APPLIED ORGANOMETALLIC CHEMISTRY, VOL. 8, 517–523 (1994)

Synthesis, NMR Spectra and Chromatographic Properties of Five Trimethylarsonioribosides

Kevin A. Francesconi,* John S. Edmonds* and Robert V. Stickt
* Western Australian Marine Research Laboratories, PO Box 20 North Beach 6020, Australia, and
† Department of Chemistry, The University of Western Australia, Nedlands 6009, Australia

Five trimethylarsonioribosides were prepared from naturally occurring and synthetic dimethylarsinylribosides (arsenosugars) by reducing them with 2,3-dimercaptopropanol and quaternizing the resultant arsine with methyl iodide. The trimethylarsonioribosides prepared in this manner were the four novel compounds methyl 5-deoxy-5-trimethylarsonio-β-D-riboside (as the iodide), (2′*R*)-2′,3′-dihydroxypropyl 5-deoxy-5-trimethylarsonio-β-D-riboside (as the formate), 3′-[(2″, 3″ - dihydroxypropyl)hydroxyphosphinyloxy] - 2′ - hydroxypropyl 5-deoxy-5-trimethylarsonio-β-D-riboside and 3-(5′-deoxy-5′-trimethylarsonio-β-D-ribosyloxy)-(2*S*)-2-hydroxypropanesulfonate, and the known (2′*S*)-2′-hydroxy-3′-(sulfooxy)propyl 5-deoxy-5-trimethylarsonio-β-D-riboside. They were synthesized to serve as standards for chromatographic analyses of arsenic compounds in marine samples and for investigations into the biotransformation of arsenic in marine organisms. NMR spectral and chromatographic data for the five trimethylarsonioribosides are presented and compared with those of their dimethylarsinyl analogues.

Keywords: Arsenic, marine organisms, trimethylarsonioribosides, dimethylarsinylribosides, arsenosugars

INTRODUCTION

The presence of arsenic in marine organisms was first reported at the beginning of this century, and much is now known about the concentrations and chemical forms of arsenic in marine samples.[1] Following the identification of arsenobetaine in marine animals[2] and of arsenosugars in marine algae,[3] interest has been directed towards the biogenesis and interrelationships of these arsenic compounds, and the possibility of their having some biochemical or physiological role in marine organisms.[4]

Fifteen arsenosugars have been isolated and identified as algal constituents.[1] Most of these arsenicals have been dimethylarsinylribosides, but the trimethylarsonioriboside **5** has also been reported as a trace constituent from two algal sources.[5,6] When added to anaerobic marine sediments under laboratory conditions, compound **5** was quantitatively converted to arsenocholine,[7] the likely immediate precursor of arsenobetaine in marine animals. The ease with which this conversion occurred in the laboratory suggested that trimethylarsonioribosides may serve as intermediates in the biogenesis of arsenobetaine. Compound **5** is the trimethylated analogue of the dimethylarsinylriboside **10**, the major arsenosugar in marine algae. Probably, trimethylated analogues of other dimethylarsinylribosides also occur in algae, but their low concentrations preclude their isolation and identification by the techniques previously employed for arsenosugars. The availability of synthetic standards would facilitate chromatographic studies on the occurrence of trimethylarsonioribosides in marine samples and of their importance in marine arsenic transformations. We report here the synthesis, NMR spectra and some chromatographic properties of five trimethylarsonioribosides.

