ELSEVIER

Analysis of chemical warfare agents
I. Use of aliphatic thiols in the trace level determination
of Lewisite compounds in complex matrices

Bob Muir*, Ben J. Slater, David B. Cooper, Christopher M. Timperley

Defence Science and Technology Laboratory, Building 383b, Porton Down, Salisbury, Wiltshire SP4 0JQ, UK

Abstract

A series of normal aliphatic thiols have been used to derivatise the chemical warfare agents Lewisites I and II (LI and LII) in hydrocarbon matrices. Varying the chain length of the thiol allowed adjustment of derivative t_R by 5.9 min for Lewisite I and 5.3 min for Lewisite II. Linear regression analysis of the chain length of the thiol derivatives of the Lewisite species, and that of a series of normal alkanes against t_R, allowed regression models to be developed for each set of compounds. Application of the models allowed thiol reagents to be chosen to give derivatives of Lewisites I and II that eluted before and after the major hydrocarbon contaminant. Limits of detection were comparable for all thiol derivatives analysed by GC–MS in the selection ion monitoring mode (all below $1 \, \mu g \, ml^{-1}$). The robustness of this approach was illustrated by successful identification of Lewisite I in samples from the Sixth Proficiency Test (organised by the Organisation for the Prohibition of Chemical Weapons, OPCW) in a matrix of $1 \, mg \, ml^{-1}$ diesel oil.
© 2004 Elsevier B.V. All rights reserved.

1. Introduction and aim of investigation

Lewisite, developed as a chemical warfare agent in 1918 by Lewis and co-workers [1,2], has never been proven to have been used in war, but remains of concern, as illustrated by its inclusion in Schedule One of the Chemical Weapons Convention [3]. It is absorbed through the skin, producing painful blisters, and has high systemic toxicity [4]. Weapons-grade material made by the UK comprised 90% Lewisite I (LI), 9% Lewisite II (LII) and 1% Lewisite III (LIII). Extensive production and filling of munitions by several countries has led to environmental contamination [5]. Demilitarisation of old munitions and polluted areas have renewed interest in the trace analysis of chemical warfare agents and their degradation products [6].

ClCH=CHAsCl₂   (ClCH=CH)₂AsCl   (ClCH=CH)₃As
     LI   **LII**   **LIII**
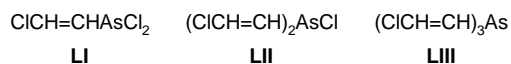
The blistering ability of Lewisite compounds is believed to be due to their reaction, or reaction of their hydrolysis products [7], with sulfhydryl-containing proteins in skin [8,9]. Lewisite I hydrolyses to species **1** and **2** which can react with two moles of thiol (Fig. 1) [10,11]. Lewisite II hydrolyses to species **3** and **4**. Lewisite II and hydrolysis product **3** can each react with a mole of thiol. Lewisite III is inert and does not react with nucleophiles such as water or thiols. An analytical method must allow determination of intact or hydrolysed arsenic compounds.

A problem with direct determination of compounds with an As-halogen group is their high reactivity and corrosive nature. Analysis of Lewisites I or II by gas chromatography results in rapid deterioration of the column and suffers the additional drawback that hydrolysis products **1–4** are relatively involatile. Lewisite III may be analysed directly but is of lesser importance. Derivatisation of reactive arsenic compounds prior to chromatography is therefore essential [12]. From reactions with thiols, alcohols and amines, it is apparent that the competitive rates of formation, or the stability at equilibrium, or both, of bonds involving the arsenic atom follow the order As–S > As–O >

* Corresponding author. Tel.: +44-1980-613599;
fax: +44-1980-613834.
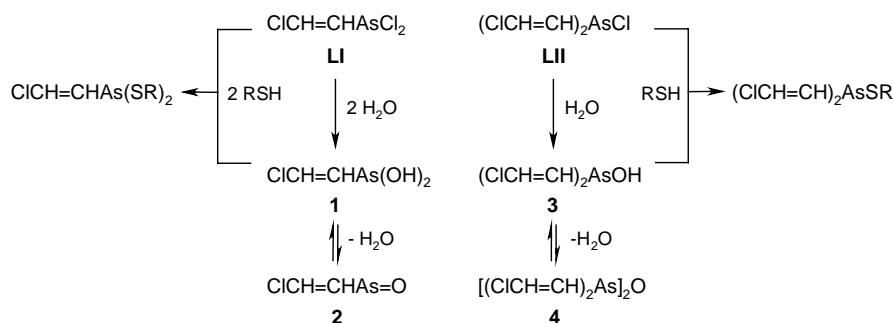*E-mail address:* bmuir@dstl.gov.uk (B. Muir).

Fig. 1. Hydrolysis pathways of Lewisites I and II and derivatisation reactions with thiols.

As–N [13]. Hence thiols are the preferred derivatising reagents.

