2CCF_3)_2$ [2.980 and 2.981 Å]. This indicates that there are certain coordination interactions between the carbonyl oxygens of the two triphenylgermylpropionate groups and the bismuth atom. The C(1)–Bi(1)–C(7) angle in compound **4**, which is affected by adjacent 0(1) and 0(3), is increased to 149.3(3)°, while the C(1)–Bi(1)–C(13) and C(13)–Bi(1)–C(7) angles are decreased to 106.1(3)° and 104.6(3)°, respectively. Correspondingly, the C(41)–Bi(1)–C(41A) angle in compound **8**, which is also affected by adjacent O(1) and O(1A), is increased to 148.8(9)°, while the C(41)–Bi(1)–C(51) and C(41A)–Bi(1)–C(51) angles are decreased to 105.6(4)°. Both these can be attributed to the $-I$ effect of Br of the aryl groups and the steric effect of the two bulky triphenylgermylpropionate groups in the two molecules. The $-I$ effect of Br enhances the Lewis acidity of Bi and leads to the stronger Bi:0=C coordination [26]. The atoms Bi(1), O(1), O(2), O(3), O(4) and C(13) in compound **4** are coplanar within −0.0794 Å, while the corresponding atoms Bi(1), O(1), O(1A), O(2), O(2A) and C(51) in compound **8** are coplanar within 0.1052 Å.

Table 6
Antitumor activity of all compounds in vitro

Compound	Inhibition ratio (%) (5 g ml^{-1}) [a]		
	KB cells	Bel-7402 cells	HCT-8 cells
1	56.67	72.69	86.35
2	63.93	72.38	90.00
3	−1.55	−5.04	2.17
4	−0.47	23.76	1.17
5	93.40	74.10	83.10
6	63.23	65.08	84.04
7	0.03	−1.91	11.63
8	4.04	11.91	−3.35
9	−1.61	−2.07	1.75
10	−1.61	0.01	3.44
11	−0.09	0.98	−0.84
12	11.85	14.82	−0.84
13	8.21	24.19	−2.95
14	14.86	71.28	90.34
15	74.65	80.36	−0.64
A [b]	3.58	−67.16	2.28
B [c]	−27.39	−19.50	6.45
Cisplatin	92.64	76.25	80.07

[a] Inhibition ratio (%) = $(A_1-A_2)/A_1 \times 100\%$. A_1: the mean optical densities of untreated cells; A_2: the mean optical densities of drug-treated cells.
[b] **A**: $Ph_3GeCH_2CH_2COOH$.
[c] **B**: Ph_3BiCl_2

In the unit cell of compound **4**, there is a surprising weak intermolecular interaction between the Br atom of aryl group and carbonyl oxygen of a neighbouring molecule. The Br(3)–O(2) distance is 2.897 Å. However, in the unit cell of compound **8** there is no corresponding intermolecular interaction.

2.6. Antitumor activity

The antitumor activity was assayed by the MTT method [27]. Antitumor activities of all compounds were listed in Table 6. The results of bioassay showed that some compounds exhibit high activities against the three cancer cells in vitro, for example, compounds **1**, **2**, **4**, **5**, **14**, and **15** have good activities. The compounds including organobismuth moiety have relatively higher antitumor activities than triphenylgermylpropionic acid. The antitumor data indicate that the antitumor activities are affected by the nature of the aryl and the triphenylgermylpropionic acids. When the triphenylgermylpropionic group is $Ph_3GeCH_2CH_2COO$ or $Ph_3GeCH_2CH(CH_3)COO$, those compounds whose Ar is Ph or 4-$CH_3C_6H_4$ have relatively higher antitumor activities; however, those whose Ar is 4-ClC_6H_4 or 4-BrC_6H_4 have no significant activity. When the triphenylgermylpropionic group is $Ph_3GeCH(Ph)CH_2COO$, the title compounds have also no significant activity. When Ar is 4-FC_6H_4, compound **14** has very high