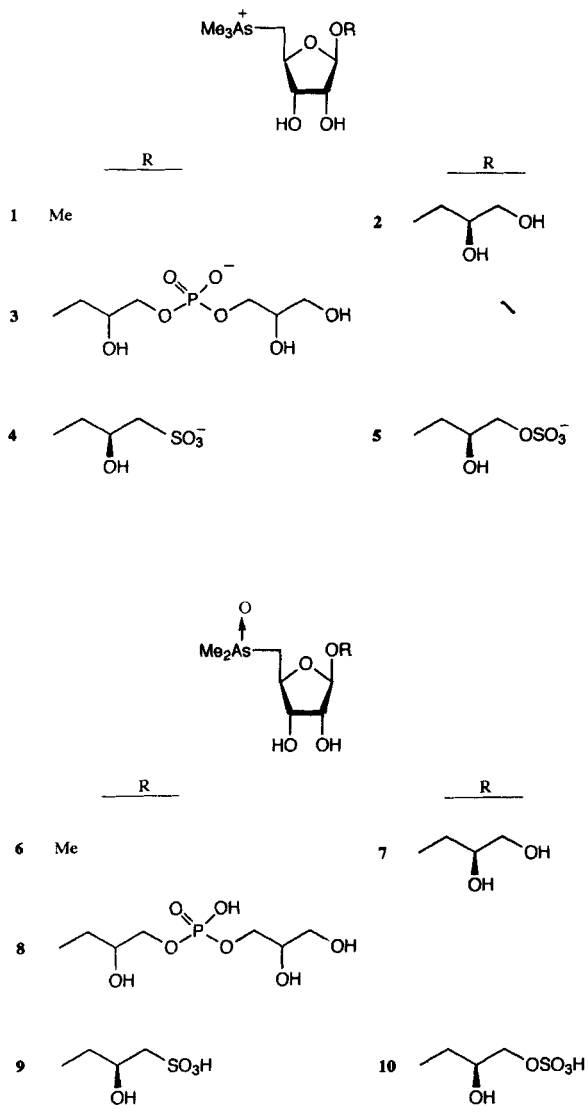
EXPERIMENTAL

Arsenic concentrations were determined by graphite furnace atomic absorption spectrophotometry with a Varian GTA-95 furnace coupled to a Varian 875 spectrophotometer. Nickel(II) nitrate served as co-analyte.

Gel permeation chromatography was carried out with Sephadex G-15 (column size 26 × 900 mm, water as eluant, flow rate 30 ml h^{-1}, fraction size 10 ml) and Sephadex LH-20 (column size 26 × 600 mm, methanol as eluant, flow rate 30 ml h^{-1}, fraction size 5 ml) media. Anion exchange chromatography was performed on DEAE A-25 Sephadex (column size 26 × 900 mm

CCC 0268–2605/94/060517–07

Received 24 January 1994
Accepted 22 April 1994



or 26 × 340 mm, equilibrated with 0.05 mol dm^{-3} Tris buffer at pH 8.0, flow rate 90 ml h^{-1}, fraction size 20 ml) and cation exchange chromatography was carried out on CM C-25 Sephadex (column size 26 × 300 mm, equilibrated with 0.1 mol dm^{-3} ammonium formate buffer at pH 6.5, flow rate 40 ml h^{-1}, fraction size 10 ml). Ion (anion or cation) exchange chromatography was carried out with buffer at the same molarity and pH as that used to equilibrate the column. Following ion exchange chromatography, buffer was separated from the arsenic compound by gel permeation chromatography—a procedure referred to here as 'desalting'.

Thin layer chromatography (TLC) was performed on glass plates precoated with layers of cellulose (0.5 mm or 0.1 mm) developed in 1-butanol/acetic acid/water (60:15:25) or in 1-propanol/NH_3 (7:3).

NMR spectra were recorded in D_2O on a Bruker AM 300 at 300 MHz (^1H) and 75.5 MHz (^{13}C). ^1H spectra were recorded relative to external 2,2-dimethyl-2-silapentane-5-sulfonate (DSS) at δ_H 0.00; for ^{13}C spectra, methanol (δ_C 49.00) served as an external standard. *J*-Values are given in Hz.

Solvents were removed under vacuum at 40 °C. Melting points were recorded on a Kofler hot stage. The Australian Microanalytical Service in Melbourne carried out C and H analyses. Optical rotations were determined in a micro cell on a Perkin Elmer 141 polarimeter at ambient temperature.

Methyl 5-deoxy-5-trimethylarsonio-β-D-riboside (as the iodide) 1

Dimethylarsinyl-β-D-riboside **6** (83 mg, 0.31 mmol), prepared as previously described,[8] was stirred in methanol (5 ml) with 2,3-dimercaptopropanol (0.4 mmol). Methyl iodide (0.2 ml) was added after 10 min and the mixture was stirred overnight at room temperature. The reaction mixture was then partitioned between ether and water; evaporation of the aqueous layer gave the iodide **1** (113 mg, 93%) which crystallized from ethanol/ether (1:1) as plates, m.p. 170–171 °C, $[\alpha]_D$ +1.3° (*c* 2.5, MeOH) (Found: C, 27.2; H, 5.1. $C_9H_{20}AsIO_4$ requires C, 27.4; H, 5.1%). ^1H NMR (300 MHz, D_2O) δ 1.99 (s, Me_3As); 2.68 (dd, $J_{5,5}$ 13.8, $J_{4,5}$ 10.5 Hz, H5); 2.86 (dd, $J_{5,5}$ 13.8, $J_{4,5}$ 2.9 Hz, H5); 3.43 (s, OMe); 4.10 (m, H2); 4.16–4.28 (m, H3,4); 4.93 (s, $J_{1,2}$ 0.0 Hz, H1). ^{13}C NMR (75.5 MHz, D_2O) δ 7.9 (Me_3As); 30.3 (C5); 56.0 (OMe); 74.2 (C2); 75.6 (C3); 77.0 (C4); 108.8 (C1).