Lewisite I has been derivatised with thioglycolic acid methyl ester and analysed by atomic emission detection (AED) and MS [14–16]. The same reagent has been used to derivatise the organoarsenical chemical agent Adamsite (*syn.* phenarzine chloride) for GC–AED and GC–MS [17] and methylarsonic acid and dimethylarsinic acid for flame ionization detection (FID) and GC–inductively coupled plasma (ICP) AED [18]. Thiols have also been used to derivatise related chemical warfare agents such as Pfiffikus ($PhAsCl_2$), Clark I (Ph_2AsCl) and Clark II (Ph_2AsCN) [19].

Reaction of intact or hydrolysed Lewisites I and II may be accomplished using mono and bis-thiols. Work in this laboratory demonstrated that Lewisite I and its hydrolysis products **1** and **2** could be derivatised with 3,4-dimercaptotoluene at ambient temperature. The method was used to detect hydrolysis product **2** at a former chemical-weapon storage site in the UK [20] and in water samples [21]. Aliphatic dithiols, such as ethane-1,2-dithiol and propane-1,3-dithiol, have been used to derivatise Lewisites I and II and their hydrolysis products [22–29]. Haas showed that a series of ω-dithiols, up to C_8, and ethanethiol and propanethiol reacted with Lewisite I [29]. The derivatives have favourable GC properties and mass spectral fragmentation patterns.

High hydrocarbon backgrounds are common in environmental samples. Often a particular hydrocarbon dominates the chromatogram, masking the signals for the Lewisite derivatives and complicating their identification by GC–MS. Grossly contaminated samples may also cause a rise in foreline pressure of the vacuum system resulting in incomplete data acquisition, perhaps before elution of the derivatives. Flame photometric detection (FPD) and atomic emission detection are also problematic due to quenching of signals by hydrocarbons. In both cases the likelihood of missing Lewisite species increases dramatically.

This study examined the gas chromatographic and mass spectral properties of a range of derivatives of Lewisites I and II of formulae $ClCH=CHAs(SR)_2$ and $(ClCH=CH)_2AsSR$, prepared from straight-chain aliphatic thiols having 2–12 carbon atoms. Their GC properties were used to predict the t_R window in which they could be detected in a high hydrocarbon background. Linear regression equations for

the derivatives and normal alkanes were devised to allow the t_R of each derivative to be predicted accurately and to permit detection by GC–FPD in a hydrocarbon-rich matrix. This paper is the first in a series on the quantification of chemical warfare agents in environmental samples.

2. Experimental

2.1. Chemicals

Lewisites I, II and III were synthesised in the laboratory using literature methods [30,31] in an efficient, dedicated fume-cupboard. Heavy rubber gloves, a chemically resistant Microgard smock (Orvec International, Hull, UK) and a face visor were worn. A Perspex safety shield was used during distillations. Ethanethiol, propanethiol, butanethiol, nonanethiol and decanethiol were purchased from Aldrich (Gillingham, UK), pentanethiol, hexanethiol, octanethiol and dodecanethiol from Acros Organics (Loughborough, UK) and heptanethiol, undecanethiol and thiethylamine from Lancaster Chemicals (Morecambe, UK). All were at least 95% pure and were used as received.

2.2. Derivatisation procedure

Lewisites I, II and III and a mixture of the compounds were prepared in hexane: 1 ml stock was derivatised using 200 μl of 1 mg ml^{-1} thiol in hexane by agitation on a vortex mixer for 10 s. 50 μg triethylamine were added prior to agitation to catalyse the reaction.

2.3. GC–MS and GC–FPD analysis

A Hewlett-Packard 5890 Series 2 GC system interfaced to a Hewlett-Packard 5971A mass-selective detector, with a DB5-MS column (30 m × 0.25 mm, 0.33 μm), was used. An initial oven temperature of 40 °C was maintained for 1 min then increased at 20 °C min^{-1} to a final temperature of 300 °C and held at this temperature for 9 min. A sample volume of 2 μl was injected in splitless mode at 250 °C at a carrier gas pressure of 15 psi (1 psi = 6894.76 Pa). The inlet was operated in constant flow mode to give a

linear velocity of 37.7 cm s^{-1} (15 psi set at 40 °C). An Agilent Technologies 6890 GC system coupled to a dual channel FPD system (scan rate 20 cycles s^{-1}) was used to analyse derivatives of Lewisites I and II in sulfur mode. The temperature programme was identical to that used for GC–MS analysis. Parameters used were: injection volume 1 μl, inlet temperature 180 °C, pressure 18.3 psi set at 40 °C (30 cm s^{-1}, 0.9 ml min^{-1}). Detector settings were as follows: temperature 250 °C, hydrogen flow 145 ml min^{-1}, air flow 110 ml min^{-1}, make-up gas (N$_2$) 15 ml min^{-1}.

2.4. Calibration and limits of detection (LODs)

Standards of Lewisites I and II, and a mixed standard containing Lewisites I, II and III, were prepared in concentrations of 0.01, 0.05, 0.1, 0.25, 0.5, 1 and 2.5 μg ml^{-1} in hexane. Lewisites I and II in the standards were derivatised with each thiol as described in Section 2.2; Lewisite III is unreactive. Derivatives were characterised from interpretation of electron impact ionization (EI) fragmentation patterns. Ions suitable for selected ion monitoring (SIM) were selected. Calibration plots were linear for each thiol derivative.