Table 7
Yields and elemental analyses of the compounds

Compound	Yield (%)	m.p. (°C)	Elemental analysis: found (calc.) (%)		
			C	H	Formula for calc.
1	90.9	161–162	56.58 (57.32)	4.08 (4.34)	$C_{60}H_{53}BiGe_2O_4\cdot CH_2Cl_2$
2	78.4	172–174	61.16 (61.30)	5.02 (4.82)	$C_{63}H_{59}BiGe_2O_4$
3	81.1	149–151	55.57 (55.62)	3.85 (3.89)	$C_{60}H_{50}BiCl_3Ge_2O_4$
4	82.8	174–176	50.38 (50.43)	3.60 (3.53)	$C_{60}H_{50}BiBr_3Ge_2O_4$
5	83.6	162–164	60.96 (61.02)	4.89 (4.71)	$C_{62}H_{57}BiGe_2O_4$
6	88.2	160 (dec)	61.84 (61.85)	5.09 (5.03)	$C_{65}H_{63}BiGe_2O_4$
7	74.3	159–161	55.82 (56.26)	4.01 (4.11)	$C_{62}H_{54}BiCl_3Ge_2O_4$
8	70.4	157–158	51.31 (51.11)	3.79 (3.74)	$C_{62}H_{54}BiBr_3Ge_2O_4$
9	85.5	102 (dec)	64.03 (64.32)	4.31 (4.57)	$C_{72}H_{61}BiGe_2O_4$
10	85.4	177–178	64.90 (64.97)	4.87 (4.87)	$C_{75}H_{67}BiGe_2O_4$
11	62.0	168–170	57.31 (57.21)	3.91 (3.95)	$C_{72}H_{58}BiCl_3Ge_2O_4\cdot CH_2Cl_2$
12	57.0	157–159	52.57 (52.63)	3.64 (3.63)	$C_{72}H_{58}BiBr_3Ge_2O_4\cdot CH_2Cl_2$
13	69.5	160–162	57.73 (57.83)	4.18 (4.04)	$C_{60}H_{50}BiF_3Ge_2O_4$
14	53.6	132–134	58.26 (58.44)	4.36 (4.27)	$C_{62}H_{54}BiF_3Ge_2O_4$
15	41.6	159–161	59.41 (59.11)	3.86 (4.08)	$C_{72}H_{58}BiF_3Ge_2O_4\cdot CH_2Cl_2$

antitumor activity to HCT-8 cells. When comparing with cisplatin, some compounds have higher antitumor activities.

These title compounds whose inhibition ratios are more than 50% are further assayed. It is found that compound **5** has very significant antitumor activity against KB cells. At concentrations of 0.5, 0.05 and 0.005 g ml^{-1}, the inhibition ratio against KB cells was 84.84, 85.76 and 83.97%, respectively. However, at the same concentrations, the inhibition ratio of cisplatin against KB cells was 42.78, 4.84 and −11.15, respectively. This shows that the activity of compound **5**, is by far more than that of cisplatin. Its IC_{50} is lower than 0.005 μg ml^{-1}, is close to the IC_{50} of taxol to KB cells ($IC_{50} = 0.002772$ μg ml^{-1}). This stands for very good activity.

3. Experimental

Elemental analyses were determined on a Yanaco CHN Corder MT-3 elemental analyzer. IR spectra were recorded on a Bruker Equinox 55 spectrometer in KBr discs. ^{1}H-NMR spectra were measured on a Bruker AC-200 spectrometer in $CDCl_3$ solution with TMS as internal standard. Mass spectra were recorded on a BIFLEX III mass spectrometer (MALDI-TOF). All reactions involving metal halides were carried out under anhydrous and oxygen-free argon atmosphere. Solvents were purified, dried, and stored by literature methods.

3.1. Reagents

The substituted *p*-triphenylgermylpropionic acids were synthesized via the following reaction [25,28]. Ar_3BiBr_2 was prepared by the method reported by Supniewski and Adams [2]. Ar_3Bi was converted into the corresponding dibromide by direct bromination, and the solid product was recrystallized from chloroform–methanol. To prepare Ar_3BiCO_3, an adaptation of the method of Barton et al. [29] was used.