(2'*R*)-2',3'-Dihydroxypropyl 5-deoxy-5-trimethylarsonio-β-D-riboside (as the formate) 2

Dimethylarsinyl-β-D-riboside **7** (9.5 mg, 0.03 mmol), synthesised by the method of McAdam,[9] was stirred in methanol (2 ml) with 2,3-dimercaptopropanol (0.04 mmol). Methyl iodide (0.1 ml) was added after 10 min and the mixture was stirred overnight at room temperature. The mixture was partitioned between ether and water and the material obtained on evaporation of the aqueous layer was chromatographed

on CM Sephadex (with ammonium formate buffer). Following desalting (Sephadex LH-20/MeOH) the formate **2** was obtained as a syrup (7.7 mg, 71%). ^{1}H NMR (300 MHz, D_2O) δ 1.99 (s, Me_3As); 2.65–2.90 (m, H5, 5); 3.55–3.77 (m, 4H, H1′, 3′); 3.9 (m, H2′); 4.15 (m, H2); 4.26 (m, H3, 4); 5.03 (s, $J_{1,2}$ 0.0 Hz, H1); 8.46 (s, $HCOO^-$). ^{13}C NMR (75.5 MHz, D_2O) δ 7.8 (Me_3As); 30.4 (C5); 62.5 (C3′); 69.2, (C1′); 70.3 (C2′); 74.4 (C2); 75.8 (C3); 77.0 (C4); 107.8 (C1); 171.2 ($HCOO^-$).

3′-[(2″,3″-Dihydroxypropyl)hydroxyphosphinyloxy]-2′-hydroxypropyl 5-deoxy-5-trimethylarsonio-β-D-riboside, 3

A portion (2.5 mg As, 0.03 mmol) of the arsenic-containing phosphoric acid diester **8** from *Sargassum lacerifolium*[8] was stirred in methanol (1.5 ml) with 2,3-dimercaptopropanol (0.04 mmol). After 10 min methyl iodide (0.1 ml) was added and the mixture was stirred at room temperature overnight. The mixture was then partitioned between ether and water and the syrup obtained on evaporation of the aqueous layer was subjected to anion exchange chromatography (column size 26 × 340 mm). A trace of arsenic eluted at the void volume (90 ml), followed by the product at 150 ml. Desalting (Sephadex G-15) yielded compound **3** as a syrup (2.5 mg As, 18.5 mg, 95% yield), $[\alpha]_D$ + 1.4° (*c* 1.8, H_2O) (Found: C, 35.4; H, 6.7. $C_{14}H_{30}AsO_4P$ requires C, 35.0; H, 6.3%). ^{1}H NMR (300 MHz, D_2O, see Fig. 1) δ 2.00 (s, Me_3As); 2.73 (dd, $J_{5,5}$ 13.8, $J_{4,5}$ 10.2 Hz, H5); 2.88 (dd, $J_{5,5}$ 13.8, $J_{4,5}$ 3.1 Hz, H5); 3.6–4.1 (m, 10H, H1′, 2′, 3′, 1″, 2″, 3″; 4.17, dd, $J_{2,3}$ 4.0, $J_{2,4}$ 0.8 Hz, H2); 4.21–4.31 (m, H3,4; 5.05, s, $J_{1,2}$ 0.0 Hz, H1). ^{13}C NMR (75.5 MHz, D_2O, see Fig. 2) δ 7.8 (Me_3As); 30.4 (C5); 62.3 (C3″); 66.1 (d, $J_{P,C}$ 6 Hz) and 66.5 (d, $J_{P,C}$ 6 Hz) (C1″,3′); 68.7 (C1′); 68.9 (d, $J_{P,C}$ 9 Hz); 70.9 (d, $J_{P,C}$ 9 Hz) (C2′,2″); 74.4 (C2); 75.8 (C3); 77.0 (C4); 107.7 (C1).