Detection limits were calculated for GC–MS-SIM as described by Miller and Miller [32]. Each standard was run in triplicate and linear regression analysis performed to give regression coefficients for each derivative. In all equations, the intercept term was found to be non-significant ($P > 0.05$) and was excluded from the final equation. The limit of detection is given by Eq. (1). Standard error and slope terms refer to parameters calculated by performing linear regression analysis on each derivative concentration and resulting peak area. The standard deviation is that of the fitted line from the predicted line.

$$LOD = \frac{3S.E.}{slope} \tag{1}$$

GC–FPD was used as a qualitative confirmatory technique in this study; hence LODs were not established for this technique.

3. Results

3.1. General characteristics of thiol derivatives of LI and LII

Bis-derivatives of Lewisite I could be prepared up to C$_8$ and those of Lewisite II up to C$_{12}$. Mono-derivatives of Lewisite I beyond C$_8$ were prepared but they gave no response by GC–MS. The lower reactivity of Lewisite I probably reflects the decreasing ease of the second substitution with increasing chain length of the thiol. As the carbon chain in the intermediate ClCH=CHAs(SR)Cl lengthens, the arsenic atom becomes more hindered, rendering attack by another molecule of thiol more difficult. The cut-off point is when the chain is eight carbon atoms long. In the

Table 1
Retention times, molecular masses, SIM ions and limits of thiol derivatives of Lewisites I and II

Aliphatic thiol[a]	Chain length	Property				
		M_w	t_R (min)	LOD SIM (ng)		SIM ions
				Single[b]	Mix[c]	
Lewisite I						
Ethanethiol	C$_2$	258	9.5	0.19	0.2	107, 136, 171
Propanethiol	C$_3$	286	10.5	0.14	0.15	107, 150, 286
Butanethiol	C$_4$	314	11.6	0.12	0.10	164, 204, 314
Pentanethiol	C$_5$	342	12.6	0.34	0.28	178, 232, 342
Hexanethiol	C$_6$	370	13.5	0.30	0.22	192, 260, 370
Heptanethiol	C$_7$	398	14.4	0.31	0.42	206, 288, 398
Octanethiol	C$_8$	426	15.4	0.57	0.37	220, 316, 426
Lewisite II						
Ethanethiol	C$_2$	258	9.1	0.12	0.14	107, 138, 258
Propanethiol	C$_3$	272	9.7	0.13	0.15	107, 150, 272
Butanethiol	C$_4$	286	10.2	0.22	0.15	107, 164, 286
Pentanethiol	C$_5$	300	10.8	0.55	0.4	145, 229, 300
Hexanethiol	C$_6$	314	11.4	0.11	0.13	117, 192, 314
Heptanethiol	C$_7$	328	11.9	0.05	0.18	131, 171, 328
Octanethiol	C$_8$	342	12.5	0.13	0.24	161, 197, 342
Nonanethiol	C$_9$	356	13.0	0.56	0.35	145, 159, 356
Decanethiol	C$_{10}$	370	13.4	0.25	0.31	145, 173, 370
Undecanethiol	C$_{11}$	384	13.9	0.33	0.42	145, 187, 384
Dodecanethiol	C$_{12}$	398	14.4	0.35	0.48	145, 201, 398

[a] Methanethiol (C$_1$) was not investigated as a derivatising agent as it differs from the other thiols in that it is a gas.
[b] Single component standards of each derivative analysed.
[c] Mixture of LIII and LI and LII derivatives analysed.

case of Lewisite II, steric hindrance is not encountered, as this compound only has one displaceable chlorine atom, not two, and derivatives with chains up to 12 carbon atoms long can be prepared without difficulty. In general, higher molecular-weight derivatives of Lewisites I and II were relatively involatile and their t_R too long to be of practical use.

3.2. Development of mathematical models and potential utility

Derivatisation with thiols allowed the t_R of Lewisites I and II to be varied (Table 1). The same GC conditions were used for C_9–C_{30} alkanes (Table 2). Many of these might co-elute with the thiol derivatives. For example, derivatives of Lewisite I from hexanethiol and heptanethiol may co-elute with the C_{22} and C_{24} alkanes, respectively, and derivatives of Lewisite II from C_4 to C_{12} thiols might co-elute with C_{16}–C_{24} alkanes. Hydrocarbons present in environmental samples in high concentrations would mask the GC–MS signals and quench the FPD and AED signals of the Lewisite derivatives.