$$GeO_2 + NaH_2PO_2\cdot H_2O \xrightarrow{HCl} HGeCl_3$$

$$\times \xrightarrow{CHR^2\&z.dbnd;CR^1COOH} Cl_3GeCHR^2CHR^1COOH$$

$$\times \xrightarrow[H^+/H_2O]{4PhMgBr} Ph_3GeCHR^1COOH$$

3.2. Synthesis of the title compounds

The title compounds were synthesized by two more convenient procedures. Procedure 1 (**1**–**12**) to a boiling solution of β-triphenylgermylpropionic acid (1 mmol) in 50 ml of acetone was added 0.5 mmol of Ar_3BiCO_3. The reaction mixture was refluxed for 8 h, cooled and filtered. The filtrate was evaporated in vacuo. The obtained solid was recrystallized from CH_2Cl_2–methanol. In procedure 2 (**13**–**15**), under an argon atmosphere, a mixture of 1.0 mmol β-triphenylgermylpropionic acid, 0.5 mmol of $(4\text{-}FC_6H_4)_3BiBr_2$ and 0.8 ml of triethylamine in toluene (40 ml) was stirred at r.t. for 24 h and filtered. The filtrate was evaporated in vacuo. The obtained solid was recrystallized as above. The yields, melting points and elemental analysis of the prepared compounds are given in Table 7.

Table 8
Crystallographic data for compound 4 and 8

Compound	4	8
Formula	$C_{60}H_{50}BiBr_3Ge_2O_4$	$C_{62}H_{54}BiBr_3Ge_2O_4$
Temperature (K)	293(2)	293(2)
Wavelength (Å)	0.71073	0.71073
Crystal system	monoclinic	monoclinic
Space group	$P2(1)/n$	$P2/c$
Unit cell dimensions		
a (Å)	13.532(4)	13.349(4)
b (Å)	23.097(6)	11.698(4)
c (Å)	18.295(5)	20.105(5)
α (°)	90	90
β (°)	104.871(5)	115.220(16)
γ (°)	90	90
Volume (Å^3)	5527(3)	2840.3(15)
Z	4	2
Density (Mg mm^{-3})	1.717	1.704
Absorption coefficient (mm^{-1})	6.471	6.298
$F(0\,0\,0)$	2776	1420
Crystal size (mm^3)	$0.22 \times 0.14 \times 0.12$	$0.30 \times 0.25 \times 0.20$
θ range for data collection (°)	2.11–26.38	1.74–25.03
Limiting indices	$-10 \le h \le 16$, $-28 \le k \le 26$, $-22 \le l \le 22$	$-7 \le h \le 15$, $-13 \le k \le 13$, $-23 \le l \le 22$
Reflections collected	31 202	9735
Independent reflections	11 211 ($R_{int} = 0.1021$)	4867 ($R_{int} = 0.1119$)
Completeness to θ	26.38° (99.2%)	25.03° (96.9%)
Absorption correction	Semi-empirical from equivalents	Semi-empirical from equivalents
Refinement method	Full-matrix least-squares	Full-matrix least-squares
Goodness-of-fit on F^2	F^2	F^2
Final R indices [$I > 2\sigma(I)$]	0.966	0.972
R indices (all data)	$R_1 = 0.0586$, $wR_2 = 0.0845$ $R_1 = 0.1440$, $wR_2 = 0.1038$	$R_1 = 0.0633$, $wR_2 = 0.0889$ $R_1 = 0.1948$, $wR_2 = 0.1190$
Largest diff. peak and hole (e Å^{-3})	1.830 and −1.073	1.115 and −0.521

3.3. Crystal structure determination

Diffraction measurements of compounds **4** and **8** were carried out at 293 K on a Bruker Smart 1000 diffractometer (graphite-monochromatized Mo–K_α radiation, $\lambda = 0.71073$ Å). The crystal class, orientation matrix and accurate unit-cell parameters were determined by standard procedures. The intensities were corrected for absorption using SADABS program. The structure was solved by heavy atom method and refined by a full-matrix least-square procedure based on F^2. Non-hydrogen atoms were refined with anisotropic thermal parameters. Crystal data are summarized in Table 8.

4. Supplementary material

Crystallographic data for the structures reported in this paper have been deposited with the Cambridge Crystallographic Data Centre, CCDC No. 211437 for compound **4** and CCDC No. 211438 for compound **8**. Copies of this information may be obtained free of charge from the Director, CCDC, 12 Union Road, Cambridge, CB2 1EZ, UK (Fax: +44-1223-336033; e-mail: deposit@ccdc.cam.ac.uk or http://www.ccdc.cam.ac.uk).

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