3-(5′-Deoxy-5′-trimethylarsonio-β-D-ribosyloxy)-(2*S*)-2-hydroxypropanesulfonate, 4*

A small portion (0.20 mg As, 0.003 mmol) of the arsenic-containing sulfonic acid derivative **9** isolated from *Ecklonia radiata*[3] was stirred in methanol (1 ml) with 2,3-dimercaptopropanol (0.005 mmol) for 10 min followed by addition of methyl iodide (0.1 ml). The mixture was stirred overnight at room temperature, partitioned between ether and water, and the resulting aqueous layer was concentrated to a syrup which was chromatographed on a column (26 × 340 mm) of DEAE Sephadex. A small quantity of arsenic eluted at the void volume (90 ml) and the rest eluted as a single band (peaking at 150 ml). After desalting on Sephadex G-15, 3-(5′-deoxy-5′-trimethylarsonio-β-D-ribosyloxy)-(2*S*)-2-hydroxypropanesulfonate **4** was obtained as a solid (0.20 mg As, 90% yield). ^{1}H NMR (300 MHz, D_2O) δ 2.00 (s, Me_3As); 2.74 (dd, $J_{5',5'}$ 13.7, $J_{4',5'}$ 10.5 Hz, H5′); 2.88 (dd, $J_{5',5'}$ 13.7, $J_{4',5'}$ 2.9 Hz, H5′); 3.08 (dd, $J_{1,1}$ 14.3, $J_{1,2}$ 6.3 Hz, H1); 3.20 (dd, $J_{1,1}$ 14.3, $J_{1,2}$ 5.8 Hz, H1); 3.69 (dd, $J_{3,3}$ 10.5, $J_{2,3}$ 3.5 Hz, H3); 3.86 (dd, $J_{3,3}$ 10.5, $J_{2,3}$ 5.4 Hz, H3); 4.18 (d, $J_{2',3'}$ 4.1 Hz, H2′); 4.22–4.33 (m, H2,3′, 4′); 5.07 (s, $J_{1',2'}$ 0.0 Hz, H1). ^{13}C NMR (75.5 MHz, D_2O) δ 7.8 (Me_3As); 30.4 (C5′); 53.8 (C1); 66.5 (C2); 70.8 (C3); 74.4 (C2′); 75.9 (C3′); 76.9 (C4′); 107.7 (C1′).

(2′*S*)-2′-Hydroxy-3′-(sulfooxy)propyl 5-deoxy-5-trimethylarsonio-β-D-riboside, 5

Procedure A. The sulfuric acid ester derivative **10** (19 mg, 0.047 mmol) previously isolated from *Tridacna maxima*[10] was stirred in methanol (2 ml) with 2,3-dimercaptopropanol (0.1 mmol). Methyl iodide (0.2 ml) was added after 10 min and the reaction mixture was stirred overnight at room temperature. The mixture was then partitioned between ether and water; evaporation of the aqueous layer gave a syrup which was applied in 2 ml of Tris buffer to a column (26 × 340 mm) of DEAE Sephadex. Arsenic eluted from the column in three major bands, peaking at 90 ml (void volume, 20% of As), 170 ml (50% of As) and 970 ml (30% of As, the elution volume expected for unchanged starting material). The void volume material was desalted on Sephadex LH-20/methanol to yield a syrup (3.4 mg). It was shown to be a mixture of compounds by ^{1}H NMR spectroscopy and was not examined further. The material eluting at 170 ml was desalted (Sephadex G-15/water) to yield a solid (9 mg) which, from ^{1}H and ^{13}C NMR spectra, appeared to be a mixture of the desired product **5** (80%) and its α-anomer **11** (20%). This material was subjected to TLC (cellulose, 1-butanol/acetic acid/water, 60:15:25), and the broadened arsenic band was

* Arsenosugars with a sulfonic acid group in the aglycon are named as sulfonic acids rather than as ribosides, and the numbering of the molecular skeleton changes accordingly.

split into three bands. ^{1}H NMR spectroscopy revealed that the central band (60% of As) contained two anomers in approximately the same proportions as before the TLC operation; the fastest running band was almost pure β-anomer and the slow running band contained the putative α-anomer as the major compound (3:1).