Linear regression analysis was used to find the relationship between t_R and thiol chain length (Eqs. (2)–(4)). All equations established a strong linear relationship between variables $r^2 \geq 0.99$ and $F = \ll 0.05$, and allowed accurate prediction of t_R:

$$t_{R\,LI} = 7.60 + 0.97x \tag{2}$$

$$t_{R\,LII} = 8.13 + 0.53x \tag{3}$$

$$t_{R\,alkanes} = 0.38 + 0.59x \tag{4}$$

Table 2
Retention times and molecular weights of various normal alkanes

| Aliphatic alkane	Chain length	M_w	t_R (min)
Nonane	C_9	128	5.0
Decane	C_{10}	142	5.8
Undecane	C_{11}	156	6.6
Dodecane	C_{12}	170	7.5
Tridecane	C_{13}	184	8.2
Tetradecane	C_{14}	198	8.9
Pentadecane	C_{15}	212	9.6
Hexadecane	C_{16}	226	10.2
Heptadecane	C_{17}	240	10.8
Octadecane	C_{18}	254	11.4
Nonadecane	C_{19}	268	11.9
Eicosane	C_{20}	282	12.5
Heneicosane	C_{21}	296	13.0
Docosane	C_{22}	310	13.4
Tricosane	C_{23}	324	13.9
Tetracosane	C_{24}	338	14.4
Pentacosane	C_{25}	352	14.8
Hexacosane	C_{26}	366	15.4
Heptacosane	C_{27}	380	16.0
Octacosane	C_{28}	394	16.7
Nonacosane	C_{29}	408	17.5
Triacontane	C_{30}	422	18.5
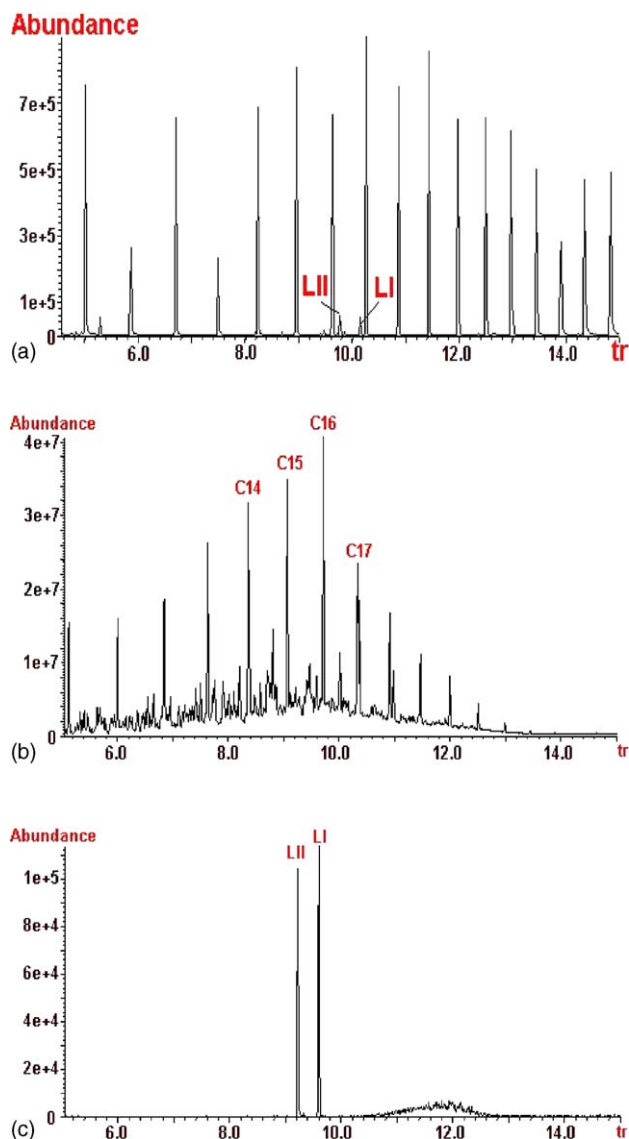
Fig. 2. Ethanethiol derivatives of Lewisites I and II (each 5 μg ml^{-1}). (a) In C_9–C_{25} alkanes (50 μg ml^{-1}), (b) TIC in diesel matrix (50 mg ml^{-1}) and (c) EIC in diesel matrix (50 mg ml^{-1}). Time scales in min.

where x is the number of carbon atoms present in thiol or alkane.

Identification of the most abundant hydrocarbon in a sample by GC–MS allows a t_R window to be calculated in which Lewisite derivatives elute between alkane peaks. Fig. 2a shows the ethanethiol derivatives of Lewisites II and I, in a mixture of C_9–C_{30} alkanes, eluting at 9.1 and 9.5 min, respectively. Fig. 2b shows a total ion chromatogram of the Lewisite species in a diesel matrix. The chromatogram is dominated by hexadecane. A t_R was chosen to allow the Lewisite derivatives to elute before this alkane. Solving Eqs. (2) and (3) with a t_R of 9.1 min (LII) and 9.5 min (LI) confirms ethanethiol as the preferred derivatising reagent to allow elution between alkane peaks. Derivatives of Lewisites II and I prepared from this thiol eluted between the C_{15} and C_{16} alkanes and avoided quenching of the FPD signals.
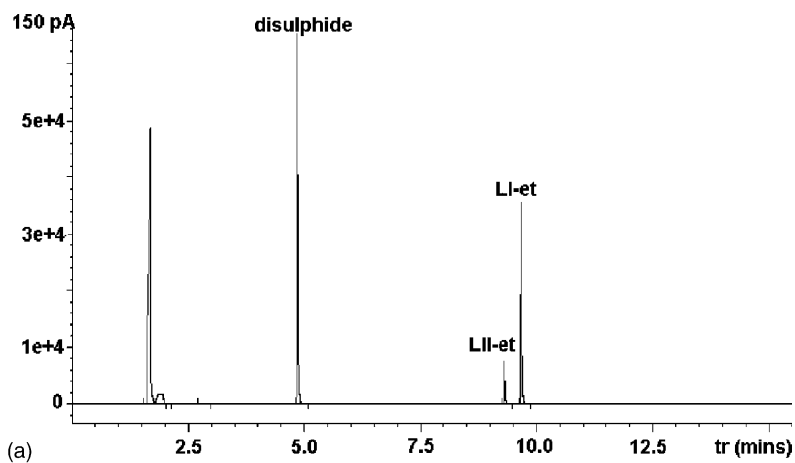
LI-et = Lewisite I ethanethiol derivative
LII-et = Lewisite I ethanethiol derivative
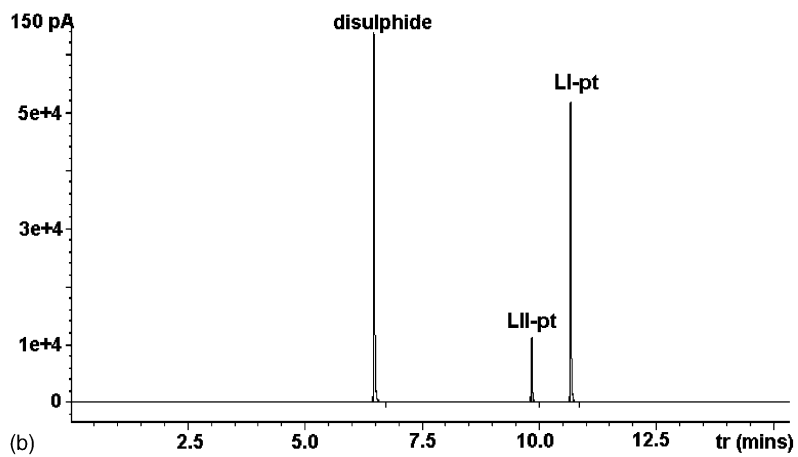
LI-pt = Lewisite I propanethiol derivative
LII-pt = Lewisite I propanethiol derivative
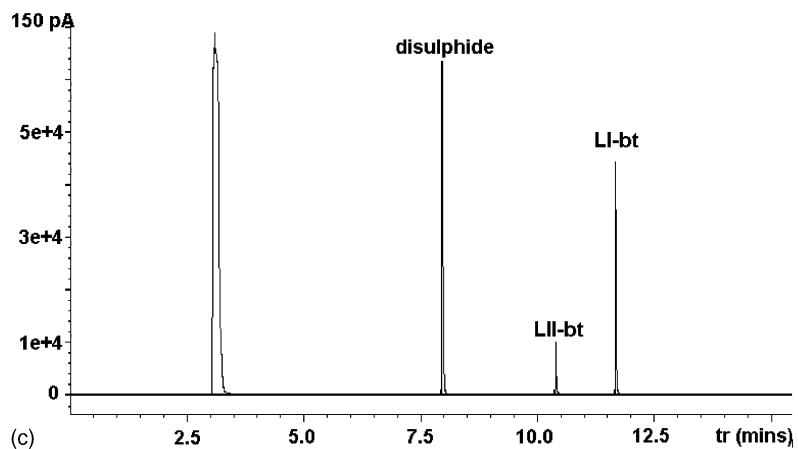
LI-bt = Lewisite I butanethiol derivative
LII-bt = Lewisite I butanethiol derivative

Fig. 3. GC–FPD chromatograms of Lewisites I and II (5 µg ml^{-1}) thiol derivatives. (a) Ethanethiol derivatives in diesel oil (1 mg ml^{-1}), (b) propanethiol derivatives in diesel oil (1 mg ml^{-1}) and (c) butanethiol derivatives in diesel oil (1 mg ml^{-1}).

An extracted ion chromatogram (EIC) is necessary to detect the derivatives by GC–MS at a concentration of 5 µg ml^{-1}. Fig. 2c illustrates the favourable signal-to-noise ratio of Lewisites I and II in a high hydrocarbon background. Where co-elution is unavoidable, e.g. the butanethiol derivative of Lewisite I, the EIC may still be used with confidence as the selected fragmentation ions from this derivative are not shared by the co-eluting alkane. Eqs. (2)–(4) can be used in two ways in GC–MS analysis of samples dominated by a particular alkane.

(i) A thiol could be chosen to allow elution of LI and LII derivatives prior to the dominant alkane and the MS turned off immediately afterwards, allowing data acquisition to continue unaffected by the rise in foreline pressure.

(ii) A thiol of higher carbon number could be chosen, thus separating the dominant alkane and Lewisite signals. A suitable solvent delay or MS off-time could be set and data acquisition commenced prior to elution of LI and LII derivatives.