Procedure B. The sulfuric acid ester **10** (0.50 mg As, 0.007 mmol) was stirred in methanol (1.5 ml) as methyl iodide (0.1 ml) and then 2,3-dimercaptopropanol (0.01 mmol) were added. The mixture was stirred at room temperature overnight, then partitioned between ether and water. The aqueous layer was evaporated to yield a syrup which was subjected to anion exchange chromatography (column size 26 × 340 mm) to give arsenic at the void volume (<2% of As), at 170 ml (65% of As) and at 980 ml (35% of As). The material eluting at 170 ml was desalted (Sephadex G-15/water) to give (2′*S*)-2′-hydroxy-3′-(sulfooxy)propyl 5-deoxy-5-trimethylarsonio-β-D-riboside **5** as a solid (0.30 mg As, 60%). NMR data for **5** have been previously reported[5,8] but are presented here for completeness. ^{1}H NMR (300 MHz, D_2O) δ 2.01 (s, Me_3As); 2.71 (dd, $J_{5,5}$ 13.8, $J_{4,5}$ 10.3 Hz, H5); 2.88 (dd, $J_{5,5}$ 13.8, $J_{4,5}$ 3.3 Hz, H5); 3.64 (dd, $J_{1',1'}$ 10.6, $J_{1',2'}$ 3.1 Hz, H1′); 3.86 (dd, $J_{1',1'}$ 10.6, $J_{1',2'}$ 4.0 Hz, H1′); 4.05–4.14 (m, H2′,3′,3′); 4.17 (dd, $J_{2,3}$ 4.0, $J_{2,4}$ 0.6 Hz, H2); 4.21–4.33 (m, H3,4); 5.05 (s, $J_{1,2}$ 0.0 Hz, H1). ^{13}C NMR (75.5 MHz, D_2O) δ 7.7 (Me_3As); 30.4 (C5); 67.7 (C2′); 68.1 (2C, C1′,3′); 74.2 (C2); 76.0 (C3); 77.0 (C4); 107.6 (C1).

Procedure C. The sulfuric acid ester **10** (0.44 mg As, 0.006 mmol) was stirred with methanol (1.5 ml) and 2,3-dimercaptopropanol (0.01 mmol) at room temperature for 5 h. Methyl iodide (0.1 ml) was then added and the mixture stirred overnight. After partitioning between ether and water the syrup obtained on evaporation of the aqueous layer was subjected to anion exchange chromatography (column size 26 × 340 mm). Most of the arsenic eluted at the void volume (65% of total) and at 170 ml (25% of total). The latter arsenic band was desalted (Sephadex G-15/water) to yield a syrup (100 μg As) shown by ^{1}H NMR to be a mixture (1:1) of the desired compound **5** and its putative α-anomer **11**.

RESULTS AND DISCUSSION

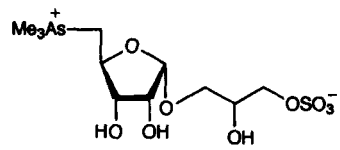
Synthesis of trimethylarsonioribosides

Shibata and Morita[5] synthesised compound **5** in 51% yield by reducing the naturally occurring **10** from *Sargassum thunbergii* with sodium borohydride and treating the resultant arsine with methyl iodide. In a study on a mechanistic model for the biological reduction of arsenicals, Cullen *et al.*[11] showed that trimethylarsine oxide was readily reduced by thiols. The reductant used in the present study was the thiol 2,3-dimercaptopropanol. Without purification, the resultant arsine was quaternized with methyl iodide. Methanol was a suitable solvent for both reactions. The polar product was readily separated from the less polar reactants by partitioning the reaction mixture between ether and water. When necessary, further purification was effected by ion exchange chromatography. In this manner, compounds **1–4** were obtained in good yield.