3.3. Limits of detection

The limits of detection for all thiol derivatives in SIM, including ions monitored, are listed in Table 1. Detection limits were similar when calibrations were constructed using single component standards or the mixed standard, confirming complete derivatisation of Lewisites I and II in the presence of excess thiol. The detection limit for Lewisite III was 0.1 ng for SIM quantitation.

Thiol derivatives of Lewisites I and II exhibit favourable LODs by GC–MS-SIM. Derivatives of Lewisites I and II with propanethiol, butanethiol and pentanethiol have superior LODs to other thiol derivatives, but any derivative should allow successful detection of Lewisites I and II at levels found in environmental samples, such as those encountered in international proficiency tests.

3.4. Validation of model: detection of Lewisite species in diesel-spiked sample

Fig. 2b shows the distribution of alkanes in a 1 mg ml^{-1} diesel oil sample. The regular distribution of hydrocarbons should allow analysis of thiol derivatives by GC–FPD in sulfur mode without quenching. Fig. 3a–c shows GC–FPD chromatograms of derivatives of Lewisites I and II with ethanethiol, propanethiol and butanethiol (5 ng) respectively in a diesel matrix (1 mg ml^{-1}). The agreement of predicted and observed t_R, calculated using Eqs. (2) and (3), was excellent (>95%) for all derivatives of Lewisites I and II, the former showing roughly twice the response of the latter. Although eluting close to pentadecane, the peaks corresponding to the derivatives of Lewisites I and II with ethanethiol are observable, suggesting no quenching of signal.
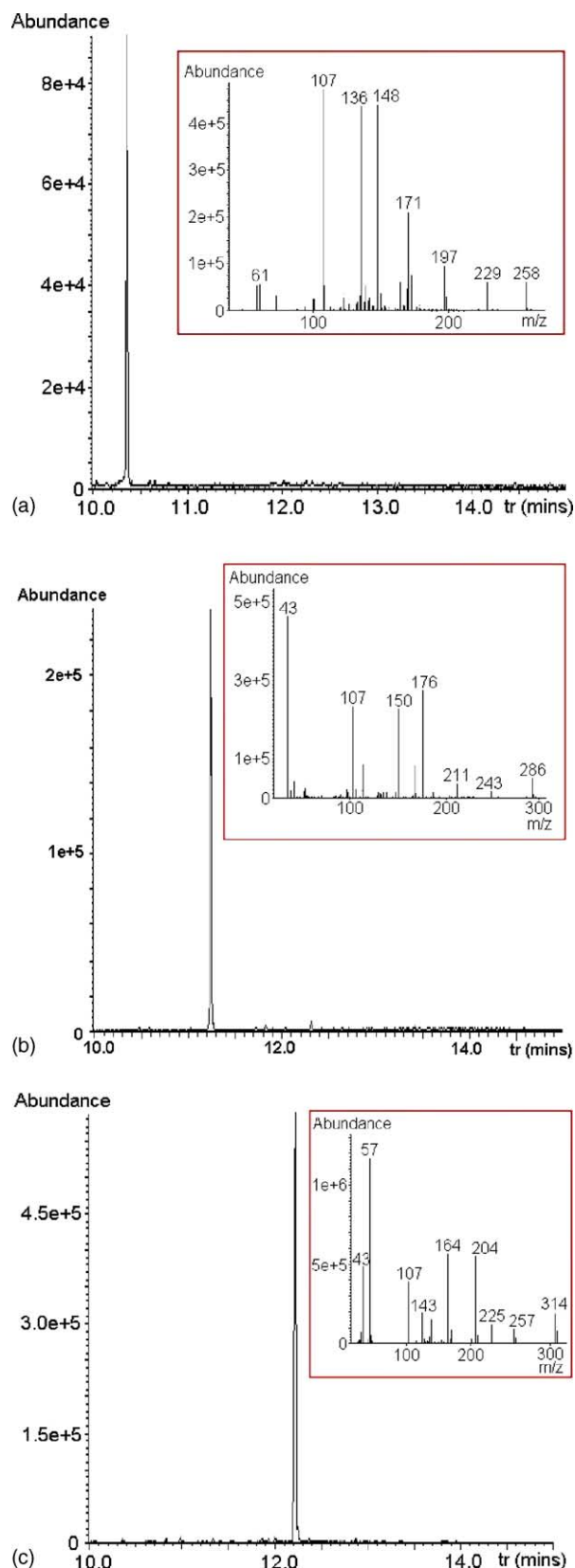

Fig. 4. GC–MS EICs of Lewisite I in proficiency test sample (organic liquid). (a) Ethanethiol derivative (m/z 136), (b) propanethiol derivative (m/z 176) and (c) butanethiol derivative (m/z 204).

(a)

LI-et = Lewisite I ethanethiol derivative

(b)

LI-pt = Lewisite I propanethiol derivative

(c)

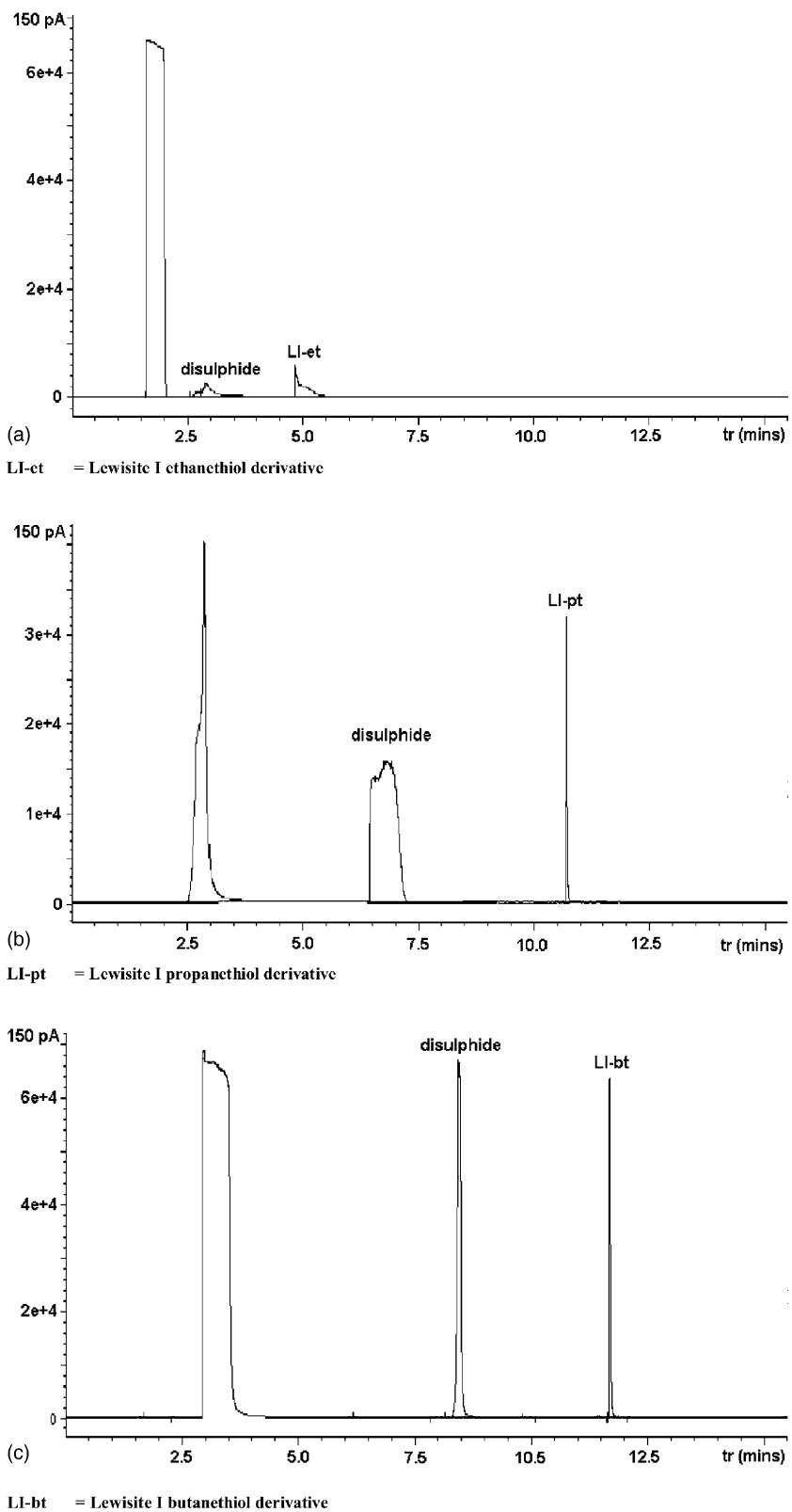**LI-bt** = Lewisite I butanethiol derivative

Fig. 5. GC–FPD chromatogram of Lewisite I in proficiency test sample (organic liquid). (a) Ethanethiol derivative, (b) propanethiol derivative and (c) butanethiol derivative.

3.5. Validation of model: detection of Lewisite species in an OPCW proficiency test sample

An organic liquid sample was supplied to the Defence Science and Technology Laboratory, Porton Down, as part of the Sixth Proficiency Test and the presence of Lewisite compounds checked by GC–MS and GC–FID.

The principle hydrocarbon was found to be dodecane that eluted between 7.5 and 8.5 min. t_R windows after 8.5 min were deemed suitable as all the dodecane had eluted after this time. Reference to Tables 1 and 2 shows that all thiol derivatives of Lewisites I and II elute after 8.5 min. The tailing of the overloaded dodecane peak apparent in Fig. 4a suggests propane and butanethiol as derivatising reagents. Eqs. (2) and (3) were solved to allow elution of Lewisites I and II species after 8.5 min.

Extracted ion chromatograms for derivatives of Lewisite I made from ethanethiol, propanethiol and butanethiol appear in Fig. 4a–c. All thiol derivatives of Lewisite I can be detected by obtaining EICs using suitable ions. Although eluting in the tail of the dodecane peak, the ethanethiol derivative was detected using the EIC. In summary, ethanethiol, propanethiol and butanethiol derivatives are suitable for detection of Lewisite I in this sample. Lewisites II and III were not detected in the sample analysed.