The synthesis of **5**, however, was not straightforward. Anion exchange chromatography of the reaction products yielded some non-acidic arsenic (20%), weakly acidic arsenic (50%) and strongly acidic arsenic (30%); the last eluted at the position expected for unchanged starting material. The non-acidic material was shown (^{1}H NMR) to be a mixture of compounds. These were not identified. The NMR spectra of the weakly acidic product suggested that it was a mixture (4:1) of the target compound **5** and possibly its α-anomer **11** (see Table 1). The most diagnostic signal in the ^{13}C NMR spectrum of the proposed α-anomer was that assigned to C1 which occurred at δ 102.8 compared with δ 107.6 for the usual β-anomer. For methyl D-ribofuranosides, resonances assigned to C1 in the α- and β-anomers

Table 1 ^{13}C chemical shifts (δ) for the compounds **11** and **5**, the putative α-anomer and the β-anomer of 2′-hydroxy-3′-(sulfooxy)propyl 5-deoxy-5-trimethylarsonio-D-riboside

11 α-anomer	**5** β-anomer	Assigned carbon
102.8	107.6	C1
78.2	76.9	C4
74.2	76.0	C3
70.9	74.4	C2
69.2	68.1	C1′
69.1	68.1	C3′
68.5	67.7	C2′
29.3	30.4	C5
8.0	7.7	Me_3As^+



11

occur at δ 103.1 and δ 108.0, respectively.[12] The presence of the α-anomer in the mixture was supported by the ^{1}H NMR spectrum where a doublet ($J_{1,2}$ = 4.3 Hz) at δ 5.22 was consistent with a *cis* configuration at C1 and C2 of the D-ribose ring. This apparent mixture of anomers could be partially separated by TLC, but compound **11** was never obtained completely free of **5**.

The quaternization of the sulfuric acid ester **10** was then attempted under two different reaction conditions. In the first experiment methyl iodide was present with compound **10** at the time of addition of 2,3-dimercaptopropanol thus enabling quaternization to occur as soon as the arsine was produced. The target trimethylarsonioriboside **5** was the major product uncontaminated with the putative α-anomer. In the second experiment compound **10** was stirred with 2,3-dimercaptopropanol for 5 h before the addition of methyl iodide. On this occasion the major products were unidentified non-acidic arsenicals and compound **5** was a minor product contaminated with an equal quantity of the putative α-anomer. The by-products in the second experiment may have resulted from instability of the arsine in the reaction medium but scarcity of starting material (in this instance, the natural product isolated from *Tridacna*[10]) precluded a thorough investigation. We are currently synthesizing **10** and plan to investigate further the mechanism of this proposed anomerisation.

NMR spectra and chromatographic properties of trimethylarsonioribosides

The NMR spectra of the five trimethylarsonioribosides showed a consistent pattern (the spectra of one of the compounds are shown in Figs 1 and 2). For each of the five arsonio compounds the three methyl groups on arsenic resonated as a singlet in the narrow range of δ 7.7–7.9 (^{13}C) and δ 1.99–2.01 (^{1}H). The ^{13}C NMR signal assigned to the methylene group attached to arsenic also registered in the narrow range of δ 30.3–

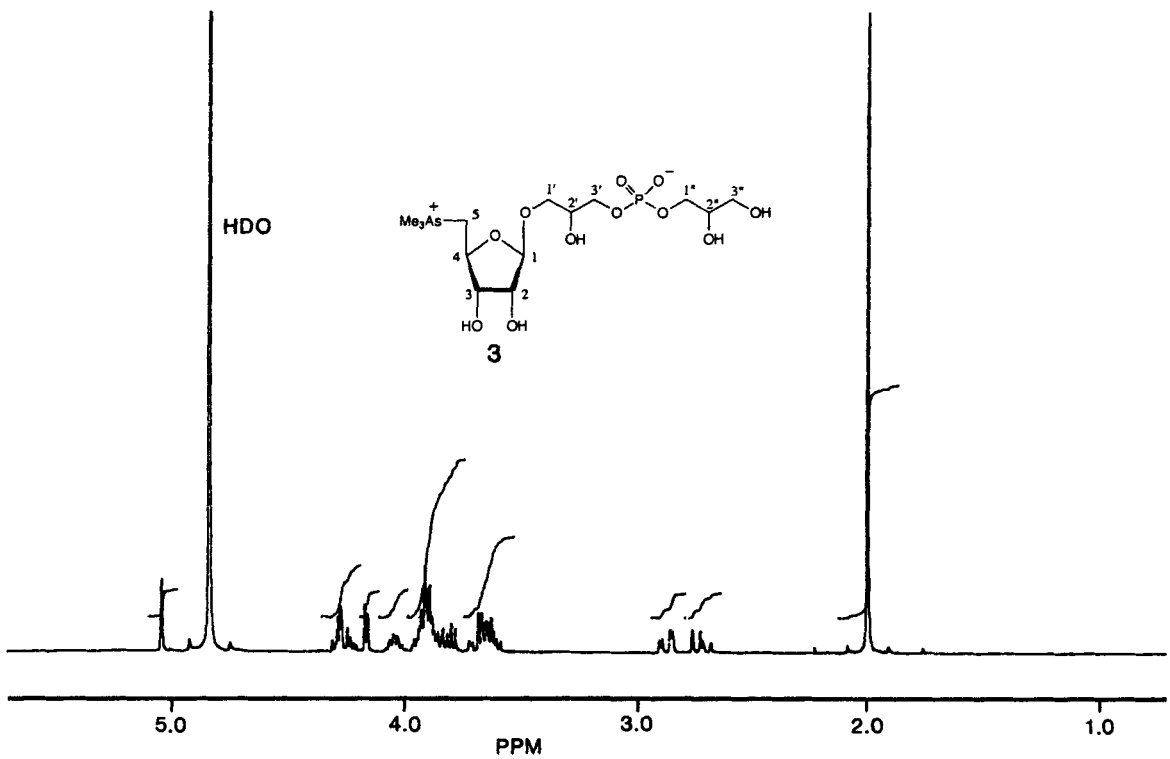


Figure 1 ^{1}H NMR spectrum of compound **3**. Signal assignments are given in the relevant section in the Experimental.

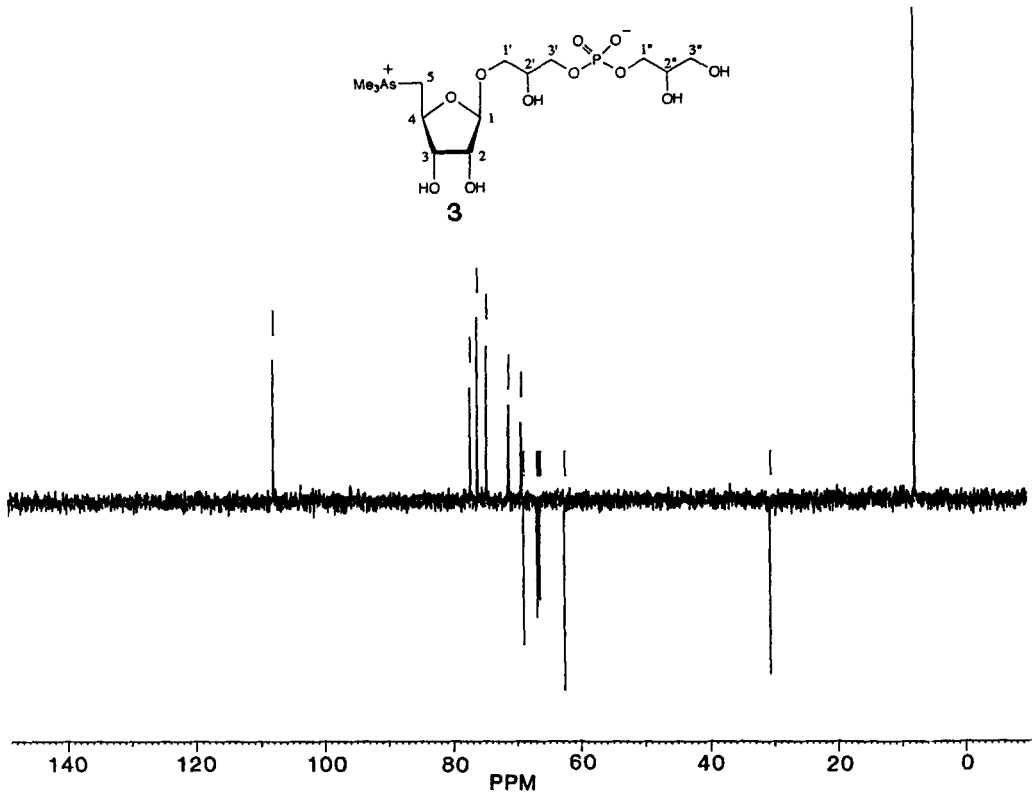


Figure 2 ^{13}C NMR spectrum of compound **3**. Signal assignments are given in the relevant section in the Experimental. A DEPT 135 experiment aided the assignments: methine and methyl carbons are displayed above the baseline, and methylene carbons are displayed below the baseline.