Supporting analysis was performed using GC–FPD in sulfur mode. Fig. 5a–c show the GC–FPD responses of the three thiol derivatives of Lewisite previously analysed by GC–MS. Propanethiol and butanethiol derivatives are easily detected in this sample (Fig. 5b and c). The poor response of the ethanethiol derivative of Lewisite I (Fig. 5a) was probably due to signal quenching by dodecane, illustrating the importance of selecting the correct thiol.

4. Conclusions

This study has provided mathematical models to predict t_R for a series of derivatives of Lewisites I and II prepared from aliphatic thiols. Derivatives of Lewisites I and II could be prepared to C_8 to C_{12} respectively. Limits of detection by GC–MS-SIM were less than 1 $\mu g\,ml^{-1}$. Lewisite I was identified in an OPCW proficiency test sample containing dodecane by derivatisation with propanethiol and butanethiol, followed by GC–MS detection. Quenching of the FPD signals by dodecane excluded ethanethiol as a derivatising agent in this instance.

A new approach for analysis of Lewisites I and II by GC–MS and GC–FPD is proposed where two of the possible thiol derivatives are prepared after identifying the dominant hydrocarbons in the sample by GC–MS. Thiol derivatives can then be selected using the mathematical model to enable detection by both GC–MS and GC–FPD.

References

[1] W.L. Lewis, G.A. Perkins, Ind. Eng. Chem. 15 (1923) 290.
[2] W.L. Lewis, H.W. Stiegler, J. Am. Chem. Soc. 47 (1925) 2546.
[3] Convention on the Prohibition of the Development, Production, Stockpiling and Use of Chemical Weapons and on their Destruction, Organisation for the Prohibition of Chemical Weapons (OPCW), The Hague, 1994.
[4] K.E. Jackson, M.A. Jackson, Chem. Rev. 16 (1935) 43.
[5] N.B. Munro, S.S. Talmage, G.D. Griffin, L.C. Waters, A.P. Watson, J.F. King, V. Hauschild, Environ. Health Perspect. 107 (1999) 933.
[6] R.M. Black, B. Muir, J. Chromatogr. A 1000 (2003) 253.
[7] M. Sartori, The War Gases—Chemistry and Analysis, Churchill, London, 1940.
[8] M. Goldman, J.C. Dacre, Rev. Environ. Contamin. Toxicol. 110 (1989) 75.
[9] L.B. Sasser, J.A. Cushing, P.W. Mellick, D.R. Kalkwarf, J.C. Dacre, J. Toxicol. Environ. Health 47 (1996) 321.
[10] C.L. Hewett, J. Chem. Soc. (1948) 1203.
[11] W.A. Waters, J.H. Williams, J. Chem. Soc. (1950) 18.
[12] W.R. Creasy, J. Am. Soc. Mass Spectrom. 10 (1999) 440.
[13] R. Haas, A. Krippendorf, Z. Umweltchem. Ökotox. 10 (1998) 141.
[14] H. Haruguchi, A. Takatsu, Spectrochim. Acta 42B (1987) 235.
[15] K. Schoene, J. Steinhanses, H.-J. Bruckert, A. König, J. Chromatogr. 605 (1992) 257.
[16] R. Haas, Environ. Sci. Pollut. Res. 5 (1998) 2.
[17] K. Schoene, H.-J. Bruckert, H. Jürling, J. Steinhanses, J. Chromatogr. A 719 (1996) 401.
[18] B. Beckermann, Anal. Chim. Acta 135 (1982) 77.
[19] R. Haas, T.C. Schmidt, K. Steinbach, E. von Löw, Fresenius J. Anal. Chem. 361 (1998) 318.
[20] D.B. Cooper, T.A. Hall, D. Utley, 1991, unpublished results.
[21] J. Chen, L.M. Zhou, G.L. Qu, Chin. J. Anal. Chem. 29 (2001) 1276.
[22] L.A. Stocken, J. Chem. Soc. (1947) 592.
[23] W.K. Fowler, D.C. Stewart, D.S. Weinburg, E.W. Sarver, J. Chromatogr. 558 (1991) 235.
[24] J.R. Smith, T.P. Logan, L.L. Szafraniec, E.M. Jakubowski, Anal. Lett. 28 (1995) 1541.
[25] R. Haas, A. Krippendorf, Environ. Sci. Pollut. Res. 4 (1997) 123.
[26] B. Szostek, J.H. Aldstadt, J. Chromatogr. A 807 (1998) 253.
[27] X. Chaudot, A. Tambuté, M. Caude, J. Chromatogr. A 880 (2000) 327.
[28] B.A. Tomkins, G.A. Sega, C.-H. Ho, J. Chromatogr. A 909 (2001) 13.
[29] R. Haas, Z. Umweltchem. Ökotox. 10 (1998) 198.
[30] S.J. Green, T.S. Price, J. Chem. Soc. 121 (1921) 448.
[31] C.S. Gibson, J.D.A. Johnson, J. Chem. Soc. (1931) 753.
[32] J.C. Miller, J.N. Miller, Statistics for Analytical Chemistry, Third ed., Ellis Horwood, Chichester, 1993.