30.4 for the five compounds. These characteristic intense signals may facilitate the detection of trimethylarsonioribosides in only partially purified extracts. Relative to their dimethylarsinyl analogues, the new compounds all recorded an upfield shift (δ 7 for methyls, δ 6 for methylenes) in the resonances for carbons on arsenic, and a downfield shift (δ 0.12–0.25) for the protons associated with these carbons.

The TLC properties of the trimethylarsonio compounds were similar to those of their dimethylarsinyl analogues, and accordingly, could not be used to distinguish between them. However, as expected by the introduction of the cationic Me_3As^+ group, the arsonio compounds were readily separated from their arsinyl analogues by buffered ion exchange chromatography (Table 2).

The retention volumes of the trimethylarsonioribosides on Sephadex G-15 chromatography (Table 2) are of interest. In the present study, Sephadex G-15 was used to separate the buffer (and other impurities) from the arsenical product following ion exchange chromatography and, consequently, the eluant was water. Under these conditions, the carboxy groups on the G-15

Table 2 Chromatographic properties of trimethylarsonioribosides. Retention volumes for the corresponding dimethylarsinyl compounds are given in parentheses

Compound	Retention volume (ml)		
	DEAE[a]	CM[b]	G-15[c]
1	360 (360)	500 (150)	— (280)
2	360 (360)	500 (150)	— (280)
3	360 (1480)	150 (110)	240 (190)
4	410 (1980)	110 (110)	265 (240)
5	450 (2680)	110 (110)	280 (250)

[a] 26 × 900 mm, 0.05 mol dm^{-3} Tris pH 8.0, void volume 360 ml. Column flow rate was 90 ml h^{-1}, 20 ml fractions were collected. [b] 26 × 300 mm, 0.1 mol dm^{-3} ammonium formate pH 6.5, void volume 110 ml. Column flow rate was 40 ml h^{-1}, 10 ml fractions were collected. [c] 26 × 900 mm, water, void volume 150 ml. Column flow rate was 30 ml h^{-1}, 10 ml fractions were collected.

medium can interact with the charged groups on the solutes so that size is no longer the major factor determining retention volumes. For example, all five trimethylarsonioribosides elute more slowly than their dimethylarsinyl analogues because of the attraction between the Me_3As^+ group and the carboxy groups on the medium. Compounds **1** and **2**, which contain the Me_3As^+ group but lack an acidic group, are not eluted from the G-15 medium with water; desalting of these compounds needs to be carried out with Sephadex LH-20/methanol.

REFERENCES

1. K. A. Francesconi and J. S. Edmonds, Arsenic in the sea. In *Oceanography and Marine Biology. An Annual Review*, Ansell, A. D., Gibson, R. N. and Barnes, M. (eds), UCL Press, London, 1993, Vol. 31, p. 111.
2. J. S. Edmonds, K. A. Francesconi, J. R. Cannon, C. L. Raston, B. W. Skelton and A. H. White, *Tetrahedron Lett.* **18**, 1543 (1977).
3. J. S. Edmonds and K. A. Francesconi, *Nature (London)* **289**, 602 (1981).
4. K. A. Francesconi and J. S. Edmonds, Biotransformation of arsenic in the marine environment. In *Arsenic in the Environment, Part 1: Cycling and Characterization*, Nriagu, J. O. (ed.), John Wiley and Sons, Inc, Wiley, New York, 1994, p. 221.
5. Y. Shibata and M. Morita, *Agric. Biol. Chem.* **52**, 1087 (1988).
6. K. A. Francesconi, J. S. Edmonds and R. V. Stick, *J. Chem. Soc. Perkin Trans. 1*, 1349 (1992).
7. K. A. Francesconi, J. S. Edmonds and R. V. Stick, *Appl. Organomet. Chem.* **6**, 247 (1992).
8. K. A. Francesconi, J. S. Edmonds, R. V. Stick, B. W. Skelton and A. H. White, *J. Chem. Soc. Perkin Trans 1*, 2707 (1991).
9. D. P. McAdam, A. M. A. Perera and R. V. Stick, *Aust. J. Chem.* **40**, 1901 (1987).
10. J. S. Edmonds, K. A. Francesconi, P. C. Healy and A. H. White, *J. Chem. Soc. Perkin Trans. 1*, 2989 (1982).
11. W. R. Cullen, B. C. McBride and J. Reglinski, *J. Inorg. Biochem.* **21**, 45 (1984).
12. R. C. Beier and B. P. Mundy, *J. Carbohydr. Chem.*, **3**, 253 (1